Urban Water Security

Robert C. Brears

Challenges in Water Management

WILEY

URBAN WATER SECURITY

Challenges in Water Management Series

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Water Resources: A New Management Architecture
Michael Norton, Sandra Ryan and Alexander Lane
2017
ISBN: 978-1-118-79390-9

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Registered Office
John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

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9600 Garsington Road, Oxford, OX4 2DQ, UK
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
111 River Street, Hoboken, NJ 07030-5774, USA

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Library of Congress Cataloging-in-Publication data applied for

ISBN: 9781119131724

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

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Cover image: © Peter Zelei images/Gettyimages

Set in 10/12pt Melior by SPi Global, Pondicherry, India

10 9 8 7 6 5 4 3 2 1

Contents

Series Editor Foreword – Challenges in Water Management

The World Bank in 2014 noted:

> Water is one of the most basic human needs. With impacts on agriculture, education, energy, health, gender equity, and livelihood, water management underlies the most basic development challenges. Water is under unprecedented pressures as growing populations and economies demand more of it. Practically every development challenge of the 21st century – food security, managing rapid urbanization, energy security, environmental protection, adapting to climate change – requires urgent attention to water resources management.
>
> Yet already, groundwater is being depleted faster than it is being replenished and worsening water quality degrades the environment and adds to costs. The pressures on water resources are expected to worsen because of climate change. There is ample evidence that climate change will increase hydrologic variability, resulting in extreme weather events such as droughts, floods, and major storms. It will continue to have a profound impact on economies, health, lives, and livelihoods. The poorest people will suffer the most.

It is clear that there are numerous challenges in water management in the twenty-first century. In the twentieth century, most elements of water management had their own distinct set of organisations, skill sets, preferred approaches and professionals. The overlying issue of industrial pollution of water resources was managed from a 'point source' perspective.

However, it has become accepted that water management has to be seen from a holistic viewpoint and managed in an integrated manner. Our current key challenges include the following:

- The impact of climate change on water management, its many facets and challenges – extreme weather, developing resilience, storm water management, future development and risks to infrastructure
- Implementing river basin/watershed/catchment management in a way that is effective and deliverable
- Water management and food and energy security
- The policy, legislation and regulatory framework that is required to rise to these challenges
- Social aspects of water management – equitable use and allocation of water resources, the potential for 'water wars', stakeholder engagement, valuing water and the ecosystems that depend upon it

This series highlights cutting-edge material in the global water management sector from a practitioner as well as an academic viewpoint. The issues covered in the series are of critical interest to advanced-level undergraduates and masters students as well as industry, investors and the media.

Justin Taberham, CEnv
Series Editor
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Acknowledgements

I wish to say a big thank you to all the people who took time out of their busy schedules to sit down for an interview as well as provide any supplementary material. Without your help this book would not have been possible. Specifically I wish to thank Jan Peter van der Hoek (Waternet); Jens Feddern and Joachim Jeske (Berliner Wasserbetriebe); Allan Broløs and Charlotte Storm (HOFOR); Marc Waage, Greg Fisher and Melissa Elliot (Denver Water); Christian Guenner (Hamburg Wasser); David Grantham, Karen Simpson, Paul Rutter and Rosie Rand (Thames Water); Wai Cheng Wong and Gayathri Kalyanaraman (PUB); Lisa Botticella (Toronto Water) and Jennifer Bailey (Waterworks Utility). Finally, I wish to thank mum who has a great interest in the environment and water and has supported me in this journey of writing the book.

Introduction

In the twenty-first century, the world will see an unprecedented migration of people moving from rural to urban areas: In 2012, human civilisation reached a milestone with 50 percent of the world's population living in urban settings. This is projected to reach 70 percent by 2050. With global demand for water projected to outstrip supply by 40 percent in 2030, cities will likely face water insecurity as a result of climate change and the various impacts of urbanisation.

Traditionally, urban water managers facing increased demand alongside varying levels of supplies have relied on large-scale, supply-side infrastructural projects, such as dams and reservoirs, to meet increased demands for water; however, these projects are environmentally, economically and politically costly. Environmental costs include disruptions of waterways that support aquatic ecosystems, while economic costs stem primarily from a reliance on more distant water supplies often of inferior quality. This not only increases the costs of transportation but also the cost of treatment. Furthermore, with the vast majority of water resources being transboundary, supply-side projects can create political tensions due to water crossing intra- and interstate administrative and political boundaries. As such, cities need to transition from supply-side to demand-side management to achieve urban water security.

Integrated urban water management (IUWM) recognises actions that achieve urban water security extend beyond improving water quality and managing quantity. In particular, IUWM integrates the elements of the urban water cycle (water supply, sanitation, stormwater management and waste management) into both the city's urban development process and the management of the river basin in which the city is located for the purpose of maximising water's many environmental, economic and social benefits equitably. IUWM activities to maximise these benefits include: improving water supply and consumption efficiency; ensuring adequate drinking water quality and wastewater treatment; improving economic efficiency of services to sustain operations and investments for water, wastewater

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and stormwater management; utilising alternative water sources; engaging communities in the decision-making process of water resources management; establishing and promoting water conservation programmes; and supporting capacity development of personnel and institutions that engage in IUWM.

In IUWM, demand management is the process by which improved provisions of existing water supplies are developed. In particular, demand management promotes water conservation during times of both normal and atypical conditions through changes in practices, culture and people's attitudes towards water resources. Demand management involves communicating ideas, norms and innovative methods for water conservation across individuals and society; the purpose of demand management is to positively adapt society to reduce water consumption patterns and achieve urban water security. Demand management instruments can be divided into regulatory and technological instruments or communication and information instruments. Regulatory and technological instruments include the pricing of water, waste and stormwater to encourage water conservation as well as ensuring the efficient distribution of water. Communication and information instruments include education of young people, public awareness campaigns to encourage water conservation as well as encouraging the installation of water-efficient technologies, such as tap inserts, to reduce water consumption. The book is case study led and provides new research on the human dimensions of IUWM. In particular, it contains nine in-depth case studies of leading developed cities of differing climates, incomes and lifestyles from around the world that have used demand management tools to modify the attitudes and behaviour of water users in an attempt to achieve urban water security. Data for each case study is collected from interviews conducted with each city's respective water utility along with primary documents. The nine cities are Amsterdam, Berlin, Copenhagen, Denver, Hamburg, London, Singapore, Toronto and Vancouver. Each city scores highly on the Siemens Green City Index for water management. The Green City Index is a research project conducted by the Economist Intelligence Unit (EIU) and sponsored by Siemens. Each city is selected as a case study for the following reasons. Amsterdam is a city attracting sustainability-related companies and investments and so is attempting to manage its resources wisely while Berlin has a history of managing its water in a closed system. Copenhagen uses a variety of demand management tools to promote water conservation due to scarcity of good quality water: the majority of the city's groundwater is contaminated from agricultural and industrial production. Denver, since facing a drought in 2002, has been using demand management tools to reduce average per capita water consumption in order to increase the city's resilience to future droughts. Hamburg has a history of relying on imported water but faces population growth challenges. Similarly, London has implemented demand management efforts in response to demand outstripping supply due to rapid population growth, along with a changing climate. Singapore has a limited surface area to collect surface water and has no groundwater supplies; hence, the city state imports nearly all of its water from neighbouring Malaysia. To reduce the country's dependency on imported water, the city has implemented aggressive water conservation campaigns in an attempt to achieve urban water security. Toronto, despite being located by the Great Lakes, has implemented water conservation efforts in response to the city government requiring its utilities to be sustainable, both environmentally and financially. Finally, Vancouver is implementing demand management strategies to ensure the city does not have to expand its storage capacity to meet rising demand.

This book will introduce readers to the transition management framework that guides cities and their transitions towards urban water security through the use of demand management strategies. A transition in IUWM is a well-planned, coordinated transformative shift from one water system to another, over a long period of time, where a water system comprises physical and technological infrastructure, cultural/political meanings and societal users. In a water system, society is both a component of the water system and a significant agent of change in the system, both physically (change in processes of the hydrological cycle) and biologically (change in the sum of all aquatic and riparian organisms and their associated ecosystems). In IUWM, transitions to new water systems are triggered by changes in the external environment of the system, leading to it being inefficient, ineffective or inadequate in fulfilling its societal function: the main drivers of water insecurity are rapid population and economic growth, increased demand for food and energy and climate change. In transitions towards urban water security, cities set a target water consumption level to achieve (per capita litres/day, for example) with the baseline for comparison being current levels of water consumption and select a portfolio of demand management tools to promote the better use of existing water supplies before plans are made to further increase supply. Overall, transitions in IUWM involve an iterative, long-term and continuous process of influencing people's beliefs and practices to achieve urban water security.

The importance of this book is that in IUWM our understanding of the social, economic and political dimensions of demand for water lags significantly behind engineering and physical science knowledge on the supply of urban water resources. As such, little has been written on the actual processes that enable the application of IUWM; therefore, it is difficult to demonstrate or compare successes across cities in managing urban water sustainably. This is despite the fact it is human attitudes and behaviour that determines the actual amount of water that needs supplying. More specifically, the emphasis on engineering, scientific and technological solutions is no longer sufficient to deal with the numerous problems and uncertainties of increasing demand and climate change on water resources. Therefore, it is critical that human dimensions are incorporated into the managing of urban water, as the perspective of society is crucial for the success or failure of any water management strategy. Nevertheless, the concept of IUWM for addressing water scarcity is changing only slowly from an emphasis on science and technology towards solutions that incorporate cultural and behavioural change. This book presents new research on the human dimensions of IUWM. In particular, the book is case study led containing nine case studies on how leading developed cities from around the world have used demand management strategies (involving regulatory and technological and information and communication instruments) to modify the attitudes and behaviour of water users in an attempt to achieve urban water security. Each case study is written from the perspective of the water utility with input from each city's respective water utility representative.

The book's chapter synopsis is as follows:

Chapter 1 provides a 'Water 101' for readers to understand what exactly constitutes water and how the quality and quantity of water can vary naturally. The chapter will then describe the impacts of urbanisation on water quality and quantity.

Chapter 2 defines what water security is and the challenges to achieving urban water security. These challenges include rapid economic and population growth, urbanisation and rising demand for energy and food as well as climate change.

Chapter 3 defines what sustainability and sustainable development is before discussing the differing approaches to sustainability. The chapter introduces sustainable water management frameworks to achieve water security and then discusses how IUWM can achieve urban water security by balancing demand for water with supply.

Chapter 4 first discusses the purpose of demand management strategies before discussing the types of demand management strategies available to urban water managers. The chapter then discusses demand management tools available to water managers in transitions towards urban water security.

Chapter 5 provides readers with a definition of a transition before discussing types of transitions, how they occur over and the various drivers and forces of transitions. The chapter then discusses how transitions can be managed.

Chapter 6 discusses transitions in the context of managing natural resources sustainably. In particular, the chapter discusses transitions in the context of climate change and natural resource scarcity before introducing readers to transitions towards the sustainable management of water to achieve urban water security.

Chapter 7 provides readers with a case study on Amsterdam transitioning towards urban water security through demand management.

Chapter 8 provides readers with a case study on Berlin transitioning towards urban water security through demand management.

Chapter 9 provides readers with a case study on Copenhagen transitioning towards urban water security through demand management.

Chapter 10 provides readers with a case study on Denver transitioning towards urban water security through demand management.

Chapter 11 provides readers with a case study on Hamburg transitioning towards urban water security through demand management.

Chapter 12 provides readers with a case study on London transitioning towards urban water security through demand management.

Chapter 13 provides readers with a case study on Singapore transitioning towards urban water security through demand management.

Chapter 14 provides readers with a case study on Toronto transitioning towards urban water security through demand management.

Chapter 15 provides readers with a case study on Vancouver transitioning towards urban water security through demand management.

Chapter 16 provides readers with a series of best practices and lessons learnt from the selected case studies of water utilities implementing demand management strategies in an attempt to achieve urban water security. The chapter then provides readers with a range of recommendations to achieve further urban water security.

1 Water 101

Introduction

Before we can manage water sustainably to achieve water security – in the face of global challenges including rapid economic and population growth, rising demand for energy and food and climate change impacting the availability of water resources – we need to understand what is water and its natural variations in terms of quantity and quality. This chapter will first describe the physical properties of water, before discussing the Earth's hydrological cycle. The chapter will then discuss natural variations to water quantity and water quality before finally providing readers with an overview of the impacts of urbanisation on water resources.

1.1 What is water?

On Earth, 97.5 percent of all water is saltwater with only 2.5 percent in the form of freshwater. Of this 2.5 percent, 70 percent is locked up in ice or permanent snow cover in mountainous regions and the Antarctic and Arctic regions, while 29.7 percent is stored below the ground (groundwater). Surface water, including rivers and lakes, comprise the remaining 0.3 percent of freshwater resources available.[1]

A water molecule is made up of two hydrogen atoms bonded to a single oxygen atom. The connection between atoms is through covalent bonding: the sharing of an electron from each atom to give a stable pair. In the water molecule structure,

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the hydrogen atoms are not arranged around the oxygen atom in a straight line; instead there is an angle of approximately 105° between the hydrogen atoms.[2] The hydrogen atoms are positive and so do not attract one another, while the oxygen atom has two non-bonding electron pairs that repulse the two hydrogen atoms.

Water molecules are described as bipolar because there is a positive and negative side of the molecule. This enables water molecules to bond with one another; this is known as hydrogen bonding. In hydrogen bonding, the positive side of the water molecule (the hydrogen side) is attracted to the negative side (the oxygen side) of another water molecule, and a weak hydrogen bond is formed.[3] The hydrogen bonding of water molecules is responsible for a number of water's properties. For instance, based on water's molecular weight (MW = 20), water should evaporate and become a gas at room temperature, given that CO_2(MW = 44), O_2(MW = 32), CO(MW = 28), N_2(MW = 28), CH_4(MW = 18) and H_2(MW = 2) are all gases at room temperature. The reason why water does not evaporate at room temperature is due to water's high specific heat capacity (a temperature increase is effectively an increase in the motion of molecules and atoms comprising the substance). When water is heated, it causes a movement of water molecules – breaking of the hydrogen bonds. However, due to water's cohesiveness, water molecules have a high resistance to increasing their motion. Therefore, it requires a lot of energy to break the hydrogen bonds. As such, water does not evaporate easily. This high heat capacity means water is resistant to radical swings in temperature which is taken advantage of by organisms. Other properties of water include adhesiveness – water molecules are attracted to other substances such as chemicals, minerals and nutrients; solvency – water is a universal solvent as it can dissolve more substances than any other liquid on Earth and uniqueness – water is unique as its solid form (ice) is less dense than liquid water, and it can change from ice to water vapour without first becoming a liquid.[4]

1.2 Hydrological cycle

The hydrological cycle is the continuous movement of water in all its phases: liquid (precipitation), solid (ice) and gaseous (evaporation) forms. Because water is indestructible, the total quantity of water in the cycle does not diminish as water changes from vapour to liquid or solid and back again. In this cycle, evaporation from oceans (505 000 cubic kilometres) exceeds the 458 000 cubic kilometres of precipitation that falls on them. Meanwhile, 119 000 cubic kilometres of precipitation falls on land, which comprises one third of the Earth's surface, and 72 000 cubic kilometres returns through evaporation to the atmosphere. The difference (47 000 cubic kilometres) is either ground or surface water that eventually returns to the ocean.[5] The average amount of time a water molecule remains in a particular part of the hydrological cycle is known as its residence time. Streams and rivers usually have residence times of only days or months, while lakes and inland seas have residence times of years to decades. In comparison, oceans and groundwater systems have residence times of 3000–5000 years (Table 1.1).[6]

Table 1.1 Principal residence times of the global water stores

Compartment	Volume (1000 cubic kilometres)	Percent	Mean residence time (years)
Oceans	1 370 000	93.943	3000
Groundwater	60 000	4.114	5000
Actively exchanging groundwater	4 000	0.274	300
Glaciers and ice caps	24 000	1.646	8600
Lakes/inland seas	230	0.016	10
Soil water	82	0.006	1
Atmospheric vapour	14	0.001	0.027
Rivers	1.2	0.0001	0.032

CLOSS, G., DOWNES, B. J. & BOULTON, A. J. 2004. *Freshwater Ecology: A Scientific Introduction*. Malden, MA: Wiley-Blackwell

The hydrological cycle contains four key components: precipitation, runoff, evaporation and groundwater storage.

1.2.1 Precipitation

Atmospheric vapour, which results in precipitation in both liquid (rainfall) and solid (snow) forms, accounts for less than 0.001 percent of the world's total water; however, due to its low residence times in the atmosphere, it is one of the main drivers of the hydrological cycle.[7]

Precipitation occurs when a body of moist air is cooled sufficiently for it to become saturated. Air can be cooled by a meeting of air masses of differing temperatures or by coming into contact with cold objects such as land surfaces. However, the most important cooling mechanism is the uplifting of air: as warm air rises, its pressure decreases while it expands and cools.[8] This cooling reduces the air's ability to hold water vapour and condensation forms. Condensation is composed of minute particles floating in the atmosphere, providing a surface for water vapour to condense into liquid water. Water or ice droplets formed around condensation particles are usually too small to fall directly to the ground as precipitation due to the upwards draught within the cloud being greater than the gravitational forces pulling the droplets down. In order to have a large enough mass to fall, raindrops grow through collision and coalescence. In this process, raindrops collide and join together (coalesce) to form larger droplets that collide with many other raindrops before falling towards the surface as precipitation. Whether precipitation is rain or snow depends on the warmth of the clouds. In warm clouds temperatures are above freezing point, and water droplets grow through collision (the coalescence process) to form rain. In cold clouds temperatures are below freezing point. These clouds contain ice crystals and supercooled water that is liquid water chilled below its freezing point without it becoming solid. In these clouds precipitation is in the form of snow.[9]

There are three types of precipitation: frontal and cyclonic, convectional and orographic precipitation. Frontal precipitation occurs in the narrow boundaries or fronts between air masses of large-scale weather systems. In this system, warm moist air is forced to rise up and over a wedge of colder, dense air. There are both warm and cold fronts each distinguished by the resulting precipitation: cold fronts have steep frontal surface slopes causing rapid lifting of warm air, resulting in heavy rain over a short duration, while warm frontal surfaces are much less steep, causing gradual lifting and cooling of air, leading to less intense rainfall but over a longer duration.[10] In cyclonic systems, there is a convergence and rotation of uplifting air. In the northern hemisphere, cyclonic systems rotate anticlockwise and in the southern hemisphere clockwise. Above and below the tropics in the northern and southern hemispheres, cyclonic systems usually have a weak vertical motion, resulting in moderate rain intensities for long durations, while in the tropics, because of greater heating of the air, there is more intense precipitation but of a shorter duration.[11] Convectional precipitation happens when the ground surface of a landmass causes warming of the air: as the warm air rises, it cools down and condenses, leading to localised, intense precipitation of a short duration. As this type of precipitation is dependent on the heat of the landmass, it is most common over warm continental interiors such as Australia and the United States. However, this type of precipitation does occur over tropical oceans with slow-moving convective systems producing significant amounts of rainfall. It is common for clusters of thunderstorm cells to be embedded inside convective systems, which commonly leads to flooding events.[12] Orographic precipitation is the result of moist air passing over land barriers such as mountain ranges or islands in the ocean. The South Island of New Zealand is an example of orographic precipitation: the warm moist air off the Tasman Sea reaches the West Coast of the South Island, and as it starts to lift over the Southern Alps, the warm moist air cools and condenses, producing significant rainfall on the West Coast, while on the leeward side the air descends and warms up resulting in low levels of cloud and rainfall.[13]

1.2.2 Runoff

Runoff, or streamflow, is the gravitational movement of water in channels. A channel can be of any size ranging from small channels in soils with widths in the millimetres to channels of rivers. The unit of measurement for runoff is the cumec, with one cumec being one cubic metre of water per second. Streamflows react to rainfall events immediately indicating that part of the rainfall takes a rapid route to the stream channel. This is known as quick flow, while base flow is the continuity of flow even during periods of dry weather.[14] Precipitation can arrive in stream channels through four ways: direct precipitation, overland flow, throughflow and groundwater flow. Direct precipitation comprises only a small amount of streamflow as channels usually occupy only a small percentage of the surrounding area; therefore, it is only during prolonged storms or precipitation events that direct precipitation contributes significantly to streamflow. Overland flow is water that instead of infiltrating soil flows over the ground surface into stream channels during periods of high-intensity rainfall. Overland flows usually occur on moderate to steep slopes in arid and semi-arid areas as these areas lack vegetation and so have dry, compact soil.[15] Throughflow is all the water that infiltrates the soil surface and moves laterally towards a stream channel. This type of flow occurs during periods of prolonged or heavy rainfall when water enters the upper part of the soil profile more rapidly than it can drain vertically. Finally, groundwater flow is water that has percolated through the soil layer to the underlying groundwater and from there into the stream channel.[16]

1.2.3 Evaporation

Evaporation is the transferral of liquid water into a gaseous state followed by its diffusion into the atmosphere. The presence or lack of water at the surface provides the distinctions in definitions for evaporation.[17] For instance, open water evaporation (E) occurs above a body of water such as a lake, stream or ocean. Potential evaporation (PE) is evaporation that would occur if the water supply was unrestricted, while actual evaporation (AE) is the quantity of water that is actually removed from a surface due to evaporation.

Evaporation over a land surface occurs two ways, either as actual evaporation from the soil or transpiration from plants. Transpiration occurs as part of photosynthesis and respiration and is controlled by the plant leaf's stomata opening and closing.[18] The main source of energy for evaporation is the sun. The term used to describe the amount of energy received from the sun at the surface is net radiation (Q^*), and its calculation is

$$Q^* = \mathrm{QS} \pm \mathrm{QL} \pm \mathrm{QG}$$

where QS is sensible heat, the heat we feel as warmth; QL is latent heat and is the heat absorbed or released during water's phase change from ice to liquid water or liquid water to water vapour (there is a negative flux (when energy is absorbed) when water moves from liquid to gas and a positive flux when gas is converted to liquid) and QG is solid heat flux and is the heat released from the soil that has previously been stored within the soil.[19]

1.2.4 Groundwater

Below the Earth's surface, water can be divided into two zones – unsaturated and saturated. In the unsaturated zone, water is referred to as soil water and occurs above the water table, while the saturated zone is referred to as groundwater and occurs beneath the water table. In the unsaturated zone, the majority of water is held in soil that is composed of solid particles (minerals and organic matter) and air. The infiltration rate is used to determine how much water enters the soil over a specific period of time. The rate is dependent on the current water content of