Vertical Flow Constructed Wetlands

Eco-engineering Systems for Wastewater and Sludge Treatment

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Alexandros Stefanakis
Helmholtz Center for Environmental Research - UFZ, Leipzig, Germany

Christos S. Akratos
Department of Environmental and Natural Resources Management, University of Patras, Patras, Greece

Vassilios A. Tsihrintzis
Centre for the Assessment of Natural Hazards and Proactive Planning, Laboratory of Reclamation Works and Water Resources Management, Department of Infrastructure and Rural Development
School of Rural and Surveying Engineering
National Technical University of Athens, Athens, Greece

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Dedication

To my lovely parents
(Alexandros Stefanakis)

To Anastasia and Zoi
(Christos S. Akratos)

To my wife Alexandra and two sons Andreas and Konstantinos for their support and patience
(Vassilios A. Tsihrintzis)

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Author Biography

Dr. Stefanakis is an Environmental Engineer, with Diploma and Doctoral degrees from the Department of Environmental Engineering, Democritus University of Thrace, Greece. He also holds an M.Sc. degree in the field of Hydraulic Engineering from the Department of Civil Engineering of the same university. His M.Sc. and Ph.D. theses focused on the ecological treatment of wastewater and sludge using natural systems, mainly constructed wetlands. He has published 13 papers in international peer-reviewed journals, several papers in conference proceedings, technical reports, lecture notes, and book chapters. His work includes numerous experiments with CW systems of different types. He has participated in many national and EU research projects in Greece, Portugal, and Germany. He has taught at the undergraduate level on the topic of environmental protection, delivered seminars in postgraduate studies programs, and has been involved in international conference organizing. He has also supervised and trained various undergraduate students. He has been awarded twice during his career for his research work. Finally, Dr. Stefanakis is also a practicing environmental engineer in Greece, dealing with the design of constructed wetlands facilities.

Dr. Akratos received his Diploma and Doctoral degrees from the Department of Environmental Engineering, Democritus University of Thrace, Greece, and now is an Assistant Professor at the Department of Environmental and Natural Resources Management, University of Patras. He has an extensive experience in constructed wetlands starting from his doctoral dissertation. The majority of his publications deal with wastewater treatment in constructed wetlands. He has published 25 refereed journal papers and has participated as a research team member in 15 research programs, most of them in the area of wastewater treatment in constructed wetlands.

Dr. Tsihrintzis is a Professor of Ecological Engineering and Technology at the School of Rural and Surveying Engineering, National Technical University of Athens, Greece. He is a Civil Engineer and has M.Sc. and Ph.D. degrees in Hydrosystems Engineering from the University of Illinois at Urbana-Champaign, Illinois, USA. Dr. Tsihrintzis' research interests concentrate, among others, in use of natural systems for wastewater treatment with emphasis on constructed wetlands, and in water resources engineering and management with emphasis in water quality and pollution control, ecohydrology and ecohydraulics. His published research work includes more than 100 papers in peer-reviewed scientific journals and over 250 papers in conference proceedings. He has also authored or coauthored books/book chapters on operations research, urban hydrology and runoff quality management, and natural systems for wastewater and runoff treatment, among others. He has participated as a PI or team member in various research projects in the USA, the EU, and Greece. Dr. Tsihrintzis has supervised more than 60 undergraduate and postgraduate student theses and 12 doctoral dissertations. He regularly teaches, among others, the course Natural Wastewater Treatment Systems, which is directly related to the proposed book. He has also served as a Professor and the Head of the Department of Environmental Engineering, Democritus University of Thrace, Greece, for several years. Finally, Dr. Tsihrintzis has an extensive professional experience as a practicing civil environmental engineer both in the USA (he was a registered Professional Engineer in California) and Greece, having designed several water management, wetland restoration, and constructed wetlands systems.

Foreword

Within the last decades, it became obvious that freshwater resources in many countries are increasingly overused and even limited. Thus, the treatment of polluted water and its reuse possibilities are in focus as a main action to solve this problem.

Water technology nowadays is generally able to "transform" highly polluted wastewater into water of varying quality up to drinking water quality. The main limitation is the needed energy input and the related costs for realization of this goal. Because of rising energy prices, especially during the last two decades, technologies with low energy demands are gaining in importance. Concerning energy demand for wastewater treatment, it can be assumed that the—still nowadays—widely applied technology of activated sludge system will be partially replaced by other less energy-consuming and less complex technologies.

Within the last decades, it was made gradually clear that using near-nature technically modified ecosystems, like ponds and wetlands, is an appropriate and attractive option for an economic and environmentally friendly treatment of wastewater. So, especially the technology of constructed wetlands (CWs) made and still makes a fast progress in research development and also in full-scale applications.

The main argument for the overall limited application of CW technology is the high area demand compared to conventional treatment systems. However, this is not an actual limitation in many regions around the world; it can be overcome by the various combinations in hybrid systems and can be argued as an activity toward the compensation of general natural ecosystem devastation in many industrialized countries.

In the context of land area demands, vertical flow CWs appear as a good compromise between highly intensive treatment systems, usually connected with a high energy input but extreme low area demand like activated sludge technology, and horizontal flow CWs, which can have almost no external energy input demand—similar to ponds—but also a higher-area demand because of the low oxygen input into the system. In general, it is expected the application of vertical-flow CWs will extend within the next years and, depending on effluent quality demands, it can be combined with other treatment systems.

Because of the fast development of vertical-flow CWs and their huge potential for implementation into practice, a book dedicated only to this technology will help to foster the distribution of knowledge about this technology, not only to scientists but especially to engineers involved in practical aspects of wastewater treatment.

In contrast to some other textbooks, the topic of wastewater treatment is here combined with the sludge treatment because of the very similar technological approach. Like vertical flow CWs for wastewater treatment, and maybe even more, sludge treatment wetlands (STWs) are still a not widely considered option to handle sludge materials, like sludge obtained from the activated sludge process. The availability of summarizing literature about the technology of STWs is even more limited. The main advantage, in comparison to the conventional applied sludge treatment technologies, is also, like in case of CWs for wastewater treatment, the low energy input and the nonuse of chemicals.

The goal of this book is to provide an extensive review of the existing scientific, technical, and economic practices of using vertical flow CWs. The authors have indeed long-term experience by working for many years in this field with many publications in refereed scientific-engineering journals. Their book summarizes the latest knowledge of two technological systems, vertical flow CWs for wastewater and sludge treatment, which have a broad future application potential. The book comes at the right time, while we get increasingly aware of the need to protect one of our main basis of life, the water, and offers us a potential to treat water and sludge in a more sustainable way, even when financial sources are limited. What is mainly needed is the knowledge about alternatives to the conventional applied technologies. The reader can get this knowledge from this book. In this book, the reader can find a synthesis of current available literature on both technological systems, which provides a deep understanding of the current state-of-the-art knowledge and use of Vertical Flow Constructed Wetlands.

Peter Kuschk
Helmholtz Center for
Environmental Research - UFZ, Leipzig, Germany
March 2014

Preface

The idea of this book was born about 2 years ago. Working for several years on the experimentation and modeling of constructed wetlands for wastewater and sludge treatment, and having designed and implemented several systems in Greece, we have realized the dynamics of the vertical flow constructed wetland systems and the need for a book on this subject. Based on the promising results of several research and design projects, and the extended literature review conducted over the years, it became clear to us that these systems offer a series of significant benefits concerning their technical efficiency, environmentally friendly character, and economic viability. However, at the same time, we realized that a single and comprehensive reference for these systems simply did not exist. Although there are several books for other types of constructed wetlands, presenting their efficiency, general operation and construction parameters, and case studies and experiences from several countries, a respective reference for vertical flow systems was not available in the literature. Existing books on the subject are mainly edited books, containing book chapters by experts in the field; even there, again, limited information is given about vertical flow constructed wetlands. Until today, the only way for someone to find relative information is to search and collect several scientific papers and perhaps some chapters from various books.

We were happy to see that Elsevier Publishing was positive and willing to publish such a book. Thus, the idea of this book became a reality.

The result of our efforts over the last two years is the book at hand. This book represents the first single reference for vertical flow constructed wetlands, which is a relatively new and still developing technology in the field of ecological and environmental engineering. This book gathers and presents the current status of knowledge and experience on vertical flow constructed wetlands for wastewater treatment and sludge dewatering. It provides information on the design, construction, operation, and maintenance of these systems, as it also thoroughly describes their treatment performance. We have made a great effort to gather and present the state-of-the-art in knowledge on this subject. The book contains a brief introduction to constructed wetlands technology, theory, fundamental knowledge of the processes taking place within these systems, applications, and design considerations.

The wetland technology today is continuously evolving with new and innovative applications. Therefore, the book addresses not only municipal wastewater treatment but also various types of industrial and agro-industrial wastewaters and, of course, one of the most promising applications, sludge dewatering and drying. Additionally, the current level of modeling of vertical flow constructed wetlands is also briefly presented. Finally, in order to present a global overview of these systems, the economics of various applications are included to describe the level of investment and operational costs of such facilities, and the relative economic benefits. Finally, the environmental footprint of implementing such systems is also addressed, in terms of greenhouse gas emissions and global environmental impact, and is compared to that of conventional treatment methods.

It is our hope that this book will be a helpful reference material for undergraduate and graduate students in civil engineering, environmental engineering, environmental science, chemical engineering, rural engineering, agricultural engineering departments, professionals dealing with wastewater treatment facility designs, and researchers in the field of wastewater treatment using constructed wetlands. For this reason, the book is written in a way to address both the scientific (providing the necessary information and justifications) and the professional point of view. It contains information from existing treatment systems and existing guidelines for designing constructed wetlands, which will be useful for both academic and professional use. It also highlights present treatment limitations, gaps in fundamental knowledge, and areas which need further investigation.

We hope that this book will be a useful and essential reference for the wetland community, and not only, and that it will assist in the better understanding and growing worldwide interest for these excellent treatment systems.

Alexandros Stefanakis
Christos S. Akratos
Vassilios A. Tsihrintzis

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Chapter 1

Introduction

1.1 NATURAL V. CONSTRUCTED WETLANDS

1.1.1 Definitions

Natural wetlands are transitional areas between terrestrial and aquatic systems, integrating characteristics of both dry and wet environments. They can be fully or partially covered by water for extended periods of time or during the whole year. They are dynamic systems, continuously evolving and changing their characteristics with time. The level of water saturation is a main factor that determines the nature of the soil and the types of plant and animal species that live in wetlands. The characteristics of natural wetlands are affected by a variety of local/regional parameters, including climate, hydrology, topography, water chemistry, vegetation, and human disturbance nowadays, among others. Due to these exact characteristics and parameters that regulate their status and appearance, natural wetlands can be found on every continent except Antarctica.

There is a variety of wetland types, which makes it difficult to formulate a precise, internationally accepted definition. One of the best and recognized definitions for natural wetlands was provided by the Ramsar Convention on wetlands in 1971 (Ramsar, 2012). This Convention adopted an international, intergovernmental definition for wetlands, based on a broad approach to describe to the best the main wetland characteristics. Wetlands are defined as "*areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six meters.*" Natural wetlands include areas like estuaries, mangroves, tidal flats, floodplains, deltas, freshwater marshes, lakes, lagoons, swamps, and springs of underground aquifers. As their name indicates, they are created without any human intervention. According to the same Convention, the same terms also include riparian and coastal zones adjacent to natural wetlands or islands or sea ponds that are deeper than 6 m, but located within the boundaries of the wetland. Moreover, Section 404 of the US Clean Water Act defines wetlands as

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follows: "*Those areas that are inundated or saturated by surface or ground water (hydrology) at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation (hydrophytes) typically adapted for life in saturated soil conditions (hydric soils). Wetlands generally include swamps, marshes, bogs, and similar areas*" (USEPA, 1972).

The IUCN (International Union for the Conservation of Nature) Natural Heritage Program, which was established in 1996, prepared a list of 77 World Heritage wetland sites with major and secondary values in 50 different countries (Thorsell et al., 1997). The world area of wetlands is difficult to estimate. Some estimates report a present total wetland area of 5.7 million km^2 (6% of Earth's surface), of which 30% are bogs, 26% fens, 20% swamps, 15% floodplains, and 2% lakes, with the addition of 0.24 and 0.6 million km^2 of remaining mangroves and coral reefs, respectively (Thorsell et al., 1997). Another estimate increases the total wetland area up to 6.9 million km^2, including 1.5 million km^2 of rice paddies (Matthews and Fung, 1987). The Global Review of Wetland Resources and Priorities for Wetland Inventory in 1999 increased the estimated global wetlands area from national inventories up to 12.80 million km^2 (Finlayson and Spiers, 1999). The data for this estimate were obtained from several sources and include inland and coastal wetlands (including marshes, lakes, and rivers), near-shore marine areas (to a depth of 6 m below low tide), and human-made wetlands such as reservoirs and rice paddies (Table 1.1).

1.1.2 Function and Values of Natural Wetlands

It is only during the last 50 years that humanity began to realize the multiple benefits of wetlands to human society. Wetlands are of special ecological importance, due to the diversity of species and population densities they support,

TABLE 1.1 Ramsar Sites Number and Area per Region (MEA, 2005)

	Total Area of Ramsar Sites (million ha, 2011)	Number of Ramsar Sites (2011)	Wetlands of International Importance (Ramsar Sites)
Africa	85	310	160
Asia	14	254	174
Europe	25	939	805
Neotropics	33	161	126
North America	23	191	117
Oceania	8	77	74
World	189	1932	1456

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