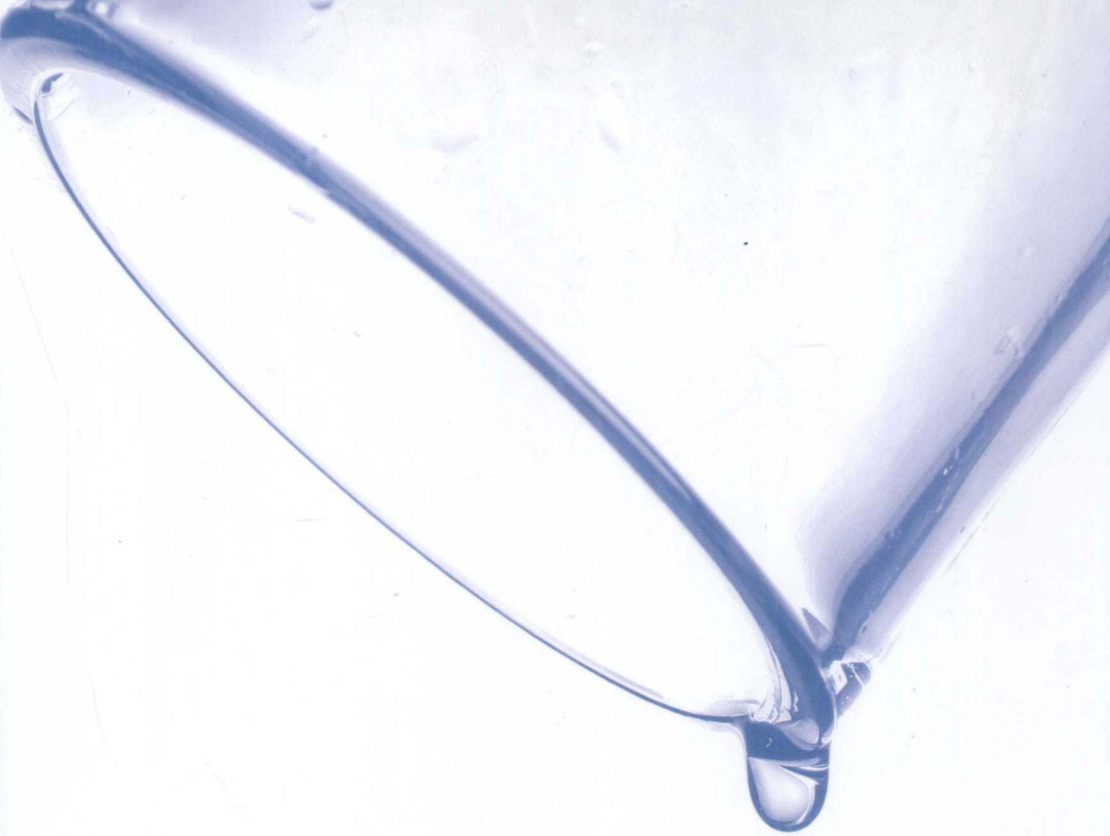

Water 4.0

The Past, Present, and Future of the World's Most Vital Resource

David Sedlak

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Yale UNIVERSITY PRESS/NEW HAVEN & LONDON

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Designed by Mary Valencia.
Set in Minion and Futura types by Westchester Book Group.
Printed in the United States of America.

Library of Congress Catalogin-in-Publication Data

Sedlak, David L.
Water 4.0 : the past, present, and future of the world's most vital resource / David Sedlak.
pages cm
Includes bibliographical references and index.
ISBN 978-0-300-17649-0 (hardback)
1. Water—History 2. Water and civilization—History. 3. Water resources development—History. 4. Water-supply engineering—History. I. Title.
GB659.6.S44 2014
333.91—dc23

2013025433

A catalogue record for this book is available from the British Library.

This paper meets the requirements of ANSI/NISO Z39.48–1992 (Permanence of Paper).

10 9 8 7 6 5 4 3

Preface

Most of the time we can go about our daily lives without knowing anything about the hidden world of water. The miles of pipes that bring water into our homes from distant locations, the treatment plants that ensure the wastes we pour into the sink and flush down the toilet don't pollute the local river, and the network of storm drains that keep the rain from flooding our homes continue to operate silently, day and night, whether or not we are aware of their existence. These unsung heroes of modern urban life and the people who run them are happy to stay out of the limelight. Except for periods when major investments are required, there really isn't much need to understand how water travels in and out of our cities. Unfortunately, it looks like we are approaching one of those periods.

The need for change bombards us through the media. How many times in recent years have you read about a city squabbling with farmers and environmental groups over water rights? Another article connecting climate change and the increasing frequency of severe droughts or exceptional floods? Or perhaps it's a government report about a familiar pharmaceutical compound showing up in drinking water? These seemingly disparate problems are all signs that water systems built in the nineteenth century and later retrofit with twentieth-century technologies may not be up to the challenges of the twenty-first century.

In response to the growing inadequacies evident in our existing approach to water, politicians, entrepreneurs, multinational corporations, and environmentalists have stepped up to advocate for their vision of a better way of handling water. Some claim that water shortages can be solved by investing in the next generation of treatment plants capable of purifying sewage to a point where it can be piped back into reservoirs or in desalination plants that can turn seawater into drinking water. Those inclined toward minimizing our impact on the environment advocate for water conservation, expanded use of local water sources, and integration of natural processes into the system designed to collect and treat water. And still others tell us that the crisis is one of our own making and that the answers to all of our water problems can be found in commonsense reform of the inefficient institutions that are responsible for allocating and regulating urban water.

How can someone who is not already an expert make informed judgments about the hidden world of urban water? About twenty years ago, when I started getting interested in these issues, I encountered a problem: the books on water intended for a general audience were too general, with large sections dedicated to disparate issues like wasteful agricultural water use, destruction of aquatic habitat, and the water and sanitation needs in the developing world. The more specialized books, reports, and scientific papers on urban water systems I eventually found, along with my own experiences working with people who were trying to overcome some of these problems, filled in many of the gaps in my knowledge, but that's not a path most of us have the time and inclination to follow.

After I learned my way around the topic, I continued to meet members of the public who craved more information about urban water issues, but it was not until 2009, when I was asked to give a talk to several thousand students and community members at Gustavus Adolphus College, that I thought I might have a way to help fill this gap. For my talk, I decided that the most effective way to make the science of potable water reuse more accessible to a general audience was to begin with an explanation of how drinking water systems have evolved over the centuries. Preparing a few slides on the history of drinking water and sewage treatment at the start of my presentation turned out to be a great way to put the problem into perspective, and it didn't require a lot of research on my part to put together a broad overview. At the time, I didn't realize that I had started a much larger project. The success I had in explaining current water problems by providing the historical background sent me on a four-year journey to fill the gaps in my knowledge about the origins of the problems that we currently face and about the wide range of solutions that are being debated by people on the front lines of our current water challenges.

For me, the greatest surprise has been the degree to which the urban water story goes beyond science and technology. As I studied the past, I came to appreciate the ways in which the water systems that we are struggling to maintain and improve are an integral part of the success of our great cities. The world of urban water has been populated by people who were trained in the practices of their times but had to invent new approaches for overcoming the problems that arose as their cities expanded. Whatever the era, when it came time to think about obtaining water, draining streets, and disposing of wastes, the engineers responsible for urban water systems first turned to the strategies that had succeeded in the past, adding incremental improvements as they increased the size of their systems to accommodate an expanding population. Eventually, they reached a point where the old ways were no longer viable. Facing the inertia that frequently accompanies calls for new spending on infrastructure, they struggled with failing water systems for decades until society finally reached a consensus about the need for change. Even after the need for a new approach was recognized, the path was not always clear. Some innovative, new ideas faded away as their shortcomings became evident. Others only improved over time as operating experience made them more efficient. After a while, the cities where the problems had been particularly acute pioneered new ways of handling water that became the norm throughout the developed world.

Viewed as just another stage in the evolution of urban water systems, our current situation does not seem so intractable. Water shortages, flooded streets, and a growing list of water pollutants, coupled with a lack of willingness to pay for upkeep and improvements, certainly feel like a crisis to the people who are struggling to keep the water moving. But our current challenges are not all that different from those that were solved by previous generations. Urban water systems will always need an occasional upgrade. Perhaps this time the added complication of climate change, along with the challenges associated with providing water to tens of millions of people living in the same watershed, is making the problem more complex. But it is difficult to imagine that the rapid advances in electronics, materials science, and biotechnology of recent decades cannot help us to solve these problems.

The repeated cycle of growth, failure, and reinvention that has occurred over the past 2,500 years of urban water systems can be likened to a series of revolutions. The first revolution, Water 1.0, occurred as the piped water systems and sewers first built by the ancient Romans were replicated in European cities that were growing very quickly during the first wave of global industrialization. As these cities continued to expand, public health suffered because the massive volumes of wastes flowing out of sewers transmitted waterborne diseases such as cholera and typhoid. Drinking water treatment, or Water 2.0, was the next revolution—stemming the spread of waterborne disease and leading to unimagined health benefits. Jump ahead half a century to a world in which modern technology and continued economic progress had caused cities to expand until the wastes pouring out of their sewers were causing more than a little bit of trouble immediately downstream. Following decades of decline in the rivers, lakes, and estuaries surrounding cities, a third revolution—Water 3.0—occurred as sewage treatment plants became a standard feature of urban water systems.

Another half century later and all signs point to the approach of a fourth revolution, Water 4.0, as continued population growth and climate change stretch the ability of urban water systems to meet our needs. At this stage of the cycle, the nature of the challenge is poorly understood by the people who will eventually have to make the big decisions. In the cities where water systems are showing the greatest signs of stress, the problems manifest themselves in different ways. In some places, it's too much water, while others struggle with chronic shortages and still others are struggling to maintain pipe networks and treatment plants that are falling apart under the pressure of escalating maintenance costs. The components of the fourth revolution are still a work in progress, with multiple paths leading to better water systems, provided that we are willing to invest the resources, energy, and political will needed to make them a reality. Decisions about the future of urban water systems are best made by an informed public. I hope that this book and the associated website (www.water4point0.com) will not only contribute to a broader, deeper understanding of the issues, but also motivate readers to become personally involved in efforts to improve their community's water system.

Acknowledgments

When I started researching and writing this book, I had no idea how much dedication it takes to create one. It would have never been written without a lot of help from people who share my passion for a better water future.

I am deeply appreciative to Naomi Lubeck for her encouragement and critical reviews of my writing. She helped me to make the transition from dull technical writing to a text that might hold the interest of someone other than an ambitious graduate student. Any lapses back into jargon and passive voice are entirely my fault.

I am also very grateful to my agent, Andy Ross, who stuck with me as I learned my way around the art and inexact science of putting together a book. When the world lost its best bookstore, it gained a fantastic literary agent. Thanks also to my acquisitions editor Jean Thomson Black at Yale University Press for editorial comments on the manuscript; to Sara Hoover for guiding me through all of the tiny but important details that go into a book; to my manuscript editor, Julie Carlson, for her thoughtful copyediting; and to Bill Nelson for his fantastic maps.

I appreciate the help of the people who shared their opinions about water or read and commented on various chapters. Peter David, Mike Kavanaugh, Sasha Harris-Lovett, and members of my research group all provided useful suggestions. Urs von Gunten, Janet Hering, and many other Swiss colleagues provided thought-provoking discussions during my sabbatical in Zurich. And I owe a special thanks to Jürg Hoigné for convincing me that the Middle Ages were a lot more than a bunch of cathedrals and crusaders. I am also grateful to Ronald Linsky, founding executive director of the National Water Research Institute, for his initial faith in my abilities. He had a big impact on the contents of the book even if he never had a chance to read the drafts.

Through the many hours of research that went into writing this book I have come to appreciate the efforts of the great scholars who plowed through the primary literature to reconstruct often forgotten moments in water history. Without them we would not understand how our water systems reached their current stage of development. I learned a lot from the works of scholars such as Martin Melosi, Joel Tarr, A. Trevor Hodge, Roberta Magnusson, and Donald Reid. Likewise, the many engineers, scientists, and policy experts whose works I relied on for my research were indispensable. I also gained a better understanding of the current state of urban water systems and efforts to create Water 4.0 through my interactions with leading practitioners like Mike Wehner, Harry Seah, Alan Plummer, and Rhodes Trussell. I apologize in advance for the errors that I have made as I tried to translate your teachings into a coherent narrative.

I cannot fully express my gratitude to my family. Meg, Jane, and Adam, I appreciate all of your patience in listening to early drafts of chapters, bearing with me during my moments of complete distraction, and maintaining a good sense of humor while touring the sewers of Paris, seeking the outlet of the Cloaca Maxima, and being dragged through various wetlands, recycling plants, and water features. I promise no sewage on the next family vacation.

Finally, I want to express my gratitude to Dick Luthy, Jörg Drewes, and the members of the National Science Foundation's Engineering Research Center on Reinventing the Nation's Urban Water Infrastructure (ReNUWIt). It's nice to know that there are so many talented people who are willing to devote their energy and creativity to writing the owner's manual for Water 4.0.

Contents

1

Water Supply in Rome, the World's First Metropolis

If water is the essential ingredient of life, then water supply is the essential ingredient of civilization. In ancient times, when people first began gathering in settlements for trade and mutual protection, they tended to locate within a short distance of their drinking water. But as settlements grew into villages and villages gave way to cities, people were forced to live farther away from their water source. Initially, the challenge of supplying areas of the city that were far from water was solved by digging a well or by paying for home delivery of water.[1] For the inhabitants of the first cities, obtaining water was just one more challenge that had to be overcome to reap the benefits of urban living.

As time passed, cities experimented with ways to import water. For example, around 700 BCE, inhabitants of the city of Erbil, in northern Iraq, dug gently sloping horizontal tunnels known as qanats to route groundwater into the city from a distance of approximately twenty kilometers (twelve miles) away.[2] Around the same time, the Greeks dug shallow canals to divert water into Troy and Athens from springs in the nearby hills.[3]

Densely packed groups of houses and the compressed soils that made up city streets also required drainage systems to prevent flooding. Early civilizations in the Indus Valley and Mesopotamia developed elaborate systems of gutters and covered channels for directing any water that accumulated in the streets into the nearest waterway. In many cases, the drainage systems included a way to collect drinking water: cisterns were built to capture clean water that ran off the roofs of buildings.[4]

These early prototypes made it clear that there were technological solutions to each of the major problems of urban water supply and drainage. But credit for the development of Water 1.0—a complete system of importing water, distributing it to homes and public spaces through a network of pipes, and returning used water to the environment—goes to the ancient Romans.

When it came time to take water to the next level, Roman water engineers didn't really have a choice: their city's water demand grew too big for the local sources. Before the Romans, the biggest cities in the ancient world rarely had more than 100,000 people. Provided that the climate was not too arid and the geology didn't preclude the use of shallow wells, cities of this size could usually manage by using local sources of water. But Rome was different. By around 300 BCE, the city's population had grown to somewhere around half a million people who not only needed to drink, but also loved baths and other forms of water recreation.[5] After Roman society began to thrive, the Tiber River (which runs through Rome), the shallow groundwater, and the local springs were no longer able to meet the needs of the thirsty city. In response, over the next five hundred years the city's engineers built a water system that ultimately imported enough water to supply Rome with a daily allotment comparable to that of our modern cities.[6]

When someone mentions ancient Rome's water supply, what first comes to mind are the graceful arches and elevated structures that crossed the arid valleys leading to the city. The iconic bridges, arcades, and viaducts of Rome are remarkable examples of the advances that Roman engineers made in structural engineering, hydraulics, and surveying. They also exemplify Rome's ability to create durable structures with concrete and masonry.[7] Yet the graceful, elevated sections of the aqueduct, while essential to the transport of water over long distances, are just a small part of the story: they made up only around 5 percent of the length of Rome's imported water system.[8] Furthermore, the Romans tried to avoid building them whenever possible, because they were costly and prone to failure. For example, the elevated section of the Aqua Claudia aqueduct took fifteen years to build and during its first two decades of use was only in service about half the time. Elevated structures were weak links in the Roman water supply chain. If the topography around the city had been more favorable, the Roman engineers would have avoided them entirely.[9]

Most of Rome's aqueducts actually consist of canals or underground pipes and tunnels that were made from masonry or cut into rock (the word aqueduct is derived from aqua—"water"—and ductus, "enclosed passage"). Although the entire Roman water system worked by gravity, maintenance of the reservoirs and aqueducts required vigilance so that damaged pipes and tunnels would be fixed quickly and debris that could block the flow of water would be removed. All of this maintenance and the construction of new aqueducts to meet the city's growing water demands required both funding from the emperor and donations by private citizens.[10]

Outside the city, much of the imported water system was hidden from view. The citizens of Rome could only see what their money had bought when the imported water entered the city on elevated structures, but these reminders of the infrastructure investment could get lost in the bustle of the city. To make the people aware of their accomplishments, Rome's leaders decorated the arches of the arcades where the aqueducts entered the city and built ornate fountains in public squares.[11] All of this extra effort can be seen as a political statement about the good works that the government had done rather than a tribute to the gods or an altruistic attempt to beautify the city. When Rome's aqueducts were rebuilt at the start of the Renaissance, the popes made sure that these decorative fountains were restored and updated for many of the same reasons.

In contrast to the Roman practice of building monuments to increase awareness of the city's hydraulic assets, most water arrives in modern cities with little fanfare. When fountains are built in public spaces, they are more likely to commemorate some nearly forgotten historical event or a deceased political figure than they are to celebrate the engineering prowess or institutional organization that was required to make the water flow. Perhaps if our water utilities took a cue from the Romans and advertised their accomplishments with beautiful fountains, they would have an easier time convincing the public about the need to invest in the upkeep of the system.

The aqueducts behind the fountains truly are engineering marvels when you consider that the Romans—without the aid of backhoes, concrete mixers, or satellite-enhanced surveying systems—built tunnels to exacting tolerances that followed the natural slopes of the hillsides. Placing the water supply underground avoided many of the challenges posed by viaducts. It also made the system more difficult for enemies to sabotage and minimized the likelihood that the water would be polluted as it flowed into the city.

Although the operation of a gravity-fed underground water delivery system may seem like a straightforward task, the Romans had to resolve a number of difficult problems in their quest to create a system that could reliably deliver water. Over a period of trial and error that spanned five centuries, the ancient Romans came up with concrete that could cure when exposed to water, arches capable of bearing the weight of massive volumes of water, and a number of other useful inventions.[12] For example, some sections of the aqueduct had to go down steep hills. Water flowing along these sections would move so fast that it would erode away the channel. The Romans solved this problem by installing stone structures in the aqueduct that made the bottom of the channel rough and so slowed the water's momentum.[13]

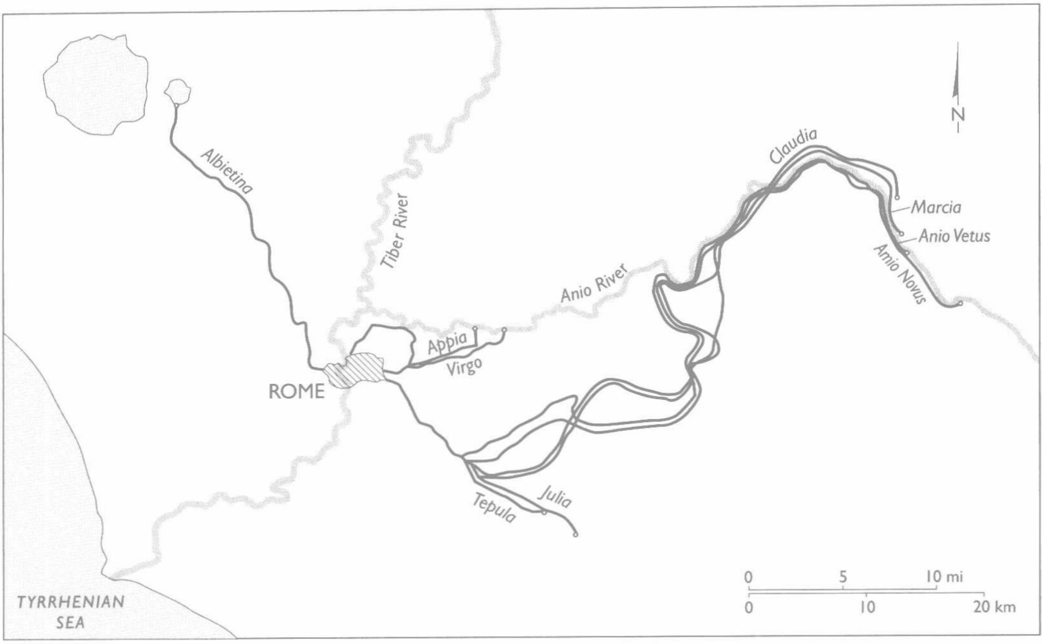
When the aqueduct crossed through a valley, it was necessary to move it up the next hill without the use of mechanical pumps. Roman engineers solved this problem by building massive inverted siphons that used the following downstream section of the aqueduct to help pull the water over the hill.[14] (If you have ever used a short length of garden hose to empty out an old aquarium or to take some gasoline out of your car's gas tank, you know how this works on a small scale: you fill the hose with water, or some other fluid, and as long as the place where the fluid leaves the hose is at a lower elevation, it will flow up and out. The Roman inverted siphons worked this way, except their "tubes" were made of bundles of lead pipes, each twenty-five centimeters [ten inches] in diameter.[15])

Roman engineers also had to grapple with changing conditions at the water source. Sometimes the water that they wanted to route through the aqueduct contained clay and sand that had been stirred up by a recent storm. If they let the sediment-laden water into the water distribution pipes, the pipes might clog. The Romans solved this problem by building wide troughs within the aqueduct system where the water velocity would slow enough to cause the particles to settle out (like sand in a lazy river) and where these particles could be removed easily by maintenance crews.[16]

Springs and streams located in the hills around the city fed the aqueducts and in most cases were easily connected to the water supply system. Sometimes, however, more complex engineering was employed. For example, the Anio Novus Aqueduct took its water from a reservoir that had originally been built to create a lake at Emperor Nero's villa. The forty-meter-high (130-foot) dam that held back the river remained the highest dam in the world for 1,500 years.[17]

A total of eleven aqueducts, with a cumulative length of over four hundred kilometers (250 miles), were built as Rome's water demand grew.[18] The Romans developed considerable expertise during the expansion of their water supply, because each successive project posed new and more difficult challenges. The knowledge that the Romans accrued while constructing their imported water systems allowed them to act as the world's first multinational construction company as they spread Water 1.0 to far-flung parts of the empire.

Ultimately, the aqueducts brought water into their capitol from distances as far away as approximately eighty kilometers (fifty miles). On a map of ancient Rome's aqueduct system, you can see the pattern that would later be repeated in the imported water systems of cities



The aqueducts of ancient Rome.

like Paris, New York, and Los Angeles: as the population needing water grew, the water system's canals extended ever farther from the city center, much like the ever-expanding root system of a growing plant.

Delivery of imported water to the fountains was quite a feat, but it solved only part of the problem. Because there were advantages to living close to the heart of the city, Rome experienced the same housing pressures that we encounter in cities today. That is, as its population density increased, detached housing became a luxury reserved for the privileged class. For the average Roman, home was an apartment in a building three to six stories high, and because Roman tenements weren't equipped with indoor plumbing, water had to be lugged upstairs. It isn't much of a surprise, then, that most Roman water use happened at street level.[19]