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Editors

Multifunctional Wetlands

Pollution Abatement and Other Ecological Services from Natural and Constructed Wetlands

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Environmental Contamination Remediation and Management

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There are many global environmental issues that are directly related to varying levels of contamination from both inorganic (e.g. metals, nutrients) and organic (e.g. solvents, pesticides, flame retardants) contaminants. These affect the quality of drinking water, food, soil, aquatic ecosystems, urban systems, agricultural systems and natural habitats. This has led to the development of assessment methods and remediation strategies to identify, reduce, remove or contain contaminant loadings from these systems using various natural, engineered or synthetic technologies. In most cases, these strategies utilize interdisciplinary approaches that rely on chemistry, ecology, toxicology, hydrology, modeling and engineering.

This book series provides an outlet to summarize environmental contamination and remediation related topics that provide a path forward in understanding the current state and the mitigation of environmental contamination both regionally and globally. Topic areas may include, but are not limited to, Water Re-use, Waste Management, Food Safety, Environmental Restoration, Remediation of Contaminated Sites, Analytical Methodology, and Climate Change.

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Foreword

The book that you hold is an attempt to unpack a big "known unknown," that is, the role that wetlands, both natural and constructed, play in water management, with the main focus on pollution abatement. It is focused and comprehensive at the same time. Characteristic features of the book include, but are not limited to:

- The wide thematic and geographic spread of the contributions in relation to natural and constructed wetlands that provides the readership with extensive empirical evidence and practical interventions on how to suitably utilize the various ecological services of wetland ecosystems.
- New data, information and knowledge that illustrate the multi-functionality of wetland ecosystems with regard to various aspects of water quality management and beyond; for example, in storm water management, habitat restoration, recreation and disaster risk reduction.
- Aligning the ecosystem services of wetland ecosystems with international processes and governance frameworks related to aquatic ecosystems, such as the Ramsar Convention, water security, ecosystems-based management, smart cities and the urban agenda, and the Sustainable Development Goals of Agenda 2030.

This book is a collection of specific case studies, and as such, it adds multiple new dimensions to a broader concept of Nature-based Solutions (NbS), which is high on the sustainable water development agenda at present. Suffice to mention that the World Water Development Report produced annually by UN-Water focuses in 2018 entirely on NbS, and hence the publication of this book is very timely.

And finally, the book is, essentially, a call for the generation of more specific knowledge and better sharing of information on the ecosystem services of wetlands that can, in turn, assist significantly in developing resilient wetlands and contribute to effective and sustainable management of water resources, both globally and locally.

The United Nations University, Institute for Water, Environment and Health (UNU-INWEH) is pleased to support the development of this publication. We believe

that the information contained in this book will be a valuable resource for water management practitioners, researchers and decision makers who are looking for innovative and effective ways to manage our water resources.

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Chapter 1
Multifunctional Wetlands: Pollution Abatement by Natural and Constructed Wetlands

Chris D. Metcalfe, Nidhi Nagabhatla, and Shona K. Fitzgerald

Introduction

Natural wetlands are complex ecological systems that incorporate physical, biological and chemical processes. These wetlands play an important role in protecting freshwater and marine ecosystems from excessive inputs of nutrients, pathogens, silt, oxygen demand, metals, organics and suspended solids, as well as providing a buffer against storms, soil stabilization and wildlife habitat (Sierszen et al. 2012; Zedler and Kercher 2005; Engelhardt and Ritchie 2002). Attempts have been made to quantify the economic benefits of these ecological systems (Woodward and Wui 2001; Barbier et al. 1997), but it is also recognized that natural wetlands have cultural value (Papayannis and Pritchard 2008). The Convention on Wetlands of International Importance, commonly known as the Ramsar Convention, held in 1971 established a global framework for conservation of natural wetlands. Estimates of the area of wetland ecosystems on a global scale vary from 917 million hectares (Lehner and Doll 2004) to more than 1270 million hectares (Finlayson and Spiers 1999). The Ramsar Convention in Article 1.1 defines wetlands broadly as, "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary,

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Fig. 1.1 The wetland continuum illustrating the extent of ecological services and the energy requirements for operation and maintenance across a range of wetland types. Figure adapted from Young et al. (1998)

with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide exceed six metres". To date, 1052 sites in Europe, 211 sites in North America, 175 sites in South America, 359 sites in Africa, 289 sites in Asia and 79 sites in Oceania have been recognized as wetlands of international importance (Ramsar Secretariat 2013).

Despite these international efforts, monitoring of 1000 Ramsar wetlands over the period from 1970 to 1999 showed that the area of these sites declined by an average of 40% (Finlayson and Spiers 1999). The loss of wetlands is especially acute in the most populous regions of the world, including India (Bassi et al. 2014) and China (Jiang et al. 2015; An et al. 2007). However, urbanization, industrialization and expansion of agriculture have threatened natural wetlands in all areas of the world, and especially in urban areas (Hettiarachchi et al. 2015). One approach to reversing this trend has been to restore degraded wetland ecosystems to full or partial functionality (Zedler and Kercher 2005; Jenkins et al. 2010; Davenport et al. 2010; Yang et al. 2016).

Alternatively, wetlands can be created to fulfil specific ecological services, such as providing wildlife habitat, retaining pollutants and treating wastewater (Guittonny-Philippe et al. 2014; Tournebize et al. 2013; Babatunde et al. 2008; Rousseau et al. 2006; Kivaisi 2001; Worrall et al. 1997). These specific ecosystem services do not have to be mutually exclusive, as both natural and constructed wetlands can carry out a variety of ecosystem functions (Hsu et al. 2011; Hansson et al. 2005; Bolund and Hunhammar 1999; Santer 1989). For instance, in urban areas, constructed wetlands can reduce the urban heat island effect, which can positively influence human health (Bolund and Hunhammar 1999). Where constructed wetlands are used for urban stormwater treatment, they not only improve downstream water quality but can also restore the natural hydrology of the urban catchment and reduce downstream erosion from large stormwater flows (Wong et al. 2012).

The concept of a continuum of functions across different types of wetlands (Young et al. 1998) is helpful for considering the degree to which a constructed wetland replicates the functions of the natural environment. As illustrated in Fig. 1.1, the range of ecosystem functions provided by wetlands increases across the continuum from artificial (or engineered) wetlands to natural wetlands, while the

amount of energy applied to operate and maintain these wetlands increases in the opposite direction. Of course, the degree of energy required to sustain the wetland is a challenge; especially in small communities in remote locations (Wu et al. 2015a) or in developing countries that lack sufficient financial and/or human resources to maintain the wetland (Kivaisi 2001).

Constructed Wetlands

Constructed wetlands are purpose-built systems that are engineered to achieve one or more of the functions of natural wetlands. Constructed wetlands include surface flow wetlands, which mimic natural inundated wetlands, or subsurface flow wetlands where the flow passes through a media bed in which plants are established. In surface flow wetlands, long detention times of typically 5–14 days and a large surface area promote removal of particulate and organic matter (Ghermandi et al. 2007). Microbial processes, including oxidation of organic matter and transformation of nutrients, occur through the plant biomass, the sediment and the decomposing plant matter on the bed surface. In subsurface flow wetlands, the detention times are typically shorter (i.e. 1–2 days) and as illustrated in Fig. 1.2, functional microorganisms are associated with the surfaces of the substrate and with the root systems (i.e. rhizosphere) of plants established in the substrate (Vymazal 2009; Stottmeisteer et al. 2003). The porous substrate also acts as a filter for reducing levels of suspended solids. In both the surface flow and the subsurface flow wetlands, plants
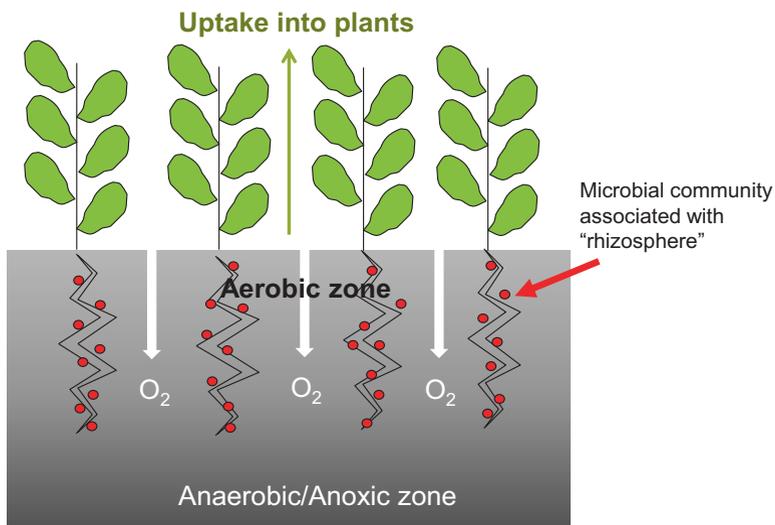

Fig. 1.2 Illustration of the functions of plant and microbial communities in natural and constructed wetlands with subsurface flow

function to oxygenate the surface layers of the sediments and thereby provide an aerobic environment for microbial activity (Valipour and Ahn 2016). In some cases, plants can accumulate and sequester nutrients (e.g. phosphorus) and pollutants (e.g. metals) from the surrounding substrate or from the water (Fig. 1.2). Recently, hybrid systems that include both vertical flow and subsurface flow systems have been shown to achieve superior pollutant removals (Vymazal 2013; Kabelo Gaboutloeloe et al. 2009). A variety of other constructed wetland designs have been proposed to enhance removals of pollutants (Wu et al. 2015b).

Constructed wetlands have been increasingly used for water reuse projects on a small scale, such as residential use for toilet flushing and gardening, or on a larger scale for irrigation of agricultural crops, golf courses and public parks, or to replenish natural wetlands and groundwater (Rousseau et al. 2006). The benefits of constructed wetlands are both social and environmental and need to be considered in the design of the wetland. The social benefits of wetlands include education and recreation, and so wetlands are often designed with interpretive signage, walking and bike paths and green space (Cunningham and Birtles 2013). These wetlands are often designed as part of an integrated urban design system with other features such as swales, grasslands and forest/shrub areas (Melbourne Water 2005).

While the benefits of constructed wetlands are many-fold, there are still challenges to their implementation, including availability of land, community support, maintenance and monitoring (Woods 1995) Given the relatively long hydraulic detention times and large surface areas required for constructed wetlands, there are often challenges in finding suitable land, especially in urban areas. Poor performance of constructed wetlands can occur where there is poor design or where the wetland is poorly maintained. Although maintenance and operation of constructed wetlands is less demanding than conventional wastewater treatment systems, they still require regular maintenance and monitoring. This includes ensuring even flow distribution, managing water levels, weed control, plant health, animal control (e.g. mosquitos, rodents, nutria) and removal of accumulated solids (Kadlec and Knight 1996). It is valuable to have community support for these projects as the community is often relied upon to help with the maintenance of the wetland. Challenges to wetland implementation can also be driven by capital costs, which will vary throughout the world, depending on material availability and labour costs.

Concepts and Context

The Water Security Agenda

The numerous challenges in managing aquatic ecosystems, and particularly wetlands are multifaceted, specific to certain regions and often, to certain places. Wetland solutions are often context specific, such as management options for pollution abatement, storm water control, disaster risk reduction or to reduce hydro-variability. The Economics of Ecosystem and Biodiversity (TEEB) report focusing on

wetlands, launched on the occasion of World Wetlands Day by the Ramsar Convention, United Nations Environment Programme (UNEP), International Union for Conservation of Nature (IUCN), and Wetlands International, among others, called for the urgent need to focus on wetlands as natural solutions to the global water crisis (TEEB 2013).

Wetlands are key elements for increasing "Water Security", which is defined by UN-Water as, "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human wellbeing, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" (UN Water 2013). The conceptual framework of UN Water for water security, illustrated in Fig. 1.3, provides for a "shared approach" that addresses current problems in the water sector. The key organizational elements in the framework include: transboundary management of shared water resources, good governance, financing of water management programs, and peace and political stability, and these elements contribute to access to safe drinking water, improvements to human health and wellbeing, protection of ecosystems and livelihoods, strengthening of water policies, institutions and knowledge systems, reduction of water-related hazards, and adaptation to climate change and resilient communities (Fig. 1.3).

This framework provides a common platform that incorporates both value and knowledge systems with technical, infrastructural, social and political interventions in order to manage aquatic ecosystems. This approach calls for a greater emphasis on understanding the multiple functions of aquatic ecosystems, in conjunction with the benefits related to health and wellbeing, livelihoods, food and energy security, and more recently, climate change mitigation and adaptation (Logan et al. 2013). This framework also emphasizes that interventions should aim to reduce the pollution that makes water unavailable or unsuitable for other uses and contributes to water insecurity. The lack of sufficient water supplies to meet the demands of water use is a situation common in countries with developing and emerging economies, leading to the current global situation where 1.2 billion people lack access to clean drinking water (WHO 2016). This framework on water security is directly applicable to the management of wetlands. An in-depth understanding of the ecosystem services of wetlands is needed to assure that business investment, conservation and restoration efforts are closely tied to policies that promote the long-term sustainability of natural wetlands, as well as the development of man-made wetlands.

The water security agenda benefits from the recent concept of "Nature-based Solutions" that has united researchers and practitioners in an innovative paradigm that addresses many water related challenges (Logan et al. 2013). This concept is described in more detail below. Past and current thinking related to sustainability planning has promoted the idea that "development investment" not only includes construction of new infrastructure, but also includes increasing the capacity of natural ecosystems (e.g. wetlands) to function as systems for risk reduction, climate adaptation, water and energy storage, enhanced aesthetic value, etc. (Hey 1994; Temmerman et al. 2013). The case studies presented in this book describe projects
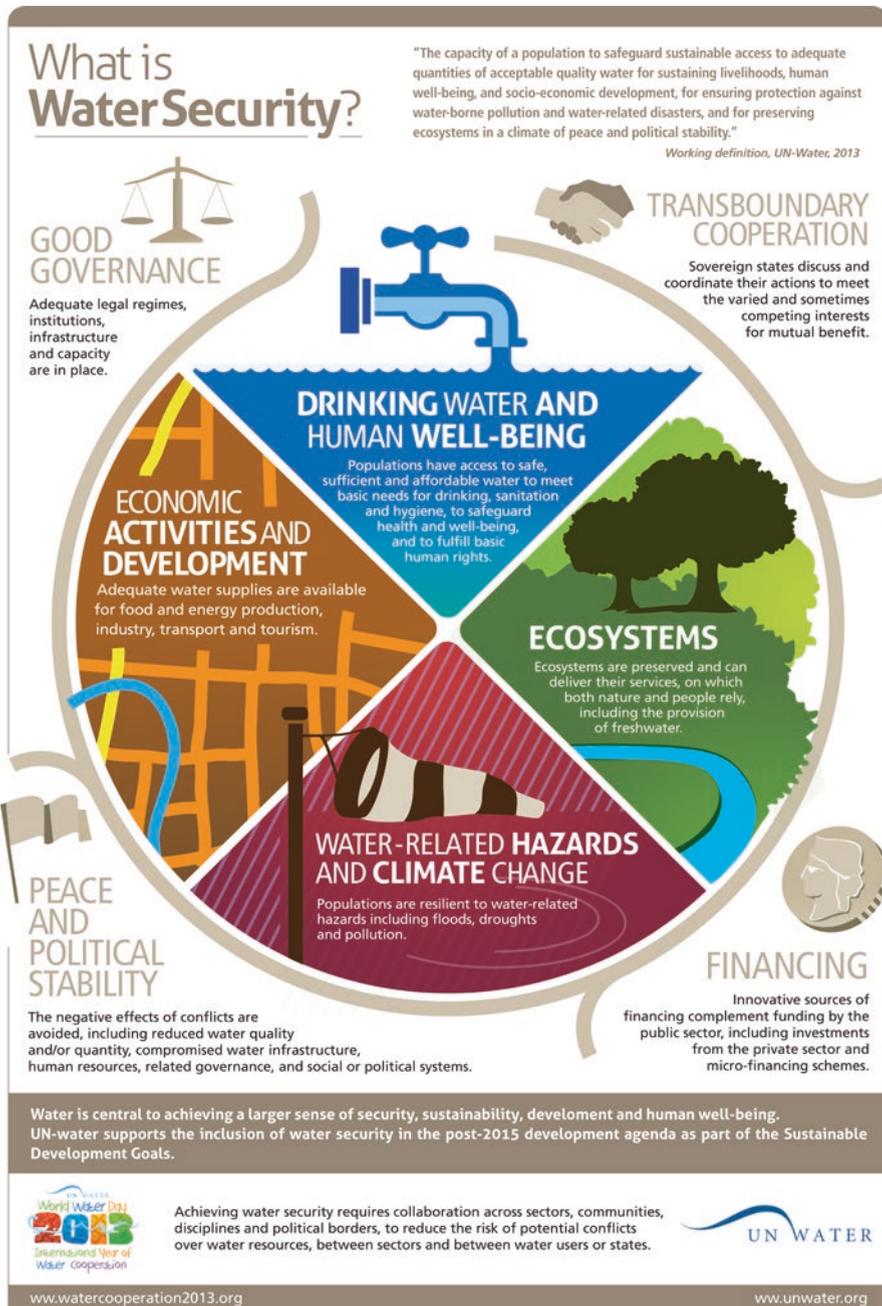
Fig. 1.3 The conceptual framework for water security outlined by UN Water, which highlights the multiple dimensions for managing aquatic systems to address future water needs; Source: UN Water (2013)

with both natural and constructed wetlands that provide evidence that wetlands are multifunctional and also provide many benefits to local communities.

Nature-Based Solutions

The term, "Nature-based Solutions" (NbS) refers to actions to alter or restore the local ecosystem and landscape to provide a solution to water management problems (Nesshöver et al. 2017). The importance of wetlands as natural infrastructure is widely discussed in the context of NbS, with a particular focus on nutrient and pollution retention, flow regulation and coastal protection (Thorslund et al. 2017). Wetland systems, whether they are "natural" or "constructed", or a combination of the two, are often more cost-effective systems for pollution control, storm water management and coastal zone protection than hard infrastructure solutions, and at the same time, provide multiple ecological functions and other benefits.

An interesting example from Yangtze River basin in China illustrates the potential of wetlands as an NbS for disaster risk reduction. Inhabited by more than 400 million people, this basin experienced a torrential storm in 1998, resulting in 4000 causalities and $25 billion USD in damage or loss of property and assets. As a disaster risk management strategy, the "32 Character Policy" in China resulted in the restoration of 2900 km^2 of floodplain wetlands with the capacity to retain 13 billion m^3 or 13 km^3 of water (Wang et al. 2007). A long-term wetland conservation network was established across the Yangtze River basin to manage water quality, preserve local biodiversity and expand wetland based nature reserves.

In the Americas, two case histories also illustrate the value of wetlands as an NbS for disaster risk reduction. In Chile, an earthquake and tsunami in 2010 resulted in $30 billion USD loss of assets and cruelly impacting lives, livelihoods and the assets of coastal communities. In the post-disaster planning, the Government of Chile made a decision to declare major portions of the coastal wetland (i.e. Yali National Reserve, Valparaiso) as a protected Ramsar wetland, while clearly recognizing the benefits of wetland ecosystems as a disaster risk reduction strategy (OECD 2016). Hurricane Katrina that flooded parts of the city of New Orleans and other areas of the state of Louisiana was the deadliest disaster in the modern history of the USA that left nearly a million people displaced. This disaster highlighted the inadequacy of hard engineered structures, floodwalls and levees for disaster risk reduction, and led to calls to investigate the services of natural wetlands as an NbS (Tibbetts 2006).

The Sustainable Development Goals

The UN has adopted the 2030 Agenda for Sustainable Development, which sets ambitious objectives for improving the lives of the global population and for protecting the environment. Sustainable Development Goal (SDG) 6 focuses on
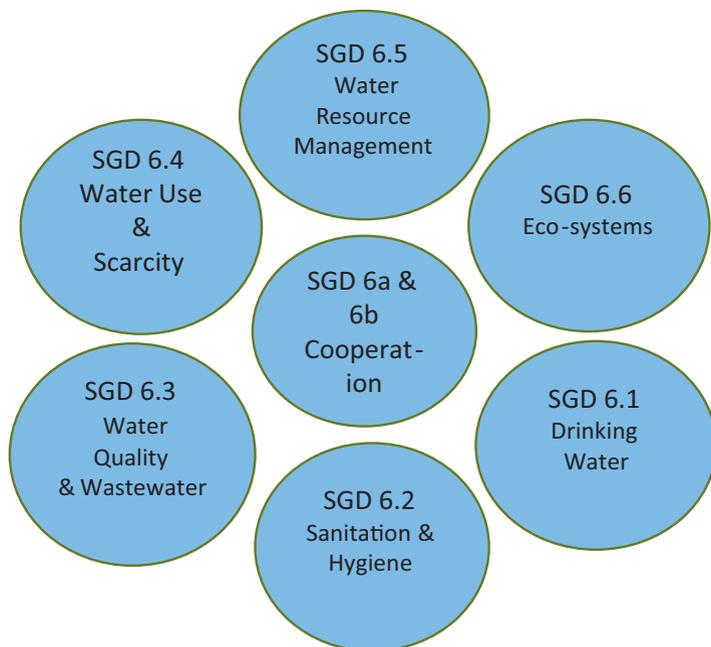
Fig. 1.4 Individual objectives identified within SGD 6. The figure was modified from an illustration provided by UN Water

objectives to ensure access to clean water and sanitation for all (UN Water 2016). However, it is clear that water serves as a foundation for many of the other SDGs, as water security is essential for societal, economic and environmental development. Of the 17 SGD goals, there are key water-related targets embedded in the goals for reducing poverty (SDG1), improving health (SDG 3), sustainable cities (SDG 11), consumption-production (SDG 12), and protecting aquatic resources (SDG 14) and terrestrial ecosystems (SDG 15).

As illustrated in Fig. 1.4, there are several objectives that contribute to the goals of SDG 6 (UN Water 2016). SGD 6.1 aims to provide access in an equitable manner to adequate amounts of safe drinking water for 100% of the population in each country. Similarly, the objective of SGD 6.2 is to provide 100% access to facilities for sanitation and hygiene. All other objectives within SGD 6 are "aspirational" goals, meaning that individual participating countries can set their own targets and develop their own monitoring programs to assess their progress. Briefly, the objective of SDG 6.3 is to improve water quality by treating wastewater and minimizing the release of hazardous chemicals and materials. SGD 6.4 focuses on reducing water use and alleviating water scarcity, while SGD 6.5 addresses the need for integrated water resource management, as well as promoting transboundary cooperation to manage shared water resources. Finally, SGD 6.6 aims to protect terrestrial ecosystems that are key to water resource management. SGD 6.a and 6.b set targets for strengthening institutions to meet these SGD 6 objectives.

Many of the targets related to SGD 6.5 and SGD 6.6 have direct relevance to wetland management. The stated objective of SGD 6.6 is to, "protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes" (UN Water 2016), so countries that participate in this process will have to implement policies and practices to protect or restore natural wetlands. Integrated water resource management practices aimed at meeting the objectives of SGD 6.5 could include natural or constructed wetlands as part of an integrated approach to managing watersheds. Of course, wetlands can also be important systems for improving water quality (i.e. SGD 6.3) and reducing water use (i.e. SGD 6.4). Although SGD 6.3 appears to focus on technological solutions for treating urban wastewater, assimilation and constructed wetlands can be part of that solution, as well. Therefore, the SGD program may be an important incentive for countries to consider natural and constructed wetlands as a water management tool.

Pollution Abatement

The primary focus of the various chapters in this book is the ecosystem functions of natural and constructed wetlands related to the removal of pollutants from water, including nutrients, suspended solids, biological oxygen demand, and toxic metals. However, the various chapters also illustrate the other ecosystem services provided by wetlands, such as coastal protection from storms and tsunamis, flood control, habitat creation and recreational space.

Several books have reviewed the topic of pollution abatement by wetlands, including monographs by Crites et al. (2006), Kadlec and Wallace (2009), Stefanakis et al. (2014), and most recently, Scholtz (2015). These are all excellent references for water management practitioners interested in learning how both natural and constructed wetlands can be used to remove pollutants from water resources. The present book will contribute to the literature on the subject of pollution control using wetlands by describing a wide variety of case histories that span time periods of up to 30 years, as well as shorter periods of time. The contributions to this book systematically examine if and to what extent research and innovation so far has addressed the large-scale dynamics of wetland systems within the larger agenda of sustainable water management (i.e. water security), pollution abatement, potable water supply, disaster risk reduction and climate change adaptation. In addition to that, the case studies were selected to illustrate the multiple functions of wetlands over various scales and in different geographical contexts, thereby, contributing to the knowledge base for Nature-based Solutions.

The geographical scope of these case histories ranges from mangrove ecosystems in tropical marine environments to freshwater tundra wetlands, and the types of wetlands range from natural systems to constructed wetlands that have been extensively managed. The case histories describe both the successes and the challenges associated with using wetlands for water pollution control and sustainable water use. Another overarching theme of the book is to illustrate how wetlands can

fulfil other ecosystem services, such as providing wildlife habitat, stormwater control and supporting recreational activities. Through the wide scope of the case histories described in the chapters in this book, the reader will gain an appreciation for the range of scenarios in which wetlands can be used to remove pollutants from water, and the challenges associated with using these natural and artificial systems.

The study from Louisiana, USA by Hunter and colleagues discusses how natural wetlands can be adapted as "assimilation" wetlands that receive treated municipal effluent. The chapter describes the benefits of these assimilation wetlands, including nutrient removal, environmental flow benefits, increased vegetation productivity, and decreased subsidence. Also, included is a description of some of the challenges that have been experienced over the long-term operation of these wetlands. In another case study of assimilation wetlands, but this time in Canada's far north, Balch and colleagues demonstrate that natural wetlands in cold environments can be used seasonally to treat municipal wastewater. Wastewater strength, hydrology and seasonal changes are key parameters influencing the performance of these systems. The authors identify knowledge gaps and discuss future research needs for maintaining these wetlands, as well as the monitoring challenges in the region.

White and colleagues describe a case study of the large constructed wetland used for "polishing" treated municipal wastewater generated by the City of Orlando and surrounding municipalities in central Florida, USA. The chapter describes the efficacy of phosphorus removal from wastewater and also discusses long-term performance challenges and adaptive strategies that have been used to manage this wetland since its construction in the 1980s. Strickman and Mitchell also examine the topic of urban wetlands, but the focus of their chapter is small wetlands that have been created in urban environments for stormwater control. These authors describe the role of these wetlands as sinks for mercury, but also describe how they can be net emitters of methylmercury produced *in situ* in the wetland. The chapter by Fitzgerald describes an urban wetland project in Sydney, Australia that demonstrates how constructed wetlands can be part of a strategy for creating "water sensitive cities". This author discusses the social and economic benefits of constructed wetlands in urban settings, and how urban wetlands can contribute to adopting and implementing the Sustainable Development Goals of the UN and the New Urban Agenda.

The chapter by Thupalli and Deen describes the benefits of mangrove ecosystems for disaster risk reduction in tropical and subtropical coastal areas, but also describes how these ecosystems contribute to pollution abatement and habitat protection, as well as protecting the livelihoods of local communities. A case is made for the need for regular consultations with communities to ensure long-term sustainability of mangrove ecosystems as green infrastructure that can accomplish comparable risk reduction role to, and hence possibly be a natural alternative to grey (built) infrastructure. The other chapter on mangroves in the Bay of Bengal region of India by Banerjee and colleagues describes the accumulation of metals by the roots and vegetation of mangroves and makes a case for the role of mangrove ecosystems for bioremediation of metal contaminated sites.

Constructed wetlands require monitoring and maintenance, and the time and labour required for these activities can be onerous. The study by Belmont and colleagues on a constructed wetland adapted for production of ornamental flowers and fish culture by an Indigenous community in central Mexico describes the critically relevant aspect of creating incentives for community participation in wetland projects. The treatment system yields fish and ornamental flowers that contribute to livelihoods in the community and are an economic incentive for maintaining the wetland. A study based in west Africa focuses on nature based solutions to achieve local-scale water security. This chapter by Yongabi and colleagues promotes the use of local aquatic plants and vegetation for pollution abatement as a low-cost alternative to conventional water treatment. Examples include using a species of water lily for removing heavy metals from water, and the use of phyto-materials from the seeds of a terrestrial plant in conjunction with sand filtration for treatment of potable water.

In aggregate, the chapters provide a synthesis of current knowledge related to natural and constructed wetlands, along with tested examples of interventions, methods and management strategies that include stakeholder participation.

Conclusions

The diverse benefits of natural and constructed wetlands make them suitable systems for improving water quality, while at the same time providing social and potentially economic benefits to local residents and long-term water security. These benefits must be balanced so that the design, operation and maintenance of the wetlands meet the requirements for pollution control, and also serve other ecological functions.

The chapters in this book are intended to inform water practitioners and researchers involved in watershed management of the range of options that are available for using natural and constructed wetlands for pollution abatement, and also some of the challenges associated with operating and maintaining these systems. The various case studies from around the world and in different settings (e.g. natural and constructed wetlands, urban to rural) will assist in understanding how technical and scientific knowledge can be integrated with community-based planning and policy development to reduce the impacts of pollution on the environment. In addition, the case histories will illustrate the importance of natural and manmade wetlands within the context of integrated water resource management, the water security agenda, the UN Sustainable Development Goals and the developing concept of Nature-based Solutions, as well as the socio-political actions required to support these management options.

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Chapter 2
Using Natural Wetlands for Municipal Effluent Assimilation: A Half-Century of Experience for the Mississippi River Delta and Surrounding Environs

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Introduction

The ability of wetlands to improve water quality is well established, with hundreds, if not thousands, of scientific studies published in peer-reviewed journals and books (e.g., Godfrey et al. 1985; Moshiri 1993; Lane et al. 1999, 2002, 2004, 2010; Hunter and Faulkner 2001; Mitsch and Jorgensen 2003; Kangas 2004; Kadlec and Wallace 2009; Hunter et al. 2009a, b; Seo et al. 2013; Shaffer et al. 2015). Use of natural eco-systems for assimilation of nutrients and suspended sediments in treated municipal

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effluent is neither new nor strictly non-traditional (Day et al. 2004). There are thousands of wetland treatment systems worldwide with hundreds of years of operational experience (Kadlec and Wallace 2009). Because wetlands naturally occupy lower landscape positions within a watershed, they are ideally located to serve as biological filters, removing nutrients and sediment from water running off the surrounding landscape before it enters an open water body such as a river or lake.

Studies throughout the world have shown that wetlands chemically, physically, and biologically remove pollutants, sediments and nutrients from water flowing through them (Zhang 1995; Day et al. 2004; Alexander and Dunton 2006; Conkle et al. 2008; Meers et al. 2008; Kadlec and Wallace 2009; Vymazal 2010; Shaffer et al. 2015). Some questions remain as to the ability of wetlands to serve as long-term storage nutrient reservoirs, but examples of long-term sustainability are cypress systems in Florida that continue to remove major amounts of nutrients in treated effluent even after 20–45 years (Boyt et al. 1977; Ewel and Bayley 1978; Lemlich and Ewel 1984; Nessel and Bayley 1984), and the Breaux Bridge and Amelia assimilation wetlands that have received treated effluent for 70 and 47 years, respectively (Hesse et al. 1998; Blahnik and Day 2000; Ko et al. 2004; Day et al. 2006; Hunter et al. 2009b).

With regard to water quality, the primary constituents of interest in treated municipal effluent are nitrogen, phosphorus, and suspended solids, which includes both mineral sediments and particulate organic matter. The basic principle underlying wetland assimilation of these constituents is that the rate of effluent application must balance the rate of removal. The primary mechanisms by which this balance is achieved are physical settling and filtration, chemical precipitation and adsorption, and biological processes that result in burial, storage in vegetation, and denitrification (Reddy and DeLaune 2008). Treated effluent typically introduces nutrients as a combination of inorganic (e.g., nitrate + nitrite (NO_x), ammonia (NH_3), and phosphate (PO_4)) and organic forms, both dissolved and particulate. Nitrogen and/or phosphorus from treated effluent can be removed by short-term processes such as plant uptake, long-term processes such as peat and sediment accumulation, and permanently by denitrification (Reddy and DeLaune 2008).

In the Mississippi River Delta, there are ten assimilation wetlands currently receiving discharge of secondarily-treated, disinfected municipal effluent and four others awaiting permits or under review, as of July 2017 (Fig. 2.1). The assimilation systems in the Mississippi River Delta are not constructed wetlands, however, they are also not "natural" wetlands because they have been highly impacted by anthropogenic activity.

The Mississippi River Delta is a profoundly altered regional ecosystem covering over 10,000 km^2. Over 25% of coastal wetlands in the Mississippi River Delta were lost in the twentieth century. One of the primary causes is the almost complete isolation of the delta plain from the Mississippi River by levees that prevent regular riverine input that occurred under natural conditions before human alterations (Day et al. 2007, 2014). The river provided fresh water, mineral sediments, and nutrients during annual floods. This annual flooding maintained a salinity gradient and provided sediments to promote wetland formation and nutrients to enhance productiv-
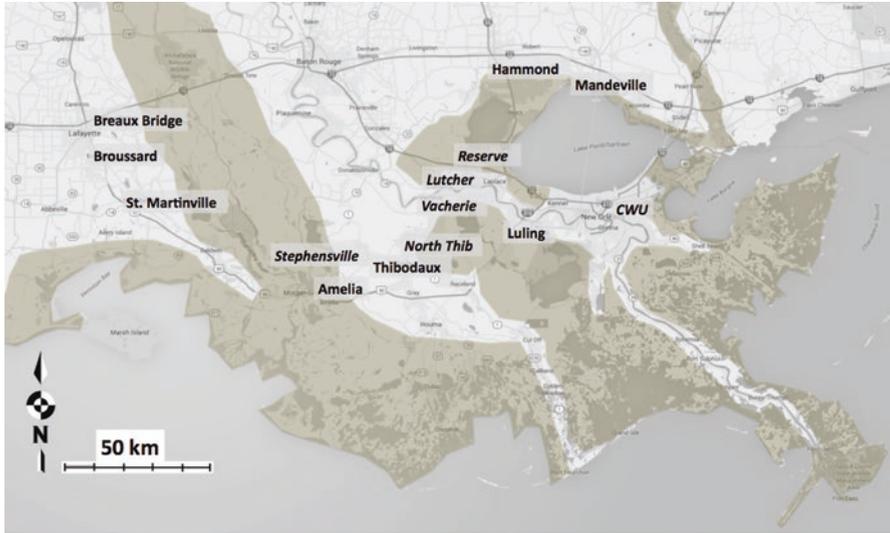
Fig. 2.1 Location of wetland assimilation projects in coastal Louisiana. Municipalities in italics indicate recently completed or ongoing ecological baseline studies. Note that Breaux Bridge, Broussard, and St. Martinville are not impacted by coastal water levels. All the other sites are at or near sea level and are impacted by sea level rise. This inhibits the ability of these sites to drain and have dry periods. Shading indicates areas with a high proportion of wetlands

ity. In addition, there has been a pervasive alteration of hydrology both in the horizontal plane due to spoil banks and canals, as well as vertically caused by enhanced subsidence due to fluid withdrawal (mainly oil and gas), compaction, and drainage. All of the wetland assimilation systems discussed here are in areas where the natural hydrology has been fundamentally altered by human activities.

Wetland assimilation in Louisiana can achieve sustainable low cost tertiary treatment of secondarily-treated municipal effluent while benefiting and restoring wetlands (Day et al. 2004; Hunter et al. 2009a, b). A properly designed wetland assimilation system can be a more economical and sustainable means of tertiary treatment compared to conventional engineering options. The cost of tertiary treatment is a concern as the U.S. Environmental Protection Agency (USEPA) is requiring increasingly stringent limits in discharge permits for wastewater treatment plants. Out of 105 major wastewater treatment facilities in Louisiana, only 12% (13 plants) monitor for nitrogen and phosphorus concentrations, compared with an average of 57% in the 12 states included in the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. Of the 13 treatment facilities monitoring nutrients in Louisiana, 10 discharge into assimilation wetlands (Hypoxia Task Force 2016).

Freshwater resources, including treated effluent, should be used in a manner that results in the greatest benefits to society. However, municipalities cannot be expected to bear all costs for wetland assimilation projects, so when possible they should be integrated into larger restoration efforts where a variety of funding sources are used.