Applied Environmental Science and Engineering for a Sustainable Future

Veeriah Jegatheesan
Perlie Velasco
Nevelina Pachova *Editors*

Water Treatment in Urban Environments: A Guide for the Implementation and Scaling of Nature-based Solutions

Examples from South/Southeast Asia

Springer

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Foreword

I am pleased to introduce *Water Treatment in Urban Environments: A Guide for Implementing and Scaling Nature-Based Solutions—South/Southeast Asian Examples*. This book represents a significant outcome of a comprehensive regional research project funded by the Asia-Pacific Network for Global Change Research (CRRP2021-06MY-Jegatheesan). The project, titled "Integrated assessment of existing practices and development of pathways for the effective integration of nature-based water treatment in urban areas in Sri Lanka, the Philippines, and Vietnam," aligns with our network's core objectives and contributes substantially to our collective goals.

In a rapidly changing world, the management of urban water resources has emerged as a complex challenge. Confronted with growing urbanization, industrialization, and climate change, conventional water treatment methods often fall short. In this context, nature-based solutions (NbS) have gained recognition as a sustainable and innovative approach to address urban water treatment challenges. This book serves as an exploration of NbS and their potential.

The authors, representing a range of countries including Australia, Sri Lanka, the Philippines, Vietnam, and Spain, have collaborated extensively on this project. Their collective expertise and dedication have resulted in a comprehensive guide for implementing NbS in urban settings. Covering aspects from initial planning to socio-economic evaluations, construction methodologies, maintenance protocols, and operational monitoring, this book provides a practical roadmap for urban planners, policymakers, engineers, and environmentalists. What distinguishes this book is its pragmatic approach. It is not a theoretical discourse but a practical guide offering insights applicable to real-world scenarios. Drawing from experiences in Sri Lanka, Vietnam, and the Philippines, it demonstrates the adaptability of NbS principles to diverse challenges, and the case studies and insights provided serve as practical tools for positive change.

The book highlights the transformative potential of NbS, which extends beyond water treatment. They serve as catalysts for cleaner air, climate resilience, pollution reduction, and the enhancement of urban biodiversity. NbS also contribute to ecological balance restoration in cities. In addition to ecological benefits, NbS offer cultural and societal advantages. They create opportunities for recreation and ecotourism and foster a deeper connection between communities and nature. This underscores the importance of NbS in promoting environmental stewardship.

In closing, I extend my gratitude to the authors, the project team, and all contributors. Their dedication to the Asia-Pacific Network for Global Change Research's ideals is evident throughout this book. May it inspire further exploration and application of nature-based solutions as a means to address pressing urban challenges.

Asia-Pacific Network for Global Change Research Linda Anne Stevenson
Kobe, Japan

Preface

The inevitable rapid expansion of urbanization brings with it numerous social benefits. However, it also presents socio-environmental challenges such as water pollution, water and food insecurity, human health issues, biodiversity loss, increased vulnerability to climate change, and associated disaster risks. Sustainable Development Goal 11, which focuses on sustainable cities and communities, aims to address these challenges and create sustainable, resilient, and livable cities.

This book focuses on the issue of water pollution caused by the growing concentration of people in cities and urban environments and how nature-based solutions (NbS) for water treatment can help to address it. NbS are known for their efficiency, cost-effectiveness, and ability to provide numerous ecosystem services, many of which are difficult to quantify. Over the past few decades, NbS have received growing attention in Europe, but their applicability and replicability in the context of Asia, specifically in South and Southeast Asia, have not received adequate attention to date. This book is focused on enabling and enhancing learning based on knowledge acquired through successful NbS employed for water treatment in that context. The book was developed based on research supported financially by the Asia-Pacific Network for Global Change Research (APN-GCR), and we express our gratitude to them for enabling the implementation of a two-year project (2021–2023) [1] entitled "Integrated Assessment of Existing Practices and Development of Pathways for the Effective Integration of Nature-based Water Treatment in Urban Areas in Sri Lanka, The Philippines, and Vietnam." Through this project, we developed a framework for integrated assessment of NbS for water treatment and examined a set of existing constructed floating wetlands in two Sri Lankan lakes and in an urban canal in Vietnam, together with the green roof system for water treatment also in Vietnam, and finally the two constructed wetlands in the Philippines. Based on those studies, we developed guides for implementing those types of nature-based solutions to

[1] Further information on the project is available at the following website: https://www.apn-gcr.org/project/integrated-assessment-of-existing-practices-and-development-of-pathways-for-the-effective-integration-of-nature-based-water-treatment-in-urban-areas-in-sri-lanka-the-philippines-and-vietnam/

assist researchers and practitioners in replicating the examined systems. This book serves as a platform for disseminating these guides. It also provides an integrated resource base for comparing and contrasting their performance.

We express our sincere appreciation to the APN academic and governance bodies for the trust in our efforts and specifically to Dr. Nafesa Ismail, Ms. Aiko Seki, Ms. Naomi Yong, and Dr. Linda Anne Stevenson for their unwavering support throughout the research process. Their clear instructions and approval of various requests have greatly facilitated the smooth execution of the project. Additionally, we would like to thank our project teams in Sri Lanka, Vietnam, and the Philippines for their tireless efforts in developing, testing, and evaluating the selected nature-based solutions for water treatment in their countries and for sharing their knowledge and insights into the implementation guides that constitute the core of the book.

It is our hope that this book will serve as a valuable resource, enabling knowledge dissemination and facilitating the widespread adoption of nature-based solutions for water treatment. By sharing our research findings and practical guidelines, we aspire to contribute to fostering more sustainable and resilient urban development in Sri Lanka, the Philippines, Vietnam, and beyond.

Melbourne, VIC, Australia — Veeriah Jegatheesan
Los Baños, Laguna, Philippines — Perlie Velasco
Barcelona, Spain — Nevelina Pachova

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About the Editors and Contributors

About the Editors

Veeriah Jegatheesan (Jega) is Professor of Environmental Engineering and former Director of Water: Effective Technologies and Tools (WETT) Research Centre at RMIT University, Melbourne, Australia. Jega is the founder and Chairman of the international conference series on Challenges in Environmental Science & Engineering (CESE) held annually since 2008. Jega has conducted extensive research on the application of membrane bioreactors, sugar cane juice clarification, seawater desalination, and the treatment of mine tailing ponds. He has over 500 publications including more than 195 peer-reviewed journal articles and 14 edited books. Jega is also the managing guest editor of 60 special issues in peer-reviewed journals. In 2019, the Stormwater Industry Association (Australia) has appointed him as one of the Governance Panel members for the Australian Stormwater Quality Improvement Device Evaluation Protocol (SQIDEP). Jega is the Editor-in-Chief of a book series entitled *Applied Environmental Science and Engineering (AESE) for a Sustainable Future* published by Springer and has been instrumental in publishing 16 books since 2015. Jega has been appointed as the Editor-in-Chief of Environmental Quality Management Journal (Wiley Publisher) from January 2020.

Perlie Velasco is Associate Professor at the Department of Civil Engineering, University of the Philippines Los Baños (DCE, UPLB). She is the lead faculty in Environmental Engineering at the department with research projects in constructed wetlands and integrated solid waste management. She got her undergraduate degree in Civil Engineering at UPLB (2005), Master's in Water Resources Engineering at the Katholieke Universiteit Leuven, Belgium (2010), and PhD degree in Environmental Engineering at the Royal Melbourne Institute of Technology, Australia (2022). Her research works focus on membrane-based recovery of dissolved methane from wastewater effluent and constructed wetlands for wastewater treatment.

Nevelina Pachova is Research Fellow and Research & Innovation Advisor at RMIT Europe, the European hub of Australian University RMIT, where she conducts research and supports the development and implementation of research and innovation projects in the field of urban development and sustainability transitions with a focus on the integration of nature-based solutions in urban development and planning, network governance, and social inclusion. Prior to joining RMIT, Nevelina worked in the field of natural resources management and poverty reduction at the different agencies of the United Nations University in Tokyo and Bonn.

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List of Abbreviations

ADF	Augmented Dickey-Fuller
AHP	Analytical hierarchy process
APN-GCR	Asia-Pacific Network for Global Change Research
ArcGIS	Aeronautical Reconnaissance Coverage GIS
APHA	American Public Health Association
BCA	Benefit–cost analysis
BMB	Biodiversity Management Bureau
BOD	Biological oxygen demand
BSWM	Bureau of Soils and Water Management
C	Consistency vector
CEA	Central Environmental Authority
CFWs	Constructed floating wetlands
CI	Consistency index
CO	Corporate office
COD	Chemical oxygen demand
CR	Consistency ratio
CSOs	Civil society organizations
CVM	Contingent valuation method
CWs	Constructed wetlands
DA	Department of Agriculture
DAO	DENR Administrative Order
DENR	Department of Environment and Natural Resources
DEWATS	Decentralized wastewater treatment systems
DILG	Department of Interior and Local Government
DLSU	De La Salle University
DO	Dissolved oxygen
DPSIR	Driver-pressure-state-impact-response
DPWH	Department of Public Works and Highways
EC	European Commission
ECC	Environmental Compliance Certificate
EIA	Environmental impact assessment

EM	Effective microorganism
EMB	Environmental Management Bureau
FCW	Floating constructed wetland
FGD	Focus group discussion
FMB	Forest Management Bureau
FSCW	Free surface constructed wetland
GIS	Geographic information system
GK	Gawad Kalinga
GRs	Green roofs
GTZ	German Technical Cooperation
HCMUT	Ho Chi Minh City University of Technology
HDPE	High-density polyethylene
HLR	Hydraulic loading rate
HRTs	Hydraulic retention times
HSFCW	Horizontal flow constructed wetland
HSSF	Horizontal subsurface flow
IAS	Impact assessment study
IEE	Initial Environmental Examination
IKI	International Climate Initiative
IRR	Internal rate of return
ISF	Informal settler families
IUCN	International Union for Conservation of Nature
KIIs	Key informant interviews
LGU	Local Government Unit
LKR	Sri Lankan Rupee
LLDA	Laguna Lake Development Authority
MBAS	Methylene blue active substances
MCDM	Multicriteria decision making
MGB	Mines and Geosciences Bureau
MWSS	Metropolitan Waterworks and Sewerage System
NAMRIA	National Mapping and Resource Information Authority
NbS	Nature-based solutions
NEDA	National Economic and Development Authority
NGAs	National government agencies
NGO	Non-governmental organisation
NPV	Net present value
NSSMP	National Sewerage and Septage Management Program
NWRB	National Water Resources Board
OLR	Organic loading rate
PBP	Payback period
PE	Polyethylene
PHIVOLCS	Philippine Institute of Volcanology and Seismology
PNRI	Philippine Nuclear Research Institute
PPCPs	Pharmaceuticals and Personal Care Products
PVC	Polyvinyl chloride

PWP	Philippine Water Partnership
PWSSMP	Philippine Water Supply and Sanitation Master Plan
QGIS	Quantum GIS
RBCO	River Basin Coordinating Council
RI	Random index
ROI	Returns on investment
ROV	Real options valuation
SCPW	Society for the Conservation of Philippine Wetlands
SDGs	Sustainable Development Goals
STP	Sewage treatment plant
TIP	Technological Institute of the Philippines
TEV	Total economic value
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids
UN	United Nations
UPLB	University of the Philippines Los Baños
USD	United States Dollar
UTM	Universal Transverse Mercator
VFA	Volatile fatty acids
VFCW	Vertical flow constructed wetland
VND	Vietnamese Dong
VSSF	Vertical subsurface flow
WDs	Water districts
WGS	World Geodetic System
WHO	World Health Organization
WQ	Water quality
WQS	Water quality standards
WTA	Willingness to accept
WTP	Willingness to pay
WW	Wastewater

Chapter 1
Introduction

Veeriah Jegatheesan, Perlie Velasco, and Nevelina Pachova

Abstract Implementing nature-based solutions (NbS) for urban water treatment offers valuable ecosystem services and societal benefits. Success relies on diverse technical and societal factors. This book offers guidelines for NbS implementation in South/Southeast Asian cities, covering constructed wetlands, green roofs, and floating treatment wetlands. Drawing from experiences in three countries, it provides detailed steps on planning, socio-economic evaluations, construction methods and costs, maintenance, and operational monitoring parameters. The book also explores approaches for scaling NbS in local contexts.

Keywords Guidelines · Ecosystem services · Nature-based solutions · Water treatment · Urban environment · Replication

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1.1 Background

Water quality poses a significant challenge worldwide as industrialization, urbanization, and climate change continue to escalate. In mitigating urban water pollution, nature-based solutions (NbS) for water treatment have emerged as a promising approach, offering multiple co-benefits that enhance the livability and resilience of cities. Several pilot and demonstration projects across Asian cities have explored the potential of NbS; however, there is a dearth of comprehensive documentation on their effectiveness and impacts. Additionally, the sustainability, replication, and upscaling of these solutions remain poorly understood. To address this knowledge gap, the Asia Pacific Network for Global Change Research funded a two-year project (October 2021 to September 2023) involving an international research team from Australia, Sri Lanka, the Philippines, Vietnam, and Spain, which includes the authors of this chapter (source: https://doi.org/10.30852/p.18686). The project's objective is to conduct an integrated assessment of existing practices and explore pathways for the effective integration of nature-based water treatment in urban areas of Sri Lanka, the Philippines, and Vietnam. This book draws upon the research conducted within the framework of the project.

Nature-based approaches to water management and treatment have experienced a renewed interest in recent decades, although the concept itself is not new. It is essential to revisit the definition of nature-based solutions (NbS). According to the European Commission (EC), NbS encompass solutions that address socio-environmental challenges such as climate change, water security, water pollution, food security, human health, biodiversity loss, and disaster risk management. These solutions are inspired by and aligned with nature, offering cost-effective means to simultaneously provide environmental, social, and economic benefits while enhancing local resilience. NbS aim to integrate a greater diversity of nature and natural features and processes into urban areas, landscapes, and seascapes through locally adapted, resource-efficient, and systemic interventions. Notably, the EC updated its definition in 2020, underscoring the importance of NbS in benefiting biodiversity and supporting the delivery of various ecosystem services.

NbS, such as roof gardens, vertical gardens, sustainable drainage systems, ponds, constructed floating wetlands (CFWs), and constructed wetlands (CWs), offer significant opportunities for decentralized water management, particularly in areas where centralized solutions are limited or economically impractical. These solutions typically require less energy than conventional systems while delivering a multitude of ecosystem services.

The implementation of NbS brings forth a range of regulating services, which encompass improved air quality, favorable local climatic conditions, reduced stormwater run-off, prevention of soil erosion, mitigation of natural hazards, increased pollination, and the creation of new habitats to support urban biodiversity. In addition, these solutions generate supporting ecosystem services that contribute to nutrient cycling, water cycling, soil formation, and photosynthesis, thereby enhancing the overall ecological balance. This, in turn, leads to provisioning ecosystem services, increasing the availability of food, fiber, fuel, biomass, freshwater, and natural medicines within the urban environment.

Moreover, the adoption of NbS also has positive implications for cultural ecosystem services. It enhances opportunities for recreation and ecotourism and fosters the development of ethical values and recognition of existence values, further strengthening the connection between communities and their natural surroundings.

Within the scope of the aforementioned project, extensive research on NbS identified constructed wetlands (CWs), green roofs (GRs) for water treatment, and constructed floating wetlands (CFWs) as promising approaches in the local context. For a considerable period, lakes in Sri Lanka have served as vital sources of drinking water and popular recreational spots. However, with the rapid urbanization and the associated by-products, these lakes are experiencing pollution, posing significant environmental challenges. In order to address this issue, the implementation of floating wetlands has emerged as an effective and cost-efficient solution for treating the incoming water in these lakes. As a result, the study focuses on the placement of CFWs in lakes, recognizing their potential to mitigate pollution and safeguard the ecological balance. Similarly, in densely populated urban areas of Vietnam, the lack of proper treatment for septic tank effluents has led to significant pollution in canals and rivers. To tackle this problem, the study proposes a twofold approach. First, by treating the septic tank effluent at its source using GRs, the study aims to prevent the introduction of pollutants into the canals. Additionally, CFWs are considered a suitable choice to address the pollutants already present in the canals, thus providing a comprehensive solution for water treatment in these urban areas. In the Philippines, constructed wetlands have been identified as crucial components in the treatment of septic tank effluents. These wetlands play a significant role in effectively treating and purifying the wastewater generated by septic systems, contributing to overall water quality improvement. By recognizing the specific challenges faced in each country and exploring the appropriate NbS, the project aims to contribute to the preservation of water resources and the protection of the environment in Sri Lanka, Vietnam, and the Philippines.

Thus, to assess their effectiveness and impacts, pilot studies were conducted in Vietnam, Sri Lanka, and the Philippines. These studies focused on a green roof system and a floating wetland in Vietnam, two floating wetlands in Sri Lanka, and two constructed wetlands in the Philippines. Detailed findings and insights from these studies, as documented by Jegatheesan et al. (2022), Dang et al. (2022), Velasco et al. (2022), and Weragoda et al. (2022), form the basis for the guidelines included in this book.

The book provides comprehensive guidelines for the establishment, operation, and maintenance of green roofs for water treatment, floating wetlands, and constructed wetlands. Additionally, it offers selected examples that delve deeper into technical, economic, social, and policy/governance aspects considered crucial for the successful implementation and maintenance of NbS, as well as their replication.

Table 1.1 Aspects considered in the NbS guides

Aspect of NbS	Factors to be considered
Technical	Overall design of an NbS (location, constraints, goals of NbS), materials required, method of construction, plant selection, maintenance, monitoring of water quality and other environmental impacts
Social	Survey questionnaires, public awareness and acceptance, willingness to pay, involvement of various stakeholders, partnerships
Economic	Computing capital and operating cost of NbS, shadow pricing, methods to compute ecosystem services
Policy/ Governance	Existing standards for the construction and maintenance of NbS, procedures to obtain permits for construction, ownership, and security of NbS

Table 1.1 summarizes the key factors considered in the development of these guidelines, ensuring a comprehensive and practical resource for practitioners and policymakers alike.

1.2 Organization of Chapters

While the primary focus of the book revolves around three specific types of NbS for water treatment, it is worth noting that various other solutions have been implemented in the past across the countries under examination. Chapter 2, titled "Mapping of Existing NbS for Water Treatment in the Philippines, Sri Lanka, and Vietnam," aims to capture these diverse approaches, providing insights into the tested NbS in each country, their performance, and the lessons learned from those experiences. This chapter sets the stage and provides a broader context for the subsequent chapters.

Chapter 3 delves into the "Suitability Mapping of Constructed Wetlands," presenting a framework for evaluating locations suitable for the application of constructed wetlands. While the chapter draws on the experiences and context of the Philippines, it offers a generic process that can be adapted by users in other countries with relevant modifications to the local context.

Moving forward, Chap. 4 focuses on the "Economic Analysis of NbS for Wastewater Treatment Under Uncertainties," while Chap. 5 examines the "Social Acceptability Assessment of NbS for Water Treatment." These chapters present methodologies employed in the Philippines but can be replicated in other contexts with necessary adaptations.

Chapter 6 provides a "Guide to Constructed Wetlands: A Philippine Perspective," followed by Chap. 7, which presents a "Guide to Green Roofs: A Vietnam Perspective." Chapters 8, 9, and 10 are dedicated to floating treatment wetlands, with Chap. 8 offering a guide based on relevant experiences from Sri Lanka, and Chap. 10 providing a guide based on experiences from Vietnam. In Chap. 9, a guide is presented for selecting plants suitable for floating treatment wetlands.

Chapter 11 explores "Pathways for the Scaling of NbS for Water Treatment: Examples from the Philippines, Sri Lanka, and Vietnam," discussing strategies to facilitate the broader adoption of NbS. It also outlines directions for future applications and research, providing a comprehensive conclusion to the book.

We anticipate that this book will serve as a valuable guide for establishing, operating, and maintaining constructed wetlands, green roofs, and floating treatment wetlands not only in the examined countries but also in other locations within the broader region. By addressing not only the technical aspects but also the relevant economic, social, and policy factors, we aim to facilitate the transition of these NbS from research pilots, which currently dominate the field, to practical applications that can contribute to achieving the targets outlined in Sustainable Development Goal 11—"Sustainable Cities and Communities."

Our hope is that the implementation of these NbS will foster inclusive, safe, resilient, and sustainable urban environments across the South/Southeast Asian region. By providing guidance that goes beyond technical considerations, we aspire to support the transformation of urban landscapes, promoting the well-being and quality of life for all residents while working toward a more sustainable future.

Acknowledgments We express our gratitude for the funding provided by the Asia Pacific Network (APN) for Global Change Research, which enabled the completion of the project resulting in this book. Our sincere thanks go to Dr. Linda Anne Stevenson, Head of Knowledge Management and Scientific Affairs at APN, as well as the dedicated staff at the APN Secretariat, including Dr. Nafesa Ismail, Ms. Aiko Seki, and Ms. Naomi Young, for their unwavering support throughout the project.

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Chapter 2
Mapping Existing NbS for Water Treatment in the Philippines, Sri Lanka, and Vietnam

Perlie Velasco, Angeli Cabaltica, Nevelina Pachova, and Veeriah Jegatheesan

Abstract A growing number of easily accessible maps are capturing the knowledge on nature-based solutions (NbS) for urban development. However, existing examples from Asia included in those maps are limited and not necessarily focused on water. Existing scientific research on NbS in Asia is focused on case studies, and no readily available database allows for meta-analysis, which is important for advancing the understanding of their effectiveness and potential for replication in different contexts. Further, many existing cases are not documented in the academic literature, especially ones implemented by civil society and local government agencies. Even the ones documented through academic research are often not widely accessible throughout the regions since they are often not available to public access and are sometimes published in local languages. Thus, this chapter aims to provide two approaches to map existing NbS focusing on water management, with NbS for water case studies in Sri Lanka, the Philippines, and Vietnam, which are Google Maps and Geographic Information System (GIS). Thus, stakeholders can easily identify the locations of NbS structures for water and wastewater management, which will be one of the key factors in adopting NbS.

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Keywords Dynamic Map · Geographic Information System · Google Maps · NbS mapping · Static Map

2.1 Introduction

Nature-based solutions (NbS) for water are small and thus often "invisible" relative to conventional water treatment infrastructure; thus, their value and potential to contribute to urban development are often ignored. Understanding the effectiveness of nature-based solutions (NbS) can be efficiently realised and learned through the experiences of existing NbS in a country. Such information would be highly relevant to research and practical aspects, as researchers need to rationalise the gap and results of their studies on its practical application. The benefits of NbS are maximised if adopted and utilised, particularly in developing countries. However, knowledge of these systems is not well disseminated or documented in these countries. With the onset and global popularity of online maps, existing NbS mapping would be one of the approaches to improve its efficient information dissemination. To date, open-access global mapping of NbS funded by various international organisations, such as the United Nations, World Bank, and International Union for Conservation of Nature, is available. Two of these interactive NbS maps are (i) Nature-based Solutions Initiative by the Department of Biology, University of Oxford (https://casestudies.naturebasedsolutionsinitiative.org/case-search/), and (ii) Urban Nature Atlas currently managed by the Environmental Science and Policy Department, Central European University (https://una.city). The former website has case studies on rural NbS and cites the latter website for urban case studies. Both websites provide an option to add an NbS project by answering the online survey form (for the Urban Nature Atlas, registration to their site is required). Table 2.1 summarises the NbS information from these two websites (rural NbS from Nature-based Solutions Initiative and urban NbS from Urban Nature Atlas) for Sri Lanka, the Philippines, and Vietnam.

As part of developing the guide on NbS implementation, the Asia-Pacific Network for Global Change Research (APN-GCR) project for 2021–2023 titled "Integrated Assessment of Existing Practices and Development of Pathways for the Effective Integration of Nature-based Water Treatment in Urban Areas in Sri Lanka, the Philippines and Vietnam" started with mapping of the existing NbS for water treatment pilots and demo sites across the three countries. For this, two open-access platforms were used: (i) Google Maps and (ii) Geographic Information System (GIS). These two are commonly used platforms for interactive data mapping and combining their location and information. Google Maps provides easy accessibility to the NbS map created, while the GIS map provides a better platform for additional data analysis, such as suitability mapping of NbS. The NbS mapping of this chapter would complement the existing information presented in Table 2.1 since the results from this study will focus more on the NbS for water and wastewater management.

Thus, the mapping methodology aims (i) to develop and test an easy to manage open-access platform for capturing and storing data on existing NbS for water treatment in Asia (technical aspect) and (ii) to give visibility to existing NbS and enable learning and exchange (societal aspect). Further, the societal aspect aims

Table 2.1 NbS database from Nature-based Solutions Initiative and Urban Nature Atlas

Country	Rural NbS (Nature-based Solutions Initiative)	Urban NbS (Urban Nature Atlas)
Sri Lanka	Bioremediation in Kalpitiya Peninsula—nitrate contamination reduction	Beddagana Wetland Park in Sri Jayawardenepura Kotte—flood and extreme heat regulations
		Green belt in the Batticaloa—12 km length, lagoon and coastal areas protection, mangrove ecosystems restoration, and coastal biodiversity improvement
Philippines	Forest Land Use Plan (FLUP) in Wao, Lanao del Sur—watershed rehabilitation and sustainable forest management	Constructed wetlands in Benguet—treatment of Balili River
		Evozone Rain Garden in Sta. Rosa, Laguna—32,000 m^2 rainwater catchment basin
		Linear park in Iloilo River Esplanade—part of the Iloilo River Rehabilitation Project, largest linear park in the Philippines
		Mangrove (Bakawan) Eco-Park in Kalibo, Aklan—floods and storm surge protection and livelihood source
		Mangrove Conservation in Del Carmen, Siargao—provides rich breeding grounds for aquatic environment, largest mangrove forest in the Philippines
		Green roof above SM North EDSA mall in Quezon City—400 m floating green ribbon, with 55 species of native trees, bushes, and flowers irrigated by the stored rainwater harvested
		Green building in Quezon City—Laguna Lake Development Authority office has wastewater treatment facility, material recovery facility, and a rainwater harvesting system (60,000 gallons capacity)

(continued)

Table 2.1 (continued)

Country	Rural NbS (Nature-based Solutions Initiative)	Urban NbS (Urban Nature Atlas)
Vietnam	Silvo-aquaculture in Mekong Delta—uses ecological aquaculture techniques (including mangroves) to reduce the risk of fisheries collapse	Vinh River Rehabilitation Project—rehabilitation and upgrade of riverbank green, sanitation, and flood risk management
	Community-based mangrove forest restoration and management in Da Loc and Nga Thuy Communes in Thanh Hoa Province—to boost resilience to flooding	APEC Sculpture Park in Binh Hien Ward, Hai Chau District, Da Nang City—to increase trees and green spaces in public parks and residential areas
	Reforestation and agricultural landscape restoration in Son Tho—to reduce the impacts of climate-related hazards	Da Nang Tree Planting Initiative—planted 900 Than Mat trees along Green Lake—Bai Bac, in the Tho Quang ward
		Kindergarten Farming in Dongnai City—welfare facility for the shoe factory's employees where the harvests are distributed to the families, and the children learn about the importance of agriculture
		Green dormitory of the Vietnam National University, Ho Chi Minh City—tree planting activity to improve the ecological and living environment of the students staying at the dorm
		House for Trees in Tan Binh District, Ho Chi Minh City—where five roofs in the residential areas have roof gardens to bring green space back into the city
		Red River Zoning Plan in Hanoi—green landscape along the 40 km banks, including public spaces for cultural and tourism purposes
		Urban Farm Office in Ho Chi Minh City—vertical farm in a concrete-framed structure covered with vegetables, fruits, and herbs to promote the production of safe food and green space in the city

(i) to provide an easily accessible basis for targeted analysis of locally tested applications of specific technologies, comparative research, and meta-analysis (formal learning) and (ii) to serve as a reference point for practitioners interested in learning from existing cases and enabling exchange among the implementing experts and agencies (informal learning).

2.2 NbS Mapping Development

Static and dynamic maps were developed to show the locations of all existing NbS sites in Sri Lanka, the Philippines, and Vietnam. Sri Lanka has six NbS project sites, while Vietnam has nine project sites, mostly in the southern part of the country. On the other hand, the Philippines has 42 NbS projects located in the Northern and central parts of the Philippines, and mostly Decentralised Wastewater Treatment Systems (DEWATS) projects of Basic Needs Services Philippines, Inc., which use green filters (or constructed wetlands) as an additional mechanism to treat various types of wastewater. The two approaches for the mapping provided in this chapter are static and dynamic mapping (Google Maps and GIS), which are discussed in detail in the succeeding subsections.

2.2.1 Static Map

Static maps were produced so they could be printed or displayed as images. Figure 2.1 shows all the project sites in the three countries. Figures 2.2, 2.3, 2.4 show the project sites in Sri Lanka, the Philippines, and Vietnam.

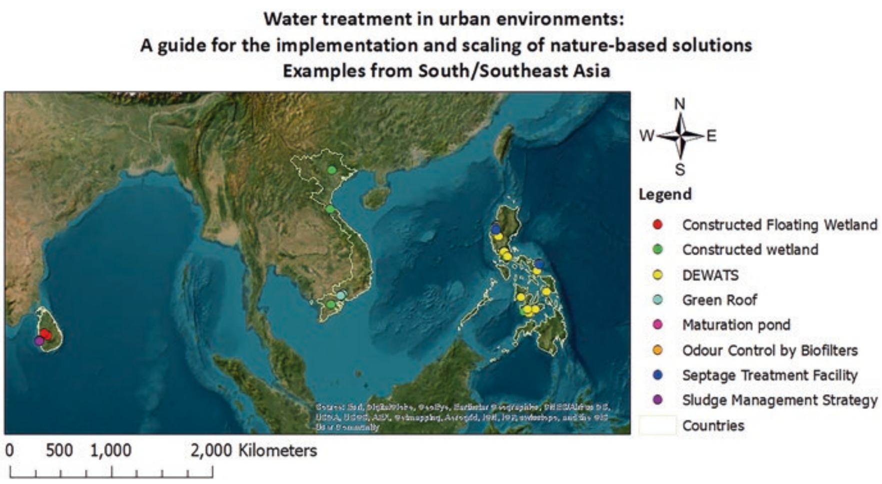

Fig. 2.1 Map of all existing NbS project sites in Sri Lanka, the Philippines, and Vietnam

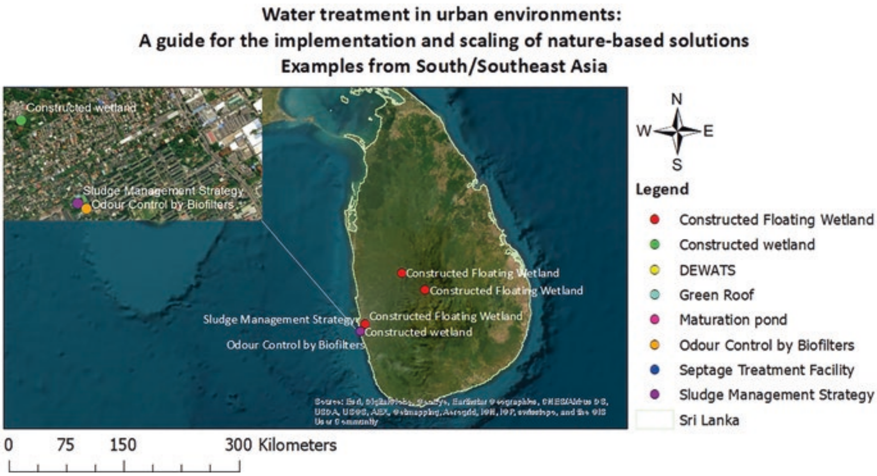

Fig. 2.2 NbS project sites in Sri Lanka with inset: three NbS sites that appear as one site in the larger map due to their proximity

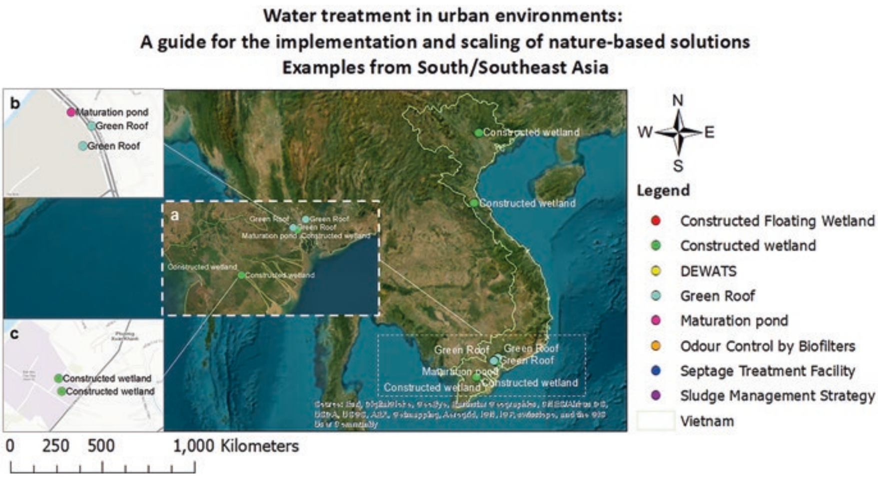

Fig. 2.3 NbS project sites in the Philippines

2.2.2 *Dynamic Map*

Dynamic maps are interactive maps that allow users to zoom in and out, click, select, search, and explore the data in different ways. The NbS for water project sites in Sri Lanka, the Philippines, and Vietnam were plotted on Google Maps, and *GIS mapping was also developed for dynamic mapping of NbS for water in the three countries.*

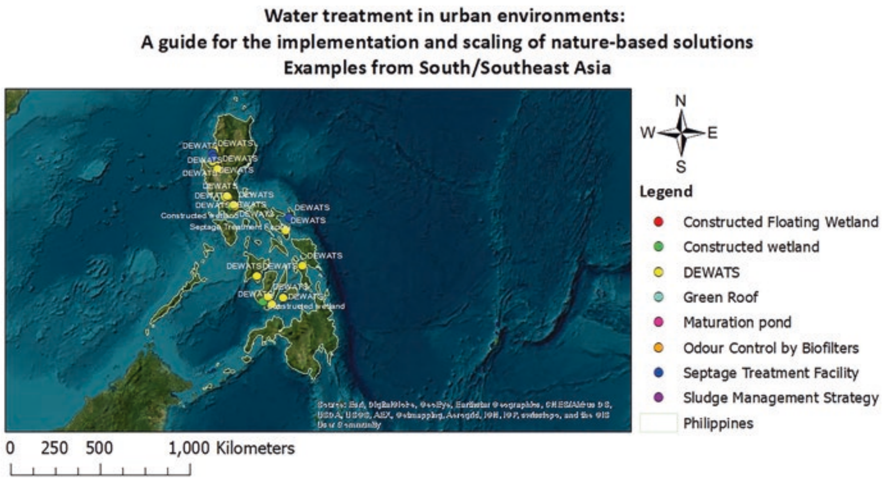

Fig. 2.4 NbS project sites in Vietnam with inset: (**a**) The NbS sites in the southern part of Vietnam; (**b**) Three NbS sites in Ho Chi Minh City that appear as one site in the larger map due to their proximity; (**c**) Two project sites in Can Tho that are at the same location

2.2.2.1 Mapping Using Google Maps

Google Maps has the option to create and personalise a map based on the needed information, which can also be shared for collaboration with the public. Figure 2.5 shows the step-by-step procedures for creating maps in Google Maps. In step 5, the database of information for the mapping can be directly inputted or edited in Google Maps by clicking the three dots beside the added layer and selecting either “Open Data Table” or “Import”. The former will open a table where the information can be inputted, while the latter will allow uploading a Microsoft Excel database file. When initially creating the map, importing the database rather than creating it in the Google Maps layer is highly recommended. The main important information for mapping the site in the base map of Google is to provide the exact location of the site by having a column for its address or latitude/longitude. When the table is imported, a window will appear (Fig. 2.6a) asking to select the column title on which the reference for the location pin in Google Maps will be based. Then another window will appear for the selection of the site title (Fig. 2.6b). Finally, the site information and format can be edited by selecting the pin to show the various editing buttons (Fig. 2.6c). Over time, the database can be updated by merging the existing Excel file with the updated file (by clicking the three dots beside the layer to be updated). This merge option can also be used to collaborate with other stakeholders with an operational NbS structure for water and wastewater management.

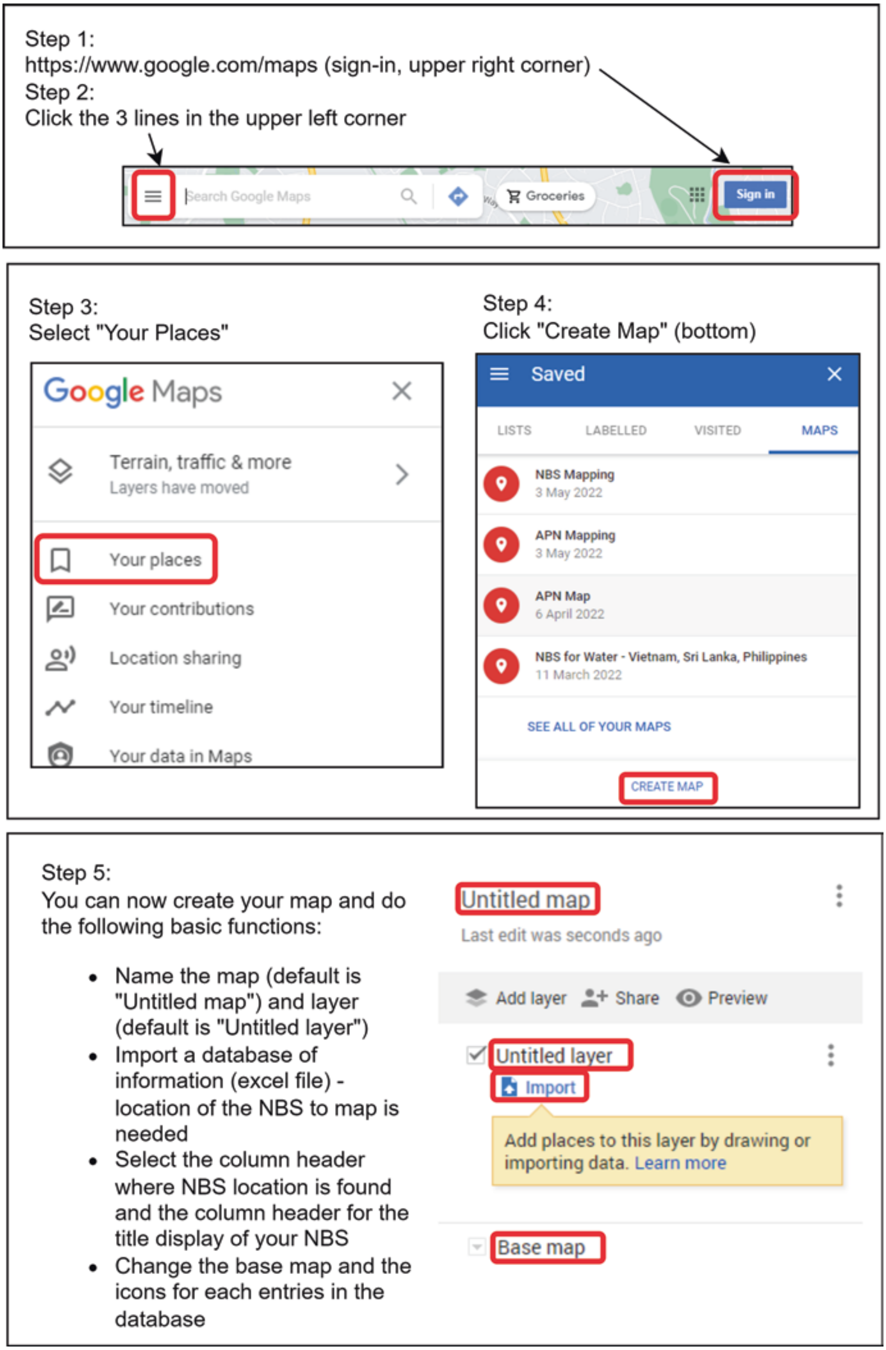

Fig. 2.5 Step-by-step procedures for mapping in Google Maps

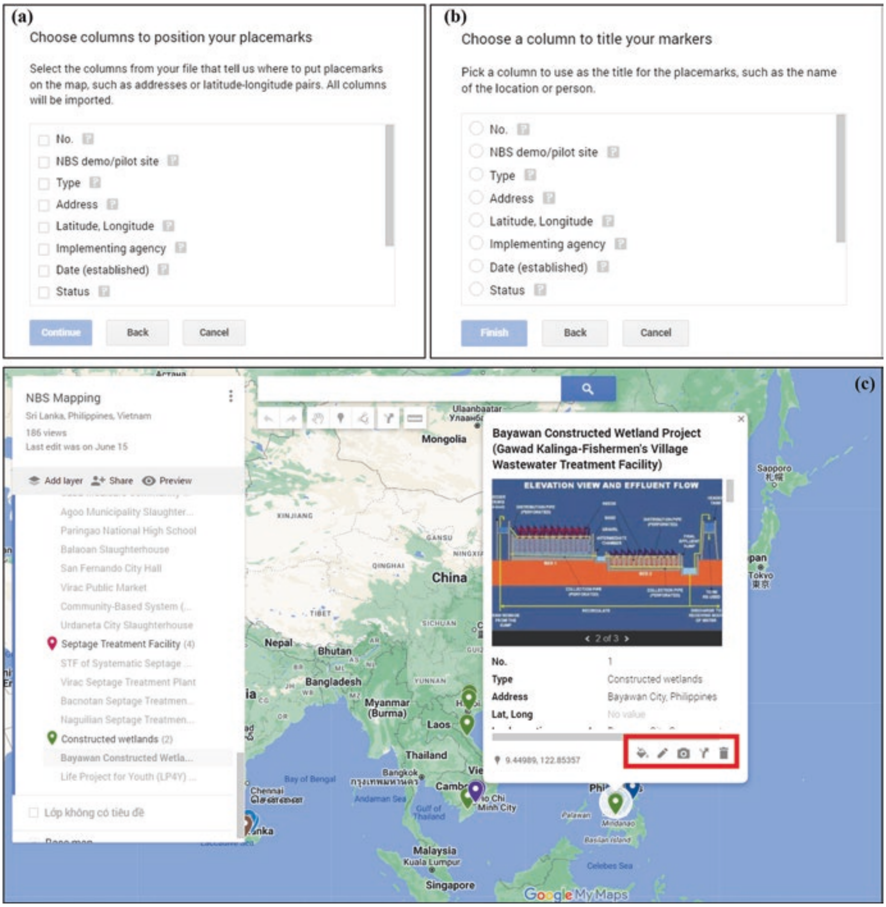

Fig. 2.6 Google Maps windows for importing database and editing each NbS site: (**a**) window in selecting the site location for pin mapping, (**b**) window in selecting the title of the pinned site, and (**c**) sample of the pinned site and options for editing (red box)

2.2.2.2 GIS Mapping Using QGIS

The web-based GIS presented here used an open-source mapping software, Quantum GIS (QGIS), and the Qgis2Web plugin. The plugin was used to generate the web map files from a QGIS project as Leaflet. The web map files were then deposited in a GitHub repository, and the GitHub Pages were used to generate the website from the files. The GitHub repository can be found here: https://github.com/NatureBasedSolutions/Map-of-Existing-NbS-for-wastewater-treatment-projects-in-the-Philippines-Sri-Lanka-and-Vietnam. The ReadMe file in the repository provides information and contact details for collaborators who may wish to add data and/or update the GIS maps. The GIS mapping process is composed of three main steps.

Step 1. Setting the map in QGIS

The map was first created in a new QGIS project. The Qgis2Web plugin replicates all the settings done in QGIS when it automatically creates the GIS map files; thus, the layers to be included in the GIS map, their rendering order, and the styling were chosen considering the intended GIS map composition while setting up the project.

The layers added in this project and their order of rendering are shown in Fig. 2.7. They include the point layer representing the location of the NbS sites in Sri Lanka, Vietnam, and the Philippines (layer name: Existing NbS Projects), the outline of the three countries (layer name: Countries), and Google basemaps. A copy of the point data (layer name: Labels) was also added for displaying the labels separately in the GIS map. The point layers carry all the information on the NbS sites.

Step 2. Generating the GIS map files using the Qgis2Web plugin

The plugin was first installed from the Plugins menu of QGIS and accessed from the Web menu after that. A window shown in Fig. 2.8 appears when the plugin is opened, and this is essentially where customisation of the GIS map is done. The first tab displays all the layers that are in the QGIS project. The layers to add, those that will be visible upon opening the GIS map, and those with information displayed in a pop-up were chosen and set here. The inclusion and placement of pop-up fields' labels were also set from here.

The Qgis2Web plugin can export the map using any of the three web mapping libraries—Open Layers, Leaflet, and Mapbox GL JS. After selecting Leaflet, the GIS map was previewed by clicking the Update Preview button (Fig. 2.9).

In the Appearance tab (Fig. 2.10), widgets such as address search, geolocate user, and measure tool were enabled. The layer list was set as collapsed, an abstract was enabled, and its position in the map was specified. Lastly, attribute filters were chosen from a list under this tab. These updates in the settings were then viewed again using the Update Preview button. After customising the GIS map layout, the files were exported using the Export button in the Export tab (Fig. 2.11) to a local folder. A progress pop-up dialog box appears to notify that the export was successful.

Step 3. Uploading the map to a web server

The last step was to upload the map to a web server, and in the case of the NbS GIS map, the code-hosting platform GitHub was used. An account was created in GitHub, and a new repository was added (Fig. 2.12). The exported files created from the Qgis2Web plugin were uploaded to the GitHub repository (Fig. 2.13), and the GIS map website was subsequently generated using GitHub Pages (Fig. 2.14).

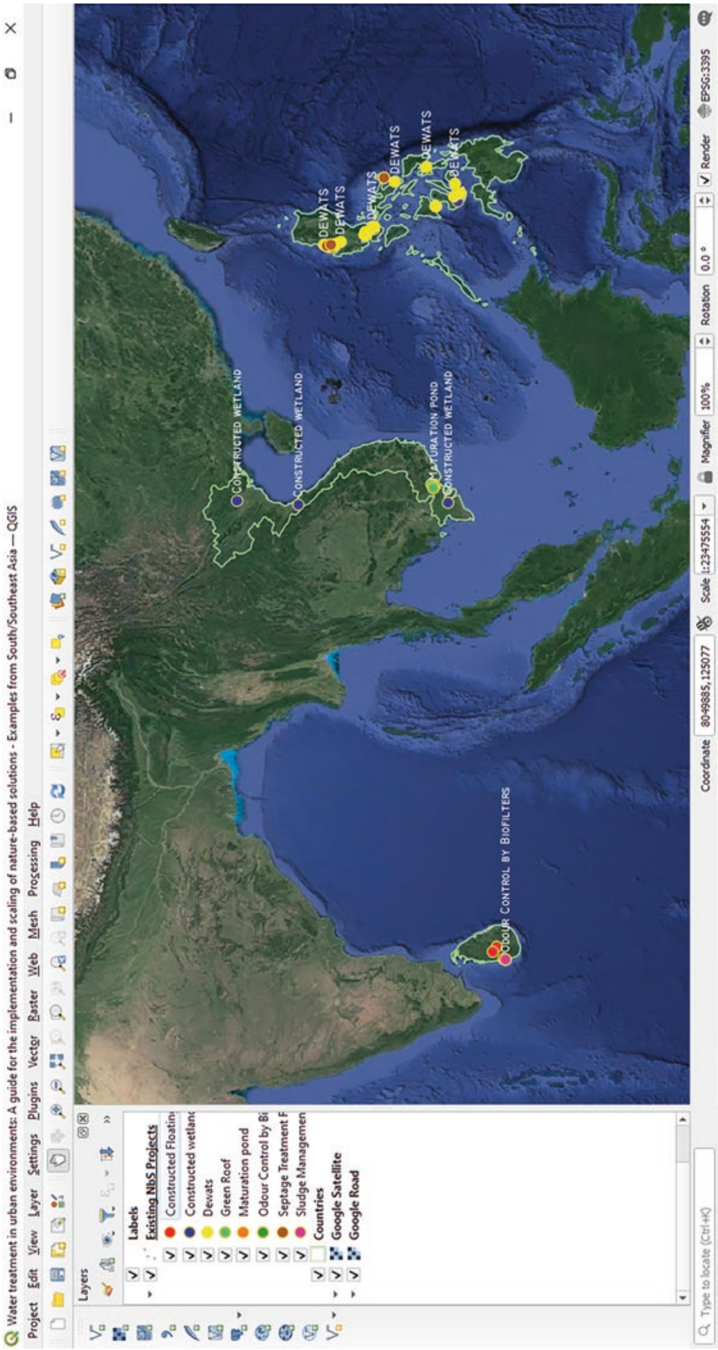

Fig. 2.7 The layers added to the QGIS project

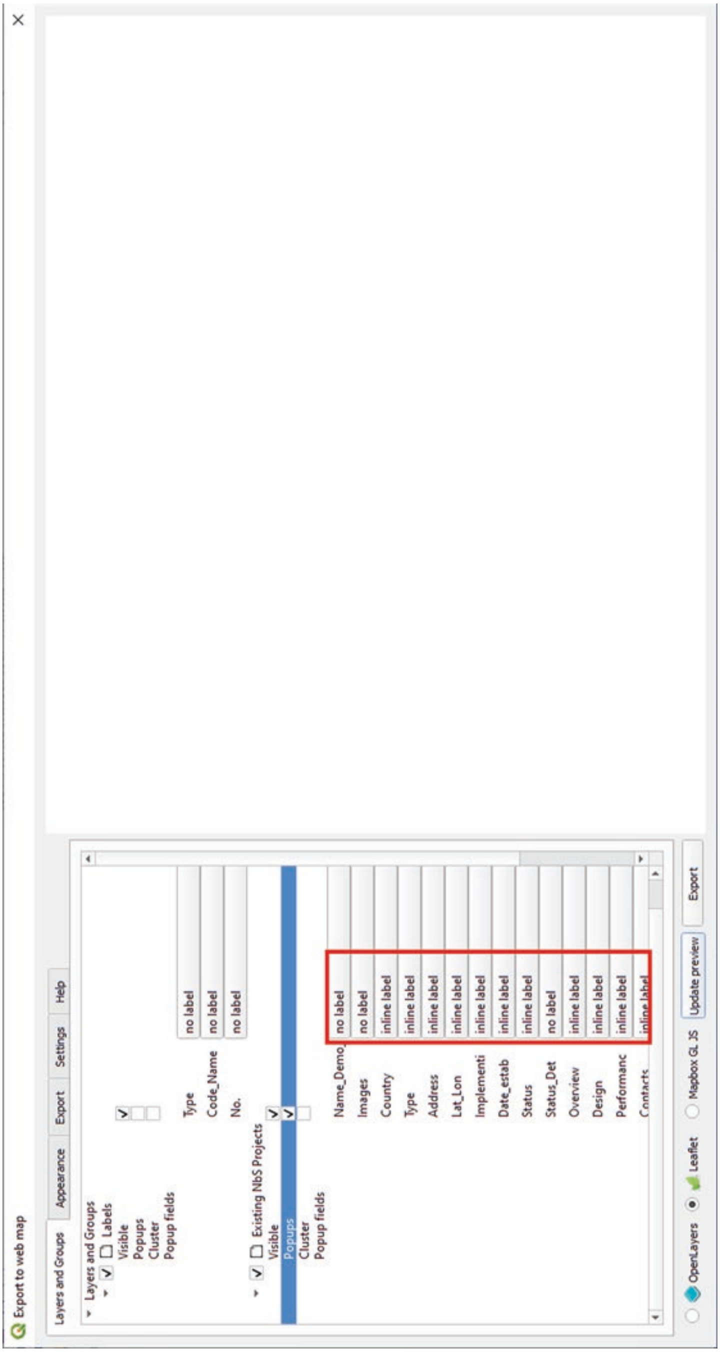

Fig. 2.8 The Qgis2Web plugin dialog box

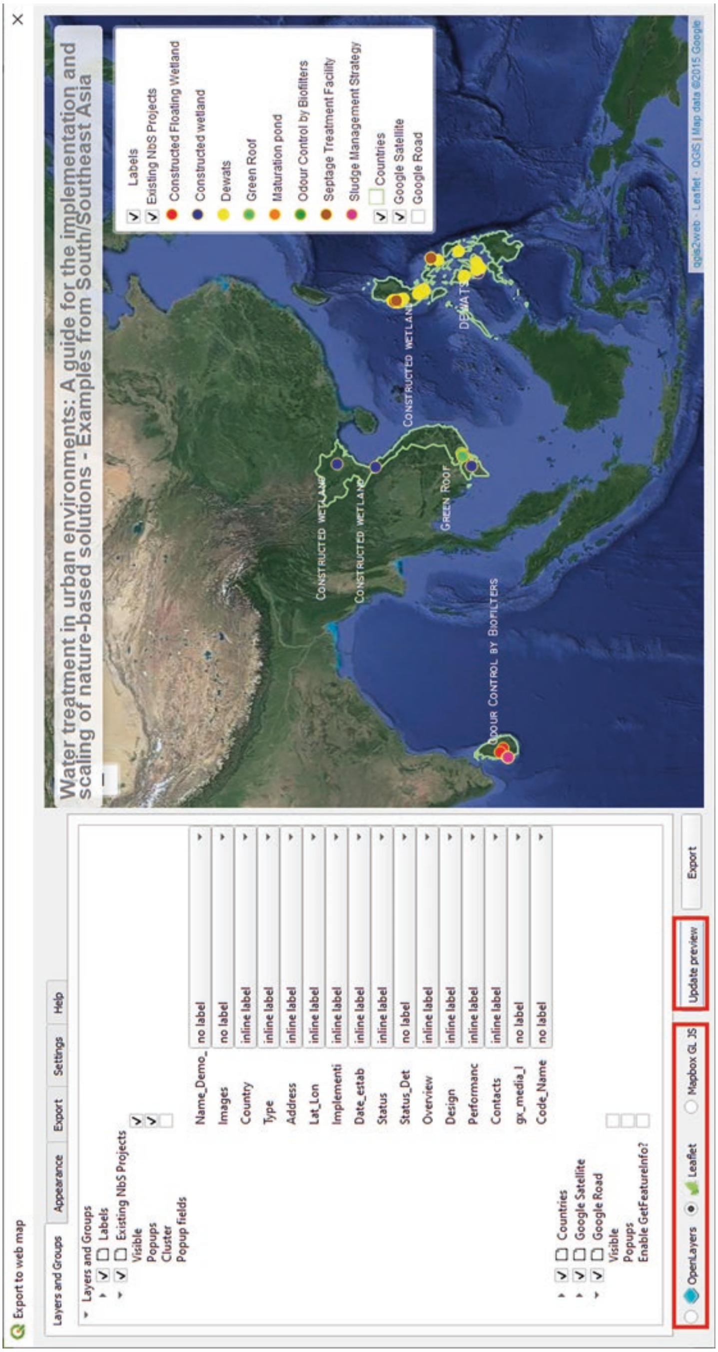

Fig. 2.9 Preview of the GIS map after clicking the Update Preview button

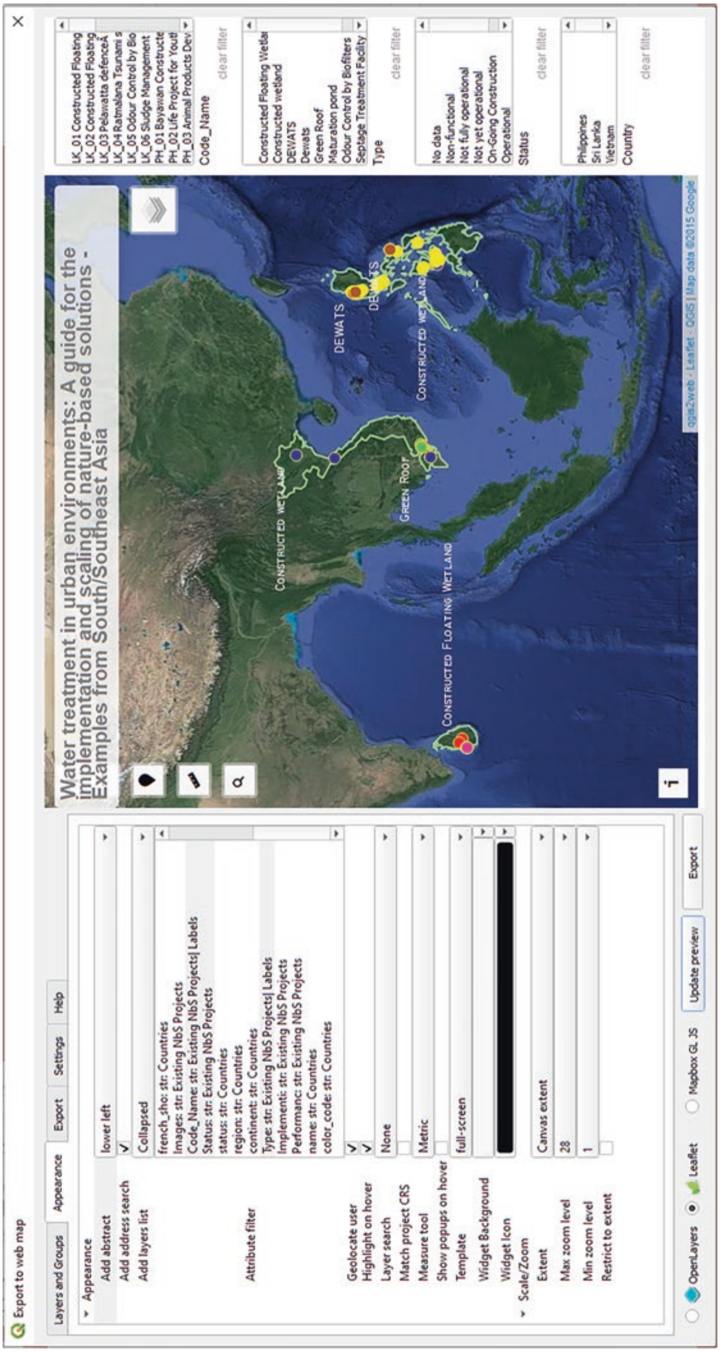

Fig. 2.10 Appearance tab of the Qgis2Web plugin on the left panel and updated preview on the right

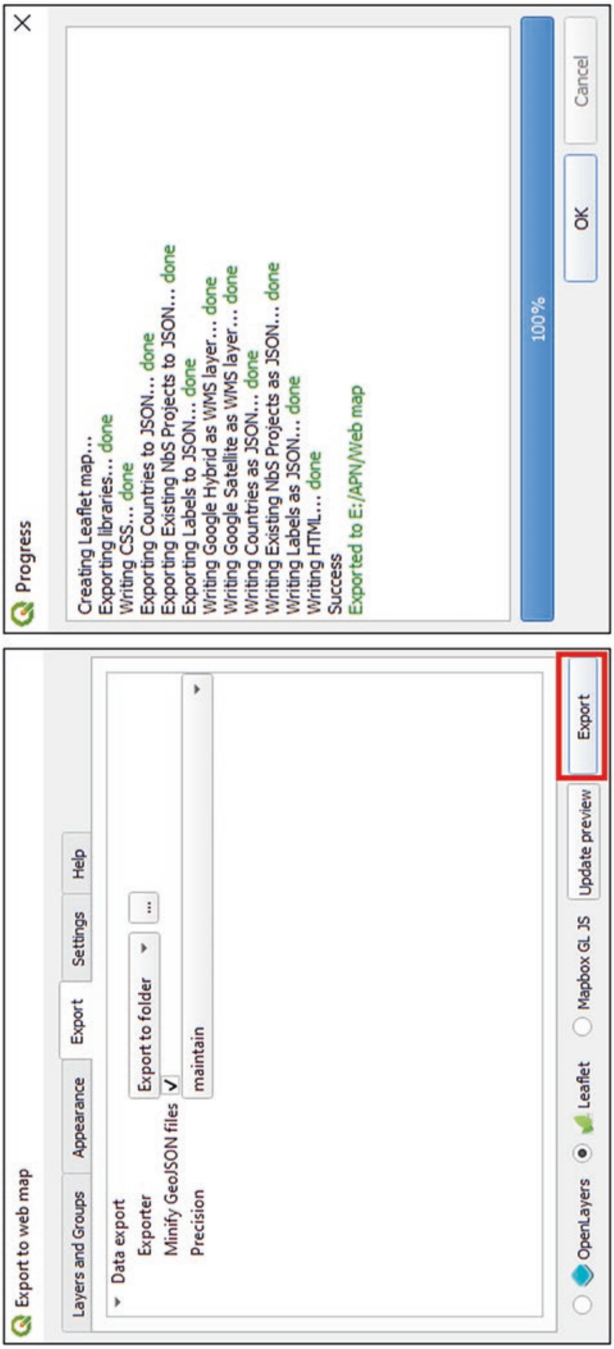

Fig. 2.11 Export tab of the Qgis2Web plugin and the progress pop-up dialog box

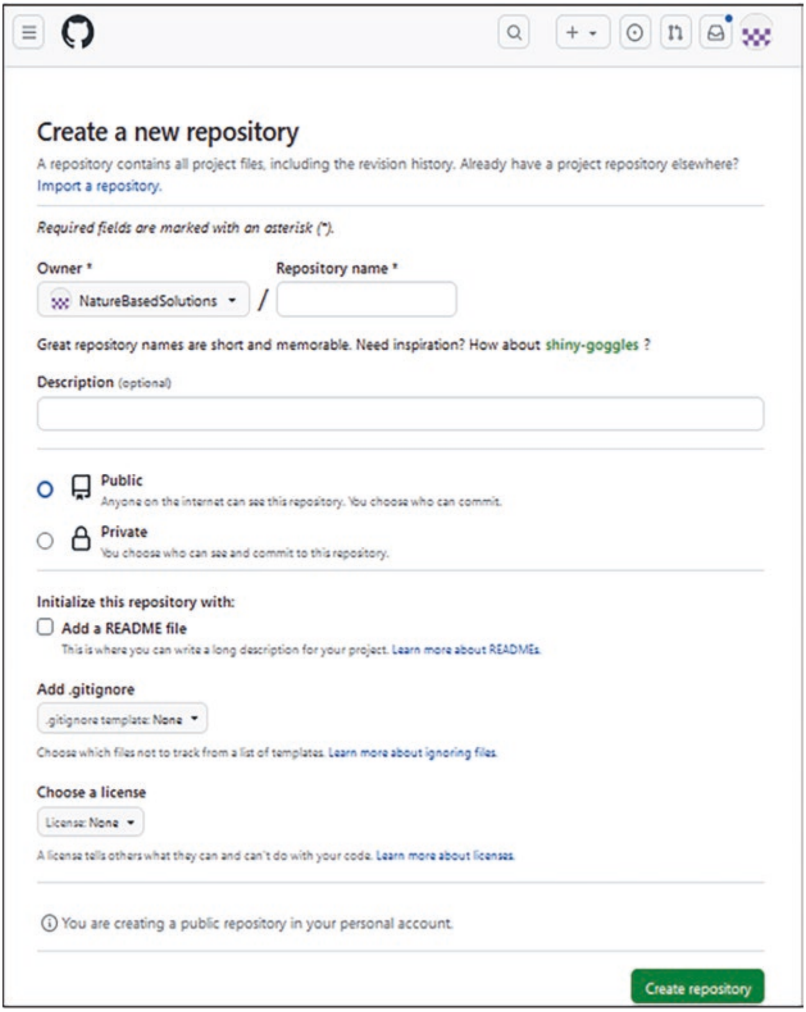

Fig. 2.12 Creating a new repository in GitHub

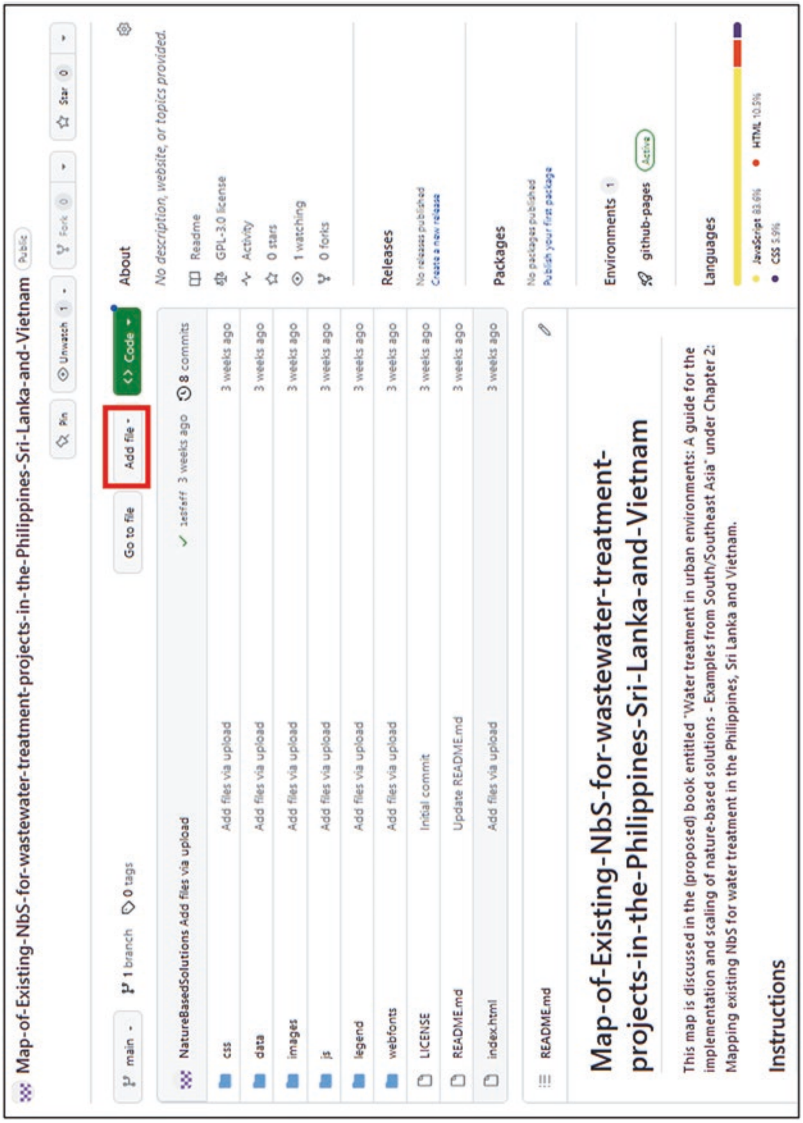

Fig. 2.13 Uploading the web map files created from Qgis2Web plugin to the repository

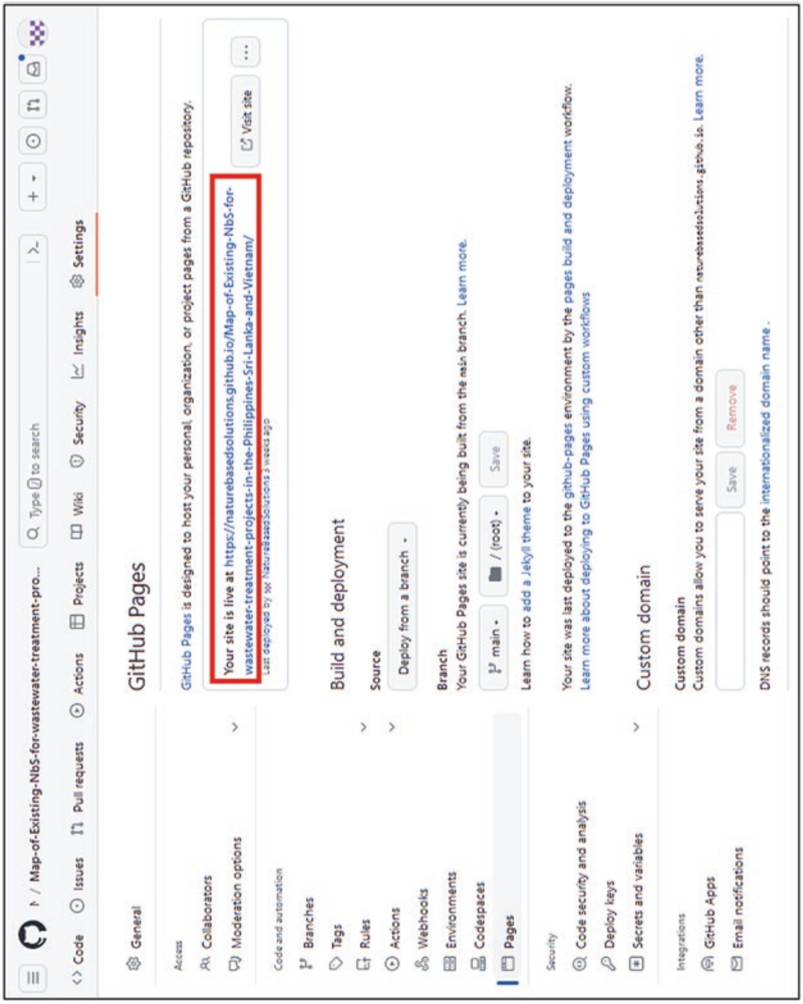

Fig. 2.14 The URL generated for the GIS map in GitHub pages

2.3 NbS Mapping Results

2.3.1 Google Maps

The website for the resulting mapping can be found here: https://www.google.com/maps/d/edit?mid=1Hb5pryV-7KXRSDL1MkIYO905KzuK5hGO&usp=sharing. The screenshot of the online map is shown in Fig. 2.15. The map contains a left panel where the list of the sites can be selected and viewed in detail, while the right panel shows the map itself. When a site is selected at the left panel, it will show the details of the NbS structure, such as type of NbS for water, address, implementing

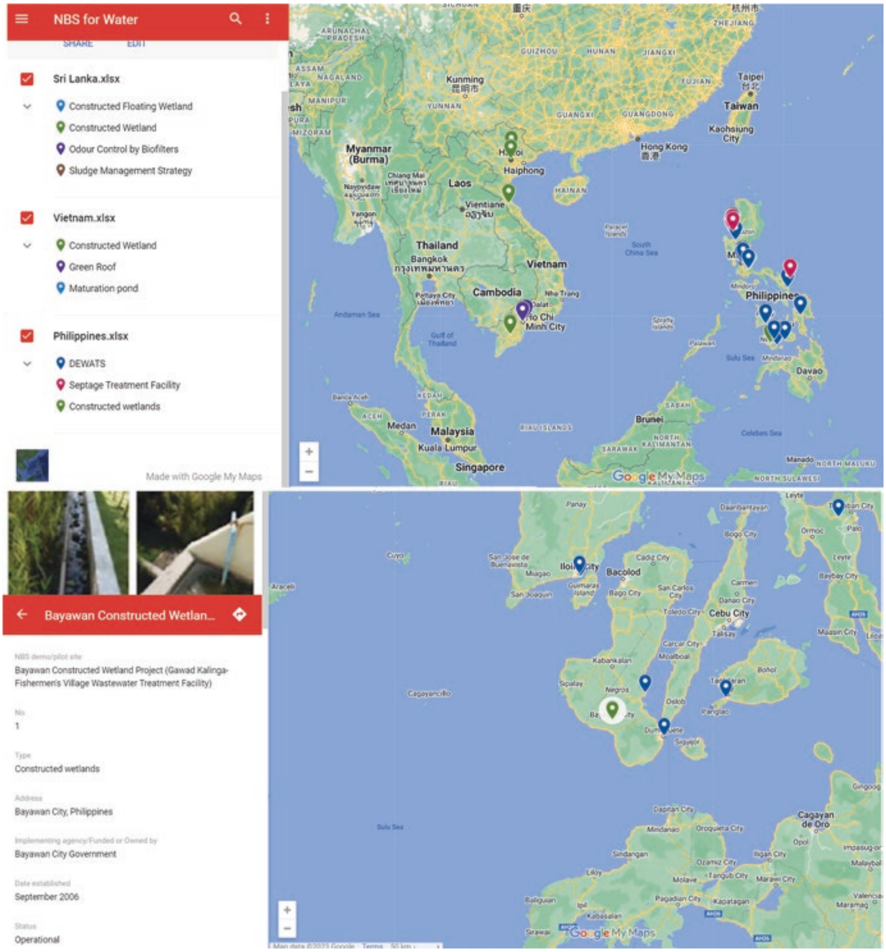

Fig. 2.15 Screenshots of NbS for water mapping for Sri Lanka, the Philippines, and Vietnam using Google Maps

agency, date of establishment, status (operational or not), photos, and design overview. Further, the map at the right panel will zoom to the pin location of the selected NbS site.

2.3.2 GIS Map

The website for the GIS map can be found here—https://naturebasedsolutions.github.io/Map-of-Existing-NbS-for-wastewater-treatment-projects-in-the-Philippines-Sri-Lanka-and-Vietnam/

Figure 2.16 shows the screenshot of the GIS map, while Table 2.2 describes the various elements of the map.

The map is interactive and will enable users to do various actions, as discussed in the succeeding subsections.

2.3.2.1 Open Pop-up Info

When interactively choosing any feature on the map, details of the feature will be displayed. Hovering over any feature will change its colour to neon blue. When the user clicks on the feature, a pop-up window will appear containing information about the feature selected (see Fig. 2.18). Table 2.3 lists the information displayed in the pop-up window for the layer "Existing NbS project sites".

2.3.2.2 Filter Display

The display on the map can be filtered based on layers and attributes (Fig. 2.19, where the NbS projects that are operational (layer: Status, attribute: Operational) and are constructed wetlands (layer: NbS Types, attribute: Constructed Wetland) are shown. Table 2.4 lists the layers and attributes used as filters for the map. It is recommended to turn off the "Labels" layer before using the filters.

2.3.2.3 Other Widgets

As mentioned in Table 2.2, users can use the widgets on the upper right corner of the map to zoom in and out of the map, to show the location of the user (using the Geolocate User icon), to search for places (using the Location Search icon), and to measure distances and areas in the map (using the Measure Tool icon). Alternatively, users can zoom in and out of the page using the mouse scroll.

Fig. 2.16 Screenshot of NbS mapping for water using GIS web map

Table 2.2 Elements of the GIS map and their description

No.	Elements	Description
1.	Title	Contains the title of the map
2.	Zoom in, Zoom out	Allows zooming in and out of the map
3.	Geolocate User	Shows user's location on map
4.	Measure Tool	Used for interactive measuring, where measuring distances and areas are supported
5.	Location Search	Allows searching for locations
6.	Map Display	– The map contains five layers, namely NbS projects (as points or dots), Labels (for the NbS type), country (represented by green lines), and two Google base maps—Google Satellite which does not contain labels and Google Roads which does. – User can turn and turn off any of the layers.
7.	Legend	– Contains the legend for the layers displayed on the map. – Ticking the items in the legend will turn on or off the layers in the map.
8.	Attribute Filters	– Allows us to filter the display on the map based on selected layers and attributes.
9.	Information	– Displays information and instructions (Fig. 2.17) on how to use the map upon hovering over the symbol "i".

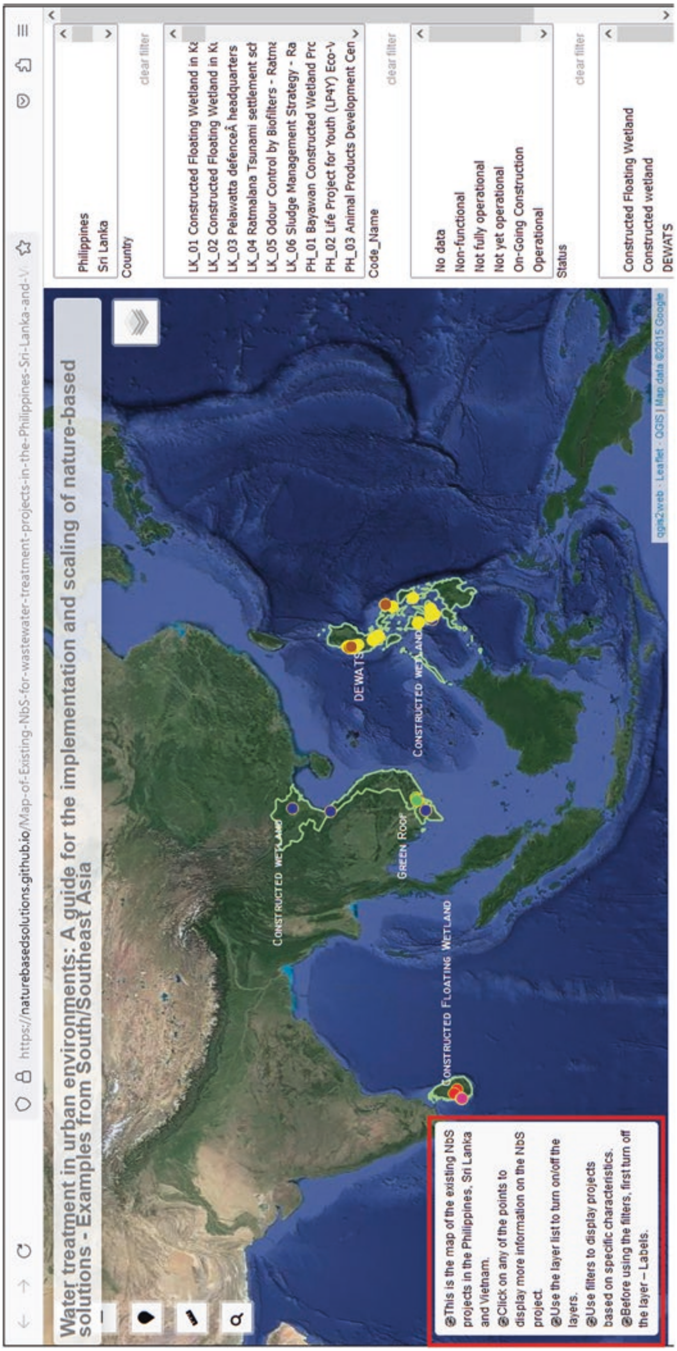

Fig. 2.17 Information upon hovering over the symbol "i"

Fig. 2.18 Pop-up window that appears upon clicking a dot

Table 2.3 Information in pop-up window

Item	Description
– Name	Name of the project
– Image	Pictures of the project site
– Country	Location of the project
– Type of NbS	Type of NbS system
– Address	Address of the project site
– Coordinates	Latitude and longitude in degrees, minutes, seconds
– Implementing agency	Implementing agency, funder, owner
– Date established	Date the project was established
– Status	Present status of the project
– Overview/Background	Description of the project
– Design	Design parameters
– Performance	Performance as measured by effluent quality
– Contacts	Contact persons or persons in-charge of the project

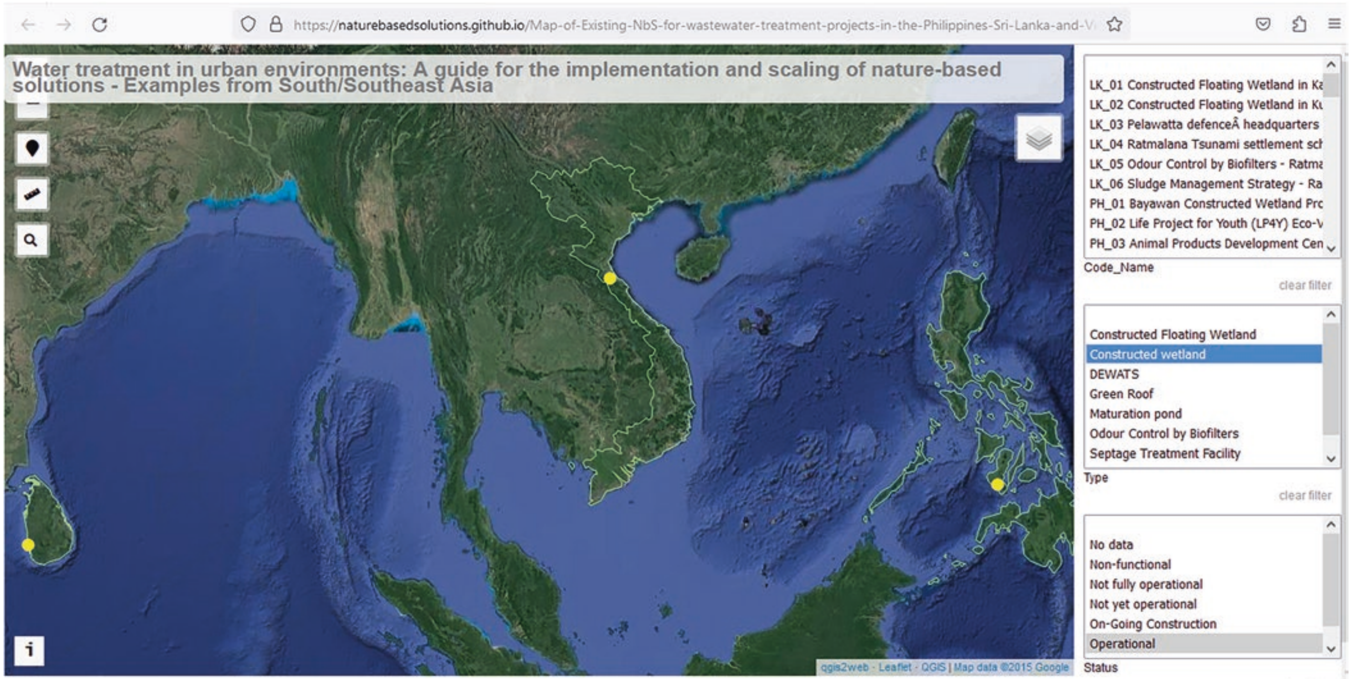

Fig. 2.19 Attribute filters that allow the display of NbS projects that satisfy the filtering layer(s) and attribute(s)

Table 2.4 Layers and attributes used as filters in the web map

Layer	Attributes
Country	Sri Lanka, Vietnam, or the Philippines
Name	Names of all 57 NbS project sites. The names start with the ISO2 country codes for easy reference. For example, *PH_01 Bayawan Constructed Wetland Project* is a project that is located in the Philippines
NbS Type	1. Constructed wetland. 2. Constructed floating wetland. 3. DEWATS. 4. Green roof. 5. Maturation pond. 6. Odour control by biofilters. 7. Septage treatment facility. 8. Sludge management strategy.
Status	1. Operational. 2. Operational with retrofitting. 3. Not fully operational. 4. Not yet operational. 5. Non-functional. 6. Ongoing construction. 7. No data.

2.4 Conclusion

The main purposes of online NbS mapping are to complement the existing NbS mapping platform for capturing data focusing on NbS for water treatment and to provide integration and analysis of baseline data drawing on different data sources. With this, mapping such structures or systems will enhance the visibility of NbS for water and wastewater management and enable knowledge sharing across the participating countries. Thus, this chapter provides procedures for developing NbS online map using two platforms: Google Maps and QGIS. The resulting online maps focused on the specific technologies driven by the needs of the project teams of the APN-GCR project (2021–2023). These listed technologies in the map were based on literature reviews used to inform the design of the specific technologies explored in the project, such as floating constructed wetlands, green roofs, and constructed wetlands or green filters. With this limitation, it is highly recommended to test the platforms in terms of their usability for a broader regional overview of a larger number of cases and ease of collaboration with users beyond the project. Further considerations for collaboration are as follows: (i) continuous growth of the dataset (how individuals or groups update the database), (ii) further research and analysis using the downloaded data, and (iii) possibilities for integrating the map with existing platforms (such as Nature-based Solutions Initiative and Urban Nature Atlas) to ensure greater accessibility and impact.

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https://casestudies.naturebasedsolutionsinitiative.org/case-search/
https://una.city

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Chapter 3
Suitability Mapping for Constructed Wetlands

Alvin Joseph Dolores, Clar Francis Camua, Rey Casas, Angelika Galicia, Perlie Velasco, Angeli Cabaltica, and Joseph Angelo Sabio

Abstract Suitability mapping aims to provide the best locations of systems or infrastructures for their conceptual design, where suitability analysis ranks the locations based on various criteria affecting the performance of the system or infrastructure. This chapter presents the guide for suitability mapping and analysis for constructed wetlands (CWs) with case studies in the Philippines. A geographic information system (GIS) software was used to map the suitable locations, while the suitability analysis used a multicriteria decision-making (MCDM) technique for Bulacan, Laguna, and Negros Oriental, Philippines. The decision criteria analysed were land use, soil type, slope, distance to water bodies, and distance to population centres. Criteria weights were derived from the literature and surveys with experts and then analysed using the Analytical Hierarchy Process (AHP) MCDM technique. A suitability map was generated using the computed weights and normalised maps of each criterion as inputs into ArcGIS Pro. The suitability analysis for the CWs in the case studies was done by taking the top 20% of the suitable locations and further evaluating them based on the actual site conditions using Google Earth.

Keywords Analytic Hierarchy Process · Constructed wetlands · Geographical Information System · Normalised Maps · Suitability analysis · Suitability mapping

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3.1 Introduction

In the Philippines, the policy on wastewater management for water security is geared towards expanding sewerage and sanitation infrastructures and broadening the scope of the National Sewerage and Septage Management Program (NSSMP) to improve the support from local government units (LGUs) and water districts (WDs) (National Economic and Development Authority 2021). One of the technologies that can be used for wastewater treatment is constructed wetlands (CWs), a type of nature-based solution for water management. CWs are proven to be effective in the treatment and disposal of various types of wastewater. CWs is a cost-effective and sustainable engineered system that uses natural processes involving wetland vegetation and substrate or filter media, promoting the physical, chemical, and biological processes in treating wastewater (Liu et al. 2014; Peñacoba-Antona et al. 2021). Further, CWs have low construction and operational requirements, making them ideal for decentralised wastewater treatment in small rural areas.

As part of the feasibility planning of CWs, it is best to know first which suitable site locations are to construct such facilities. Identifying suitable locations is critical for CWs implementation since these facilities usually require a larger area than conventional wastewater treatment facilities, which is usually challenging to prove CWs feasibility. Available Geographic Information System (GIS) applications can be used to easily map and analyse these suitable locations, depending on the objective and characteristics of the infrastructure being sited. GIS application would be effective in suitability mapping since it allows efficient processing of a large amount of spatial data and provides more accurate and easily accessible information. GIS has multiple functionalities utilising both spatial and attribute data. One of its many capabilities is that it overlays various layers or maps relevant to the same geographical region (Rossi et al. 2023). On the other hand, suitability analysis or ranking of the suitable locations can also be done in the GIS software by incorporating the results from multicriteria decision-making (MCDM) techniques, e.g. Analytic Hierarchy Process (AHP). MCDM methods are popular tools for structuring and evaluating complicated decision problems by evaluating and ranking solutions or options (in this case, the spatial suitable locations). The general steps for MCDM are (i) identifying the factors or criteria affecting the solutions, (ii) assigning the weights for each factor, and (iii) ranking the options (Taherdoost and Madanchian 2023).

Among the MCDM methods, AHP is a frequently employed and popular method for site selection, owing to its simple and direct approach to decision-making. AHP is an analytical problem-solving technique developed by Thomas L. Saaty in the 1970s. The fundamental idea behind AHP is to recognise that not all criteria hold equal importance or weight in a decision-making process. It acknowledges that some criteria are more significant than others and allows decision-makers to assign weights to these criteria when evaluating different alternatives (Asadabadi et al. 2019). The study by Peñacoba-Antona et al. (2021) provided a methodology for the suitability mapping and analysis of CWs in two Spanish provinces, Bizkaia (oceanic location) and Malaga (Mediterranean location). Similarly, this chapter aims to (i) present a method for suitability mapping of CWs for domestic wastewater treatment in the provinces of Bulacan, Laguna, and Negros Oriental, Philippines, using GIS and AHP, based on the study of Peñacoba-Antona et al. (2021), (ii) present the generated suitability maps for these provinces, and (iii) validate the generated suitability maps by evaluating the most suitable locations found for each province through satellite images and hazard maps.

The generated suitability maps could assist practitioners in identifying suitable locations for CWs. Further, this study could contribute to the scientific research communities to fill the related research gap, locally and globally. Ultimately, suitable maps can be used as part of the guide tool for the easy and successful implementation of CWs, promoting a nature-based approach to manage and preserve water resources.

3.2 Constructed Wetlands (CWs) for Wastewater Treatment

Vymazal (2022) defines wetlands as areas that experience shallow water flooding or prolonged soil saturation, resulting in the development of hydric soils capable of supporting specialised macrophytes adapted to anaerobic conditions. This definition makes wetlands suitable for wastewater treatment purposes. However, wetlands were historically used as disposal sites rather than treatment systems because these were conveniently located closer to discharge points, such as rivers or other waterways (Hoffmann et al. 2011). Unfortunately, this uncontrolled wastewater disposal has led to the degradation and destruction of natural wetlands, with many becoming saturated with nutrients and experiencing severe environmental damage. Despite these issues, the use of natural wetlands persisted. Additional problems arose, including challenges with system maintenance and unpredictable treatment efficiency.

CWs are purpose-built systems that leverage the inherent mechanisms observed in natural wetlands, enabling efficient conversion and elimination of contaminants. These carefully designed systems integrate wetland vegetation, solids, and the accompanying microbial communities to emulate the purification processes found in their natural counterparts. However, they operate within a controlled and optimised environment, offering enhanced effectiveness (Vymazal 2022).

Wallace and Knight (2006) reported that the origins of engineered treatment wetlands could be traced back to 1901 when the first system was patented. This initial system resembled a vertical flow CWs, although there is limited documentation regarding its widespread adoption. On the contrary, Hoffmann et al. (2011) argued that the first known individual to explore the potential of wastewater treatment through CWs was the German scientist Dr. Käthe Seidel in 1952. Utilising studies conducted after that, the first full-scale CWs were built in the Netherlands in 1967 (Tourbier and Pierson 1976). Subsequently, there was a significant increase in CWs installations during the 1980s and 1990s as the application expanded to different types of wastewater (Vymazal 2022). CWs are continuously being recognised for their use in wastewater management due to their relatively low operational and maintenance requirements and environmentally friendly approach, particularly recommended for developing countries (Rahman et al. 2020).

Omondi and Navalia (2020) identified multiple advantages and disadvantages of CWs, as summarised in Table 3.1, which are important considerations in conceptual designs and implementation of CWs.

The nature-based approach, low operational and maintenance costs, and positive environmental impact make CWs an attractive option for sustainable wastewater management in various settings, ranging from small-scale decentralised systems to large-scale municipal applications. However, properly assessing the site for certain criteria is still essential for maximising treatment efficiency, ensuring site suitability, and complying with regulations. Thoroughly assessing the site based on specific criteria ensures that CWs function optimally, deliver environmental benefits, and provide long-term solutions for wastewater management.

3.3 Methodology for Suitability Mapping of Constructed Wetlands

The case studies for the suitability mapping of CWs for domestic wastewater treatment were conducted in Bulacan, Laguna, and Negros Oriental, following the methodology established by Peñacoba-Antona et al. (2021). The approach incorporated the use of GIS in conjunction with AHP and summarised in the following steps: (i) preparation of spatial data for the site criteria and constraint maps using Aeronautical Reconnaissance Coverage Geographic Information System (ArcGIS), (ii) implementation of AHP to evaluate the suitability criteria for CWs, and (iii) generation of the suitability map that illustrates the varying levels of suitability for CWs across different areas within Bulacan, Laguna, and Negros Oriental. Figure 3.1 presents the methodological framework of the case studies.

Table 3.1 Advantages and disadvantages of CWs (Omondi and Navalia 2020)

Advantages of CWs	Disadvantages of CWs
• Natural wastewater treatment and environment-friendly solution. • Cost-effectiveness compared to conventional systems, requiring minimal energy input and chemicals, which reduces long-term operational costs. • Enhanced biodiversity conservation and aesthetics by providing habitats for various plants, birds, insects, and wildlife. • Effective removal of nutrients and other pollutants using plants, microorganisms, and natural processes.	• Larger land area requirement than conventional wastewater treatment systems, resulting in land availability and affordability crucial in the design. • Performance efficiency of CWs may vary seasonally or in different locations due to changing environmental conditions. • Toxic chemicals can temporarily reduce effectiveness of treatment. • Requires a minimum amount of water for successful operation.

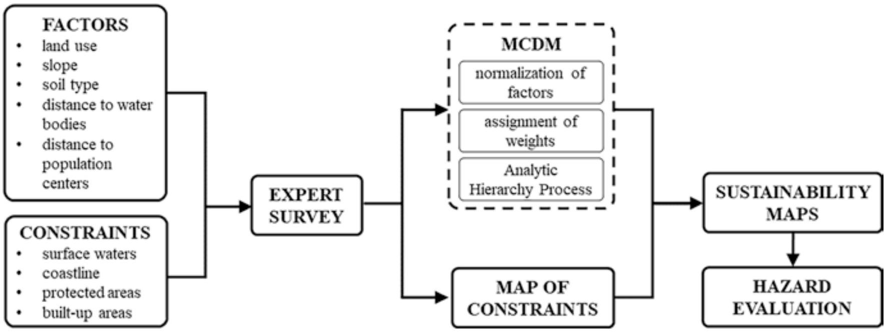


Fig. 3.1 Methodological framework of the study

3.3.1 Determination of Suitability Factors and Constraints

Suitability analysis requires the identification of several criteria that may be geophysical, environmental, or socioeconomic in nature (El Baroudy 2016; Bato 2018; Mohammed et al. 2019). For this particular study, the following criteria were considered in the suitability analysis: land use, slope, soil type, distance to water bodies, and distance to population centres. Moreover, several constraints were included in the study. These constraints considered are those factors that would be unsuitable for the construction of CWs. A constraint may be dictated by factors such as, but not limited to, protected areas, economic zones, and safety requirements. For the case studies, the following constraints were considered: surface water, coastline, protected areas, and built-up areas. The hazard assessment was considered after the suitability map was created as part of the validation process.

3.3.2 Acquisition of Criteria and Constraint Maps

The border maps specified for Bulacan, Laguna, and Negros Oriental were obtained. These border maps served as the fundamental base maps, providing the spatial framework for conducting the suitability mapping. Subsequently, spatial data for the identified criteria and constraints were acquired from various publicly available databases from various government offices and groups, such as National Mapping and Resource Information Authority (NAMRIA), Provincial Environment and Natural Resources Offices, Humanitarian Exchange Data, and Protected Planet.

3.3.3 Consultation with Experts

If there are no policies set for siting CWs in a location, then it is necessary to consult with experts who have knowledge and expertise in constructed wetlands, as well as the study areas. The consultation aimed to (i) determine the levels of importance of the identified criteria or factors (Fig. 3.2), (ii) obtain the varying degrees of importance of the classifications within each criterion or factor (Fig. 3.3, Part 2), and (iii) set the buffer distances for the identified constraints (Fig. 3.3, Part 3). The complete survey forms were uploaded and discussed on the website: https://doi.org/10.30852/p.18686. This site is the Asia-Pacific Network for Global Change Research (APN-GCR) project for 2021–2023 titled "Integrated Assessment of Existing Practices and Development of Pathways for the Effective Integration of Nature-based Water Treatment in Urban Areas in Sri Lanka, the Philippines and Vietnam", of which this study is part. The following experts were consulted for the case studies:

- Expert A is an Engineer IV in the University Planning and Maintenance Office, Office of the Vice Chancellor for Planning and Development, University of the Philippines Los Baños (UPLB).
- Expert B is an Assistant City Engineer and manager of the Bayawan City, Negros Oriental, Philippines (Waste Management and Ecology Center).
- Expert C is a Water and Environmental Resources Management Specialist at Green STEPS, Inc., and a member of the Society for the Conservation of Philippine Wetlands (SCPW).

A comprehensive assessment was conducted from the input of experts to determine the weights assigned to each criterion. In the survey, as shown in Fig. 3.2, experts were asked to compare two distinct criteria based on their level of importance. The answers provided by the experts were based on the nine-level scale of Saaty (1987) (table shown in Fig. 3.2). These were used to create pairwise comparison matrices, which helped establish the relative importance and priorities of the criteria.

Then, the results from Parts 2 and 3 of the survey (Fig. 3.3) were used to prepare criteria and constraint maps for the suitability mapping of CWs in the study areas using ArcGIS. Suitability analysis requires the quantification of the classifications within each criterion. Thus, the experts were consulted regarding the importance of each classification relative to the other classifications within the identified criterion. The classifications under each criterion are listed in Table 3.2.

Part 1. Site Suitability Criteria for Constructed Wetlands

In this study, the determining factors in siting constructed wetlands are land use, slope, soil type, distance to water bodies, and distance to population centers.

1. **Land Use** – considers the adequacy of particular land use to build a constructed wetland. For instance, burnt areas are classified as very appropriate since it is an open space with no to little vegetation while forests are classified as not appropriate due to obstructions and high vegetation.
2. **Slope** – considers the cost of excavation and embankment.
3. **Soil type** – considers the appropriateness of soil in construction and operation. Generally, it is desired to use impermeable (clay) since wastewater is involved.
4. **Distance to water bodies** – considers the distance of transport from the constructed wetlands unit to the water body discharge point.
5. **Distance to population center** – considers the distance of wastewater collection from the source to the constructed wetlands unit.

In this part, you will be asked to compare each factor to one another based on its relative importance. You may refer to Table 1–1 to answer the survey questions.

Table 1–1. Nine-level scale for pairwise comparison.

IMPORTANCE LEVEL	DESCRIPTION	NUMERICAL VALUE
Equally important	Two elements have equal importance	1
Moderately More Important	Experience or judgment slightly favors one element	3
Strongly More Important	Experience or judgment strongly favors one element	5
Very Strong More Important	Dominance of one element proved in practice	7
Extremely More Important	The highest-order dominance of one element over another	9
Intermediate Values	Compromise is needed	2, 4, 6, 8

Source: Saaty, 1987

Part 1. Site Suitability Criteria for Constructed Wetlands

Instruction: Kindly choose the number of your preferred choice based on your opinion on which of the factors is more important.

–9 = being your most preferred choice is on the left side
1 = being the choice of both criteria are of equal importance
9 = being your most preferred choice is on the right side

Note: The negative signs are only used to imply more importance to the criteria on the left side.

1.) Land Cover VS Slope*

Land Cover	–9	–8	–7	–6	–5	–4	–3	–2	1	2	3	4	5	6	7	8	9	Slope

Mark only one oval per row.

	–9	–8	–7	–6	–5	–4	–3	–2	1	2	3	4	5	6	7	8	9
1.)	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

2.) Land Cover VS Soil Type*

Land Cover	–9	–8	–7	–6	–5	–4	–3	–2	1	2	3	4	5	6	7	8	9	Soil Type

Mark only one oval per row.

	–9	–8	–7	–6	–5	–4	–3	–2	1	2	3	4	5	6	7	8	9
2.)	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

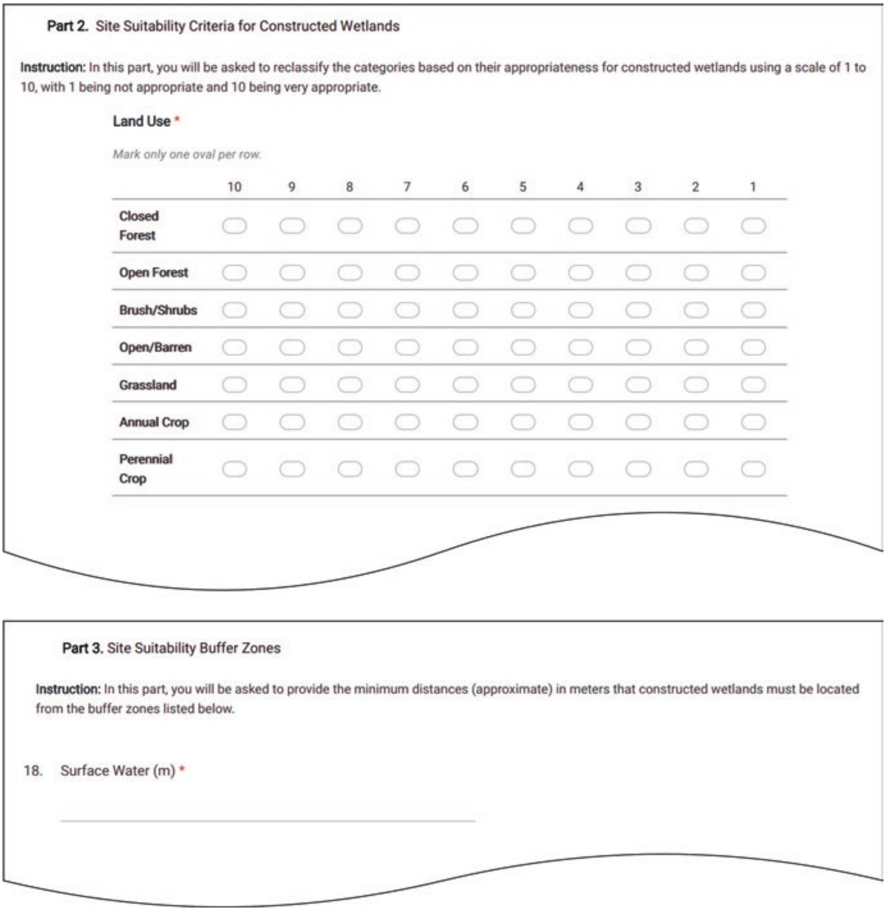
3.) Land Cover VS Distance to Water Bodies*

Land Cover	–9	–8	–7	–6	–5	–4	–3	–2	1	2	3	4	5	6	7	8	9	Distance to Water Bodies

Mark only one oval per row.

	–9	–8	–7	–6	–5	–4	–3	–2	1	2	3	4	5	6	7	8	9
3.)	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Fig. 3.2 Sample of the survey questionnaire for the pairwise comparison (Part 1)



Part 2. Site Suitability Criteria for Constructed Wetlands

Instruction: In this part, you will be asked to reclassify the categories based on their appropriateness for constructed wetlands using a scale of 1 to 10, with 1 being not appropriate and 10 being very appropriate.

Land Use *

Mark only one oval per row.

	10	9	8	7	6	5	4	3	2	1
Closed Forest										
Open Forest										
Brush/Shrubs										
Open/Barren										
Grassland										
Annual Crop										
Perennial Crop										

Part 3. Site Suitability Buffer Zones

Instruction: In this part, you will be asked to provide the minimum distances (approximate) in meters that constructed wetlands must be located from the buffer zones listed below.

18. Surface Water (m) *

Fig. 3.3 Sample of the survey questionnaire for the experts to provide the weights for each criterion (Part 2) and to set the buffer distances for the identified constraints (Part 3)

Table 3.2 List of classifications considered per criterion

Criterion	Classifications
Land use	Closed forest, open forest, brush/shrubs, grasslands, annual crop, perennial crop, open barren
Slope	Relatively flat (0–8%), moderate (8–18%), steep (18–30%), very steep (30–50%), extremely steep (>50%)
Soil type	Hydrosol, silty clay loam, fine sandy clay loam, sand clay loam, silt loam, loam, clay loam
Distance to water bodies	Based on numerical value of distance
Distance to population centres	Based on numerical value of distance

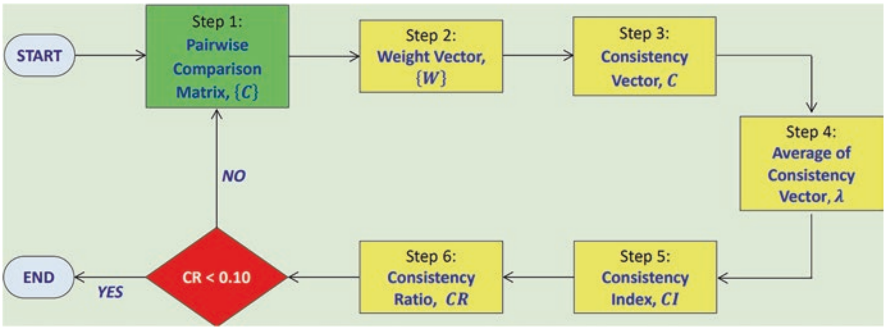


Fig. 3.4 Steps for AHP criteria weighting (Saaty 1987)

3.3.4 Evaluation of Criteria Weighting using AHP

Before using the computed weights in the suitability mapping, a consistency assessment of these weights was carried out using a series of equations to calculate the consistency ratio (CR). These steps are summarised in Fig. 3.4 (Saaty 1987).

The first step involved computing each criterion's consistency vector (C) by multiplying the weighted sum value with the inverse of the criteria weights, as shown in Eq. (3.1).

$$C = \left[\{C\} * \{W\}\right] * \{W\}^{-1} \tag{3.1}$$

where:

C—is the consistency vector

$\{C\}$—is the pairwise comparison matrix

$\{W\}$—is the weight vector

$\{W\}^{-1}$—is the inverse of the weight matrix

The eigenvalue (λ) of the matrix was calculated by taking the average of the consistency vectors. The eigenvalues obtained were then utilised to compute the consistency index (CI) using Eq. (3.2).

$$\mathrm{CI} = \frac{\lambda - m}{m - 1} \tag{3.2}$$

where:

CI—is the consistency index

λ—is the average of consistency vectors

m—is the number of criteria considered

Finally, the consistency ratio was determined by dividing the CI by the random index (RI), as shown in Eq. (3.3). This calculation assessed whether computed weights were appropriate and consistent for application in the suitability mapping.

$$CR = \frac{CI}{RI} \tag{3.3}$$

where:

CR—is the consistency ratio

CI—is the consistency index

RI—is the random index

The RI value was determined based on the number of criteria considered in the study. The specific values for the RI corresponding to different numbers of criteria can be found in Table 3.3. In Eq. (3.3), the RI used is 0.12 (based on Table 3.3) since the matrix size is five, which is also the number of criteria used.

The matrix is consistent if the CR is less than 5% for a 3 × 3 matrix, less than 9% for a 4 × 4 matrix, and less than 10% for larger matrices. In the case studies, there are five factors or criteria evaluated; thus, CR should be less than 10% due to the 5 × 5 matrix. If the resulting consistency ratio exceeds 10%, the criteria weights were re-evaluated with the help of the experts until a CR value less than or equal to 10% was achieved.

3.3.5 Preparation of Criteria and Constraint Maps

The acquired maps of land use, slope, and soil type were clipped to the administrative boundaries of Bulacan, Laguna, and Negros Oriental, reprojected to World Geodetic System (WGS) 1984 Universal Transverse Mercator (UTM) Zone 51 N, and then rasterised to a similar resolution. These three criteria maps were then reclassified based on the survey results using a quantitative appropriateness scale of 1 (not acceptable) to 10 (extremely appropriate) as graded by the experts (Fig. 3.3, Part 2). The average scores based on the experts' decisions were used as the final reclassification values for land use, slope, and soil type. For those maps that were a function of distances (distance to water bodies and distance to population centres), Euclidean distance spatial analyst tool was used to transform the maps into discrete

Table 3.3 RI values based on the number of criteria (Saaty 1987)

Number of criteria	RI values
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

rasters and allow for the measurement of the relevant distances. All criteria maps were normalised into the same scale ranging from 0 (least suitable) to 255 (most suitable). Equation (3.4) shows the map algebraic expression used to normalise the reclassified criteria maps based on the Raster Calculator of ArcGIS.

$$\frac{(C_R - C_R.\text{min}) \times 255}{(C_R.\text{max} - C_R.\text{min})} \tag{3.4}$$

where:

C_R—is the reclassified criteria map

$C_{R.\text{min}}$—is the minimum value

$C_{R.\text{max}}$—is the maximum value

Buffers for the five criteria considered in the study were established using the minimum distance provided by the experts (Fig. 3.3, Part 3). Buffer zones were merged and assigned with a suitability value of zero. The final buffer map would render certain areas restricted from the construction of CWs.

3.3.6 Generation of Suitability Map

Suitability mapping of CWs was performed using ArcGIS Pro Version 3.1.2. All the normalised criteria maps and their corresponding weights (computed through AHP) were used to generate suitability maps. In this process, a Python syntax (Eq. 3.5) was employed to multiply the normalised maps by their assigned weights and overlay the individual maps into a unified suitability map. Once a preliminary suitability map for CWs was generated, the buffer zones were subtracted from the preliminary map to generate the final suitability map.

$$C_1 \times W_1 + C_2 \times W_2 + C_3 \times W_3 + C_4 \times W_4 + C_5 \times W_5 \tag{3.5}$$

where:

C—is the normalised criteria map

W—is the criteria weight

In addition, the study utilised a classification approach to partition the suitability map into two distinct categories: high suitability and low suitability. Pixels within the top 20% with the highest suitability scores (with suitability values of 204–255) were designated as areas with high suitability, while the remaining 80% were classified as areas with low suitability. This categorisation facilitated the identification of potentially suitable sites for CWs.

The most suitable site was chosen for each of the study areas. These sites were verified, plotted, and measured remotely using Google Earth Pro. The wastewater treatment capacity for the CWs was estimated assuming the following: (i) assuming full utilisation of the areas, (ii) a rated capacity of 180 m^3/day, and (iii) a reference value based on the total area of facilities in Bayawan City's CWs, which amounts to 2700 m^2 (Jegatheesan et al. 2022).

3.3.7 Evaluation of Hazards

An assessment of environmental hazards was conducted to ensure the safety and appropriateness of the identified suitable sites. The assessment specifically focused on evaluating seismic, volcanic, and hydro-meteorological hazards in the chosen sites. The study utilised GeoRisk Philippines' HazardHunterPH, a readily available database developed by the Philippine Institute of Volcanology and Seismology (PHIVOLCS). The application provides comprehensive assessments of seismic, volcanic, and hydro-meteorological hazards.

3.4 Suitability Mapping of Case Studies

3.4.1 Criteria and Constraint Maps

The reclassification of the criteria maps of land use, slope, and soil type can be seen from the reclassification values from Table 3.4, in which closed and open forests are the least priority for the construction of CWs. Meanwhile, open/barren areas were considered the most appropriate land use type for the construction of CWs. Moreover, mangrove forests, marshlands, swamps, fishponds, built-up, and inland waters were deemed to be not suitable for the implementation of CWs under any circumstances and have a reclassification value of 0.

Consistent with the study of Peñacoba-Antona et al. (2021), the site suitability decreases as the slope of the area increases. Lower slope profiles were deemed more appropriate by the experts for the steady flow of wastewater from the entrance to the outflow. As a result, slopes within the 0%–18% range were deemed highly suitable, while slopes greater than 18% were reclassified as less suitable for CWs. For the soil type, clay and clay loam were considered the most appropriate for CWs construction based on the experts' judgments. Conversely, complex and beach sand received the lowest suitability rating for CWs.

Finally, the average minimum distances from the experts' survey served as buffers to the constraints, as summarised in Table 3.5 and shown in Fig. 3.5.

3.4.2 Criteria Weights

After two iterations of consultation with the experts, a list of consolidated criteria weights was computed, as shown in Table 3.6. The consistency ratios from the three experts were determined to be 7.16%, 9.94%, and 8.49%. All consistency ratios were within the acceptable range, which makes the consolidated criteria weights suitable for further use in the suitability mapping of CWs. It is shown that distances to water bodies and population centres obtained the highest weights among the five

Table 3.4 Land use reclassification based on their suitability for CWs

Criteria	Sub-criteria	Value
Land use	Inland water	0
	Built-up	0
	Mangrove forest, marshlands, swamps, and fishponds	0
	Closed forest	1
	Open forest	2
	Brush/shrubs	6
	Grassland	8
	Annual crop	8
	Perennial crop	8
	Open/barren	10
Slope	0%–8%	10
	8%–18%	7
	18%–30%	3
	30%–50%	2
	50% and above	1
Soil type	Complex	1
	Beach sand	1
	Hydrosol	2
	Mountainous land	3
	Silty clay loam	5
	Fine sandy loam	5
	Sandy clay loam	5
	Silt loam	7
	Gravelly loam	7
	Loam	8
	Clay loam	9
	Clay	9

Table 3.5 Constraint minimum distances (in metres)

Constraint	Minimum distance (in m)
Surface water	190
Coastline	213
Protected areas	350
Built-up areas	270

criteria, with 45.2% and 23.2%, respectively. This is consistent with the findings of Peñacoba-Antona et al. (2021), where these two emerged as the highest contributing factors in the determination of site suitability for CWs.

According to the experts, water bodies and population centres cannot be easily altered or modified through engineering interventions, which makes them crucial in assessing the suitability of areas for CWs. Further, water bodies are natural features

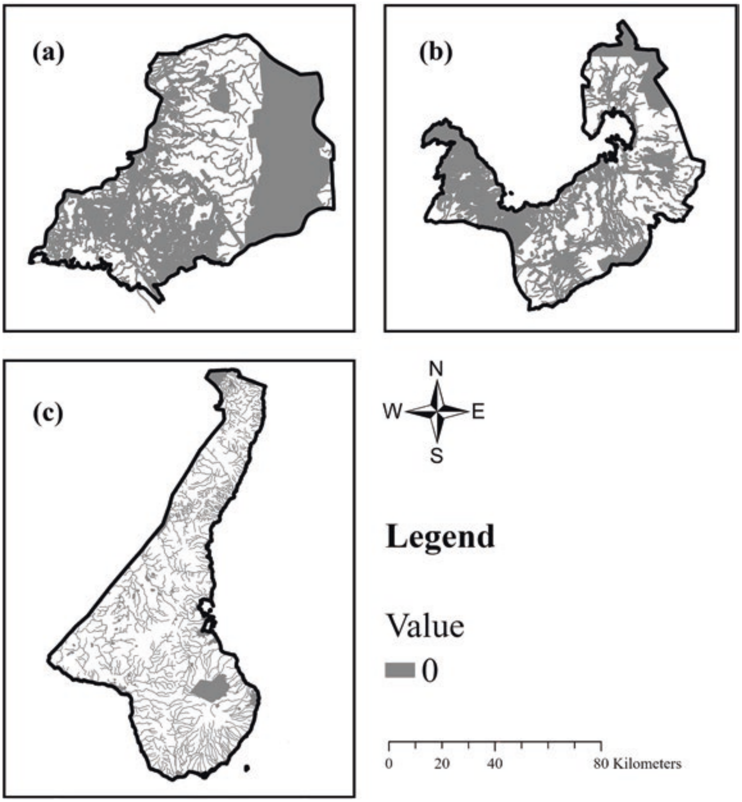


Fig. 3.5 Constraints maps of the study sites: (**a**) Bulacan, (**b**) Laguna, and (**c**) Negros Oriental, with grey colour representing the constraints

Table 3.6 Consolidated criteria weights based on the survey (Part 1) with the experts

Criteria	Criteria weights	Experts' remarks
C1: Land use	0.095	Can be easily changed through policy intervention
C2: Slope	0.149	Can be altered through engineering interventions
C3: Soil type	0.072	Can be altered through engineering interventions
C4: Distance to water bodies	0.452	Natural features that are too costly to divert
C5: Distance to population centers	0.232	Displacement may lead to huge socioeconomic costs

that are costly to alter, difficult to divert, and heavily protected by existing policies. Peñacoba-Antona et al. (2021) stated that water bodies offer multiple economic advantages in the construction of CWs. Thus, the proximity of CWs to water bodies may lead to easier access to water resources, reduced reliance on piping or pumping systems, and lesser land modification costs. Meanwhile, population centres often act as socioeconomic hubs which, aside from also being protected by laws, may make any alterations costly.

On the other hand, the experts perceived soil type, land use, and slope as the lesser impactful factors in the site selection of CWs. Modifying these factors through engineering and policy interventions to suit the needs of CWs is relatively easier. Moreover, CWs may be constructed across a wide range of land use classifications, soil types, and slopes, thus making the infrastructure adaptable to these factors.

3.4.3 Generated Suitability Maps

The constraint maps with zero value were then multiplied by the produced preliminary suitability maps to finalise the mapping. Figure 3.6 shows the final suitability maps of CWs in the provinces of Bulacan, Laguna, and Negros Oriental. The categorisation provides a clear and intuitive representation for local government units and decision-makers to identify and prioritise areas that have high suitability. This enables informed and sustainable planning decisions, ensuring that resources and efforts are directed towards areas with the greatest potential for successful CWs projects in Bulacan, Laguna, and Negros Oriental.

The areas with the highest suitability for CWs were concentrated around water bodies. The coastal provinces (Bulacan and Negros Oriental) have suitable areas near their perimeter. On the other hand, Laguna, as a non-coastal province, has suitable locations near inland water bodies, such as rivers and streams, due to the absence of coastal regions. However, no suitable sites were found near Laguna Lake since it is heavily protected by environmental policies. From the identified high-suitability areas, one site per study area was selected as the most suitable site for the construction of CWs, as summarised in Table 3.7.

The characteristics of the potential sites were also investigated. The investigation of the most potential site in Bulacan revealed that it has annual crops as their primary land use, with slope profiles ranging from 0% to 8%, and clay loam soil type. Likewise, in Laguna, the most potential area for CWs is characterised by perennial crops as their land use, with slopes ranging from 3% to 8%, and loam as the soil type. In Negros Oriental, the most potential site has land use for annual and perennial crops, as well as brushes/shrubs. The soil type was either fine sandy loam or clay, while the slopes range from 0% to 3%.

The summary of the seismic, volcanic, and hydro-meteorological hazard assessments of the most suitable sites in Bulacan, Laguna, and Negros Oriental from the HazardHunterPH app is presented in Table 3.8.

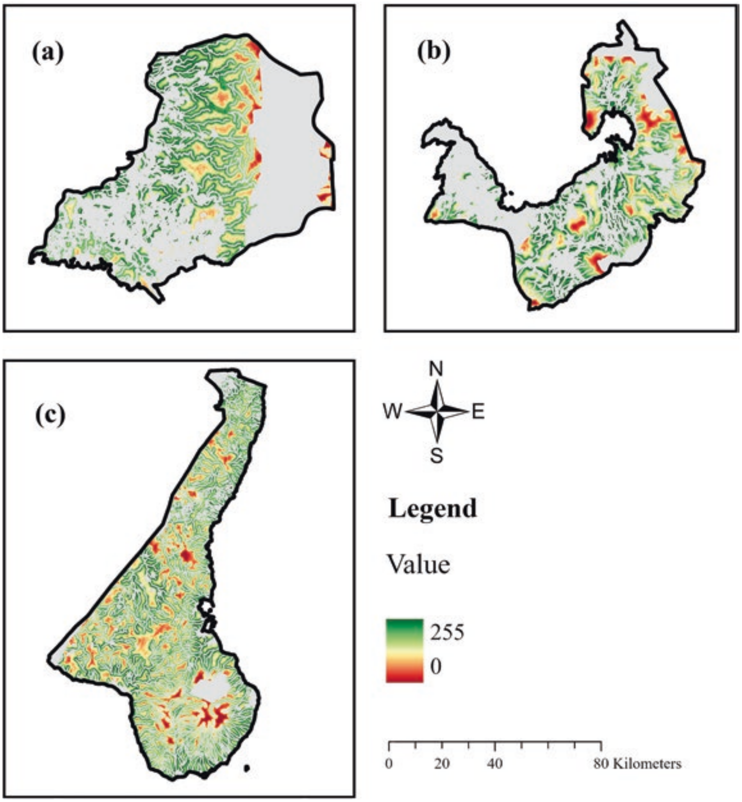


Fig. 3.6 Final suitability maps of the study sites: (a) Bulacan, (b) Laguna, and (c) Negros Oriental, with green colour representing the locations with high suitability for CWs

Table 3.7 Details of the most suitable site per province

Province	Location	Potential Land Area (in km^2)
Bulacan	Camias and San Agustin, San Miguel, Bulacan	2.92
Laguna	Buboy, Pagsanjan, Laguna	0.67
Negros Oriental	Cawitan and San Jose, Santa Catalina, Negros Oriental	0.69

3.5 Conclusion

The guide for suitability mapping for CWs is presented in this chapter, with case studies in the three provinces of the Philippines: Bulacan, Laguna, and Negros Oriental. The presented suitability maps were developed based on the study of Peñacoba-Antona et al. (2021). The mapping was performed using ArcGIS, and the analysis with AHP to locate suitable locations for implementing the CWs. The criteria considered in the suitability mapping were identified based on related studies

Table 3.8 Summary of hazards assessment of the most suitable sites in Bulacan, Laguna, and Negros Oriental

Hazard	Bulacan	Laguna	Negros Oriental
Seismic hazards assessment			
Ground rupture	Safe; Approximately 31.7 km northwest of the Valley Fault System: West Valley Fault	Safe; Approximately 28.3 km west of the Unnamed Fault	Safe; Approximately 13.9 km west of the East Negros Fault System; Southern Negros Fault
Ground shaking	Prone; Intensity VIII	Prone; Intensity VIII	Prone; Intensity VIII
Earthquake-induced landslide	Safe	Safe	Prone; low susceptibility
Liquefaction	Moderately susceptible	Safe	Safe
Tsunami	Safe	Safe	Safe
Volcanic hazards assessment			
Nearest active volcano	Approximately 63.6 km east of Pinatubo	Approximately 17.1 km northwest of Banahaw	Approximately 124.5 km south of Kanlaon
Lahar	Safe	Prone; Low	Safe
Pyroclastic flow	NA	Safe	Safe
Ashfall	Prone	Prone	Prone
Hydro-meteorological hazards assessment			
Rain-induced landslide	NA	Low susceptibility; no identified landslides	Low susceptibility; no identified landslides
Severe wind	117.1–220 kph (20-year return period); 117.1–220 kph (500-year return period)	117.1–220 kph (20-year return period and 500-year return period)	88.1–117.1 kph (20-year return period); 117.1–220 kph (500-year return period)
Storm surge	Safe	Safe	Data are being updated

with the addition of other criteria from experts, including land use, slope, soil type, distance to water bodies, and distance to population centres. On the other hand, the constraints considered include surface water, coastline, protected areas, and built-up areas.

From the generation of suitability maps for the case studies, the critical factors are the inputs from the experts surveyed, such as the weights of the criteria to the suitability of the location and buffer distance of the CWs to these criteria. Further, the accuracy of the spatial maps of the criteria used in ArcGIS is equally important. There are cases where the suitable locations in the map had different land use, and the difference could be due to the outdated maps used. Thus, validation through onsite or satellite surveys should be done. Lastly, collaboration with the stakeholders, such as local government units and residents, should be done to verify the identified potential sites for the implementation of CWs.

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Chapter 4
Economic Analysis of NbS for Wastewater Treatment Under Uncertainties

Casper Boongaling Agaton, Patricia Marie Caparas Guila, and Anne Dominique Hitape Rodriguez

Abstract Nature-based solutions (NbS) for wastewater treatment are environmentally friendly and sustainable approaches that utilise natural processes to remove pollutants and improve the quality of wastewater. In most developing countries, NbS are underutilised due to the lack of community awareness, policy support, financing mechanisms, and various uncertainties. This chapter provides support for technological, environmental, social, and governance aspects of NbS project implementation by presenting an integrated economic analysis of NbS under investment uncertainties. First, the viability of the project is analysed by applying an economic valuation of the ecosystem services offered by NbS. Next, the project is evaluated using benefit–cost analysis (BCA) from financial and societal perspectives. Then, the BCA is extended by integrating decision flexibility and the uncertainties in NbS implementation. Lastly, the proposed economic analysis framework is tested using the case study of existing constructed wetlands, an NbS for domestic wastewater treatment in Bayawan City, Philippines.

Keywords Benefit–cost analysis · Constructed wetlands · Economic valuation · Nature-based solution · Real options

4.1 Introduction

Nature-based solutions (NbS) provide effective and sustainable methods for wastewater treatment by utilising natural processes and ecosystems to treat and purify wastewater, offering several benefits over traditional treatment methods. Among the

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NbS used for wastewater treatment include constructed wetlands (CWs), reed beds, sand filters, algae ponds and bioreactors, soil infiltration systems, floating treatment wetlands, oyster and shellfish reefs, and aquaponics (Gonzalez-Flo et al. 2023; Weragoda et al. 2023; Liu et al. 2020; Canet-Martí et al. 2021; Hynes et al. 2022; Martínez-Hernández et al. 2020; Pistocchi 2022). Each of these methods has specific design considerations and suitability depending on factors such as wastewater characteristics, site conditions, and treatment goals. These NbS technologies are already used in urban planning and water management demonstrating to be more efficient, cost-effective, adaptable, multi-purpose, and long-lasting compared to "grey infrastructure" alternatives (Liquete et al. 2016). However, the success and sustainability of the implementation of NbS depend on a range of diverse technical, environmental, socio-political, and economic factors that need to be taken into account.

The economic aspect is critical in decision-making and the widespread implementation of NbS projects. This aspect ensures financial viability, optimises resource allocation, attracts funding opportunities, generates economic benefits, assesses cost-effectiveness, and supports the long-term sustainability of the project. Among the financial tools used for economic analysis of NbS projects are the net present value (NPV), internal rate of return (IRR), payback period (PBP), and returns on investment (ROI) (Abdelhay and Abunaser 2021; Ghafourian et al. 2021). These tools, albeit useful in decision-making, could undervalue the NbS project by only considering its costs and benefits while excluding its ecosystem services benefits. For instance, CWs for wastewater treatment provide provisioning (biomass and water supply), regulating (wastewater treatment and purification, climate regulation, flood prevention, and erosion control), cultural (recreation and aesthetic, biodiversity, education, and research), and supporting (habitat formation, nutrient cycling, and hydrological cycle) services (Agaton and Guila 2023). By looking at this perspective, the ecosystem services can be considered as additional benefits in the valuation of the NbS project.

Investments in NbS for wastewater treatment can involve various uncertainties that decision-makers need to consider. These may include supporting policies and regulations on NbS project implementation, financial and technological uncertainties, climate change impacts, sustainability of the project, and public acceptance (Nika et al. 2020; den Heijer and Coppens 2023; Velasco et al. 2023; Vogelsang et al. 2023). Addressing these uncertainties requires decision-makers to have a proactive and adaptive approach by conducting a thorough assessment of the project, engaging experts and stakeholders, building contingency plans, and monitoring the performance of NbS projects over time. Given these circumstances, extending the economic valuation by applying real options analysis in NbS projects can provide valuable insights and strategic advantages to evaluate investment decisions. Real options analysis in NbS projects enables decision-makers to better manage investment uncertainties, prioritise investments, and incorporate flexibility in making strategic decisions (Vogelsang et al. 2023; Batac et al. 2022). By considering real options, NbS projects can be designed and implemented in a more adaptive and economically viable manner.

This chapter aims to provide decision support for the implementation of NbS for wastewater treatment from an economic perspective. The analysis considers the ecosystem services provided by the NbS as an input to the benefit analysis of the project. Then, uncertainties are incorporated into the analysis by applying the real options valuation. The next section details the step-by-step procedure including the identification of benefits-ecosystem services, identification of the project costs, economic valuation, identification of project uncertainties, and real options valuation. The third section applies these steps in the analysis of a case study of CWs in Bayawan City, Philippines. The fourth section discusses the levers for real options valuation as well as the challenges and solutions for applying the proposed economic model in implementing NbS projects. The last section concludes the economic aspect of NbS for wastewater treatment.

4.2 Economic Analysis Under Uncertainty

Along with the technical, environmental, social, and governance, the economic aspect is a crucial part of analysing the feasibility of an NbS project. This aspect provides a clear understanding of the financial implications of the project, its cost-effectiveness, and long-term sustainability. By incorporating economic considerations, project planners can design and implement NbS for wastewater treatment that maximises environmental benefits and ecological services while ensuring financial viability and efficient resource allocation.

In this economic analysis guide, various aspects of NbS implementation are considered including the project costs, ecosystem services benefits, and the challenges and uncertainties in project implementation. Figure 4.1 summarises the step-by-step process in this integrated economic analysis under uncertainty. The next subsections will discuss each box in detail.

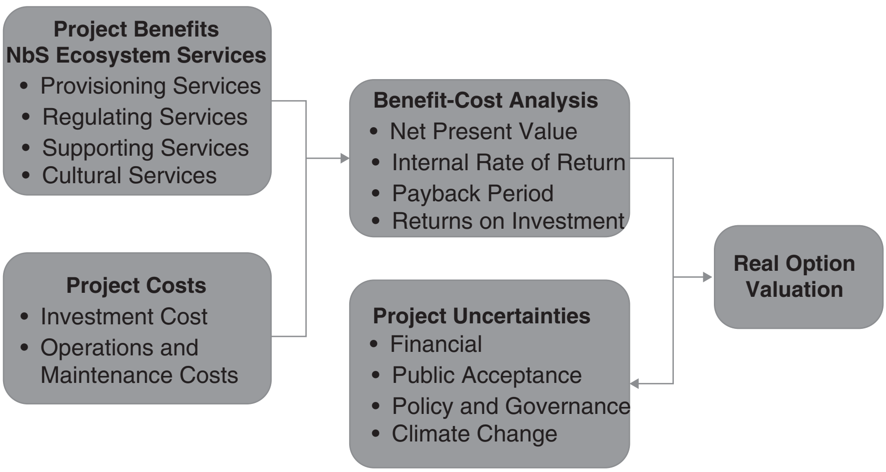

Fig. 4.1 Flowchart of economic analysis under uncertainty

4.2.1 *Identifying the Economic Benefits: Ecosystem Services of NbS for Wastewater Treatment*

Valuing the economic benefits of an NbS project involves assessing the positive financial impacts as well as the economic contribution to society or the community. Financial benefits are usually the revenues or the market value of the goods and services of the project. However, NbS projects are "living systems" that provide a wide range of ecosystem services and co-benefits (Castellar et al. 2021). Considering NbS for wastewater treatment as an ecosystem, the economic benefits of the project can be attributed to the ecosystem services it provides including the provisioning, regulating, supporting, and cultural as presented in Fig. 4.2.

Provisioning services are the tangible goods and products that NbS provides directly to humans or communities. These are the essential resources obtained from nature that can be directly consumed or used. Examples of provisioning services include biomass for food, cattle fodder, and fuel, as well as treated water for reuse in agriculture and other applications.

Regulating services involve the regulation and maintenance of ecological processes, which support the well-being of human societies and their environment. These services are essential for ecological balance and sustainability. Examples of regulating services are wastewater treatment/purification eliminating water contaminants, climate regulation by reducing greenhouse gas emissions, and minimisation of flooding and soil erosion through vegetation and sediment stability.

Supporting services are fundamental to the functioning of ecosystems and aid in the delivery of other ecosystem services. These are not directly consumed or used by humans but are essential for ecosystem health and productivity. Examples of supporting services are habitat for wildlife, biodiversity, nutrient cycling through vegetation, and management of urban water by storing and purifying water.

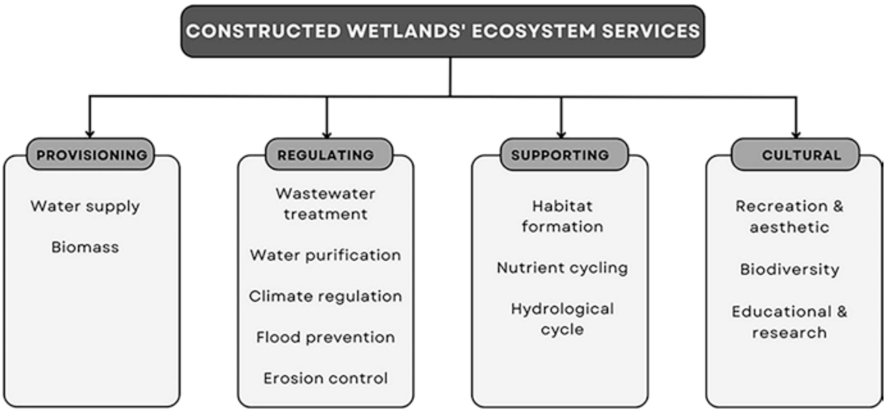

Fig. 4.2 Ecosystem services of constructed wetlands as a nature-based wastewater treatment (source: Agaton and Guila 2023)

Lastly, cultural services are non-material benefits resulting from human interactions with ecosystems, contributing to the cultural, aesthetic, and spiritual aspects of human societies. NbS provides cultural services in the form of recreational and tourism benefits by offering opportunities for outdoor activities, tourism, and nature-based experiences. Additionally, NbS offers aesthetic and spiritual values through natural landscapes and culturally significant sites that may inspire and enrich human lives. Also, NbS may be utilised for educational and research activities, facilitating learning, and contributing to local education and recreation.

4.2.2 Evaluating the Economic Costs: NbS Project

The economic costs of an NbS project refer to the financial expenditures incurred during the planning, implementation, operation, and closure/decommissioning. These vary from the project's scale, design, location, specific requirements, and other factors. Evaluating the economic costs is a crucial aspect of project analysis as it guides in assessing the project's financial feasibility and long-term sustainability. Here are some of the economic costs that may be considered in NbS for wastewater treatment projects.

Investment costs, overnight costs, or capital costs are expenditures needed to start an NbS project. These are the initial costs incurred during the planning (feasibility studies), site preparation, engineering and design, construction materials and equipment, infrastructure development, and installation of necessary components. These may also include land acquisition, labour for the construction, and machinery/technology. If the project is financed through loans or other forms of financing, interest expenses and charges should also be considered as part of the economic costs.

Operations and maintenance costs are the ongoing expenditures required to operate and maintain the NbS facility over its lifespan. These include salaries of employees, utility costs (energy costs for pumps or aeration systems), regular monitoring and water quality testing, preventive and routine maintenance and repairs, replacement of components or equipment, and skills training/updating of the workers. Operation and maintenance costs should also consider periodic investments to ensure the continued effectiveness and efficiency of the NbS system.

Land or project site costs should also be taken into account if the NbS project requires the acquisition or lease of land or site. This includes purchasing/leasing a piece of land for the construction of the NbS project or obtaining the necessary rights for access and project operation.

Ancillary costs are additional costs incurred from the application of permits, licences, and regulatory compliance, as well as those incurred in public/stakeholder consultation, community engagement, and other administrative or legal requirements.

4.2.3 Benefit–Cost Analysis

Benefit–cost analysis (BCA) or cost-benefit analysis is a systematic approach used to assess the economic desirability of a project or investment by quantifying and comparing the total benefits generated to the total costs incurred over a specified time frame. Monetisation of the impacts of a project facilitates the calculation of each alternative's net social benefit, determines the soundness of each proposal, and permits the ranking of alternatives by net social present value (Stromeyer and Barney 2018). Hence, BCA helps decision-makers evaluate the efficiency and profitability of projects, enabling them to make informed investment decisions. The most commonly used BCA tools for financial analysis include the NPV, IRR, PBP, and ROI. The calculation of each tool for NbS projects is outlined below.

Net present value (NPV) is the most common financial tool used to evaluate the profitability and value of a project. It measures the difference between the present value of cash inflows and outflows over a specific period. NPV takes into account the time value of money, which means that future cash flows are discounted to their present value. NPV of an NbS project (NPV_{NbS}) can be calculated using Eq. (4.1).

$$\mathrm{NPV}_{\mathrm{NbS}} = \sum_{T_{\mathrm{NbS}}}^{t=1} \frac{B_t - C_t}{(1+r)^t} - I_{\mathrm{NbS}} \tag{4.1}$$

where B_t and C_t are benefits and costs at period t; r is the discount rate; T_{NbS} is the valuation period or the lifetime of the NbS project; and I_{NbS} is the initial investment cost. The financial B_t refers to the revenues or the market value of goods and services provided by the project. Considering the ecosystem services of the NbS project, B_t can be calculated using any of the economic valuation techniques presented in the next subsection. Meanwhile, C_t consists of all operations and maintenance costs for the project. The NPV value indicates the profitability of the investment. A positive NPV indicates that the project is expected to generate more cash inflows than the initial investment, thus adding value to the investor. A negative NPV suggests that the investment is likely to incur losses or fail to meet the required rate of return.

The internal rate of return (IRR) is another financial tool used to evaluate the profitability and attractiveness of an investment or project. As shown in Eq. (4.2), it represents the discount rate or the annual rate of return that makes the NPV equal to zero. This means that, at this rate, the present value of expected cash flows equals the initial investment. It is used to assess the relative profitability of different investment opportunities and to compare them against a required rate of return or a hurdle rate. The project is implemented if the computed IRR is greater than the hurdle rate set for the project.

$$\mathrm{NPV}_{\mathrm{NbS}} = \sum_{T_{\mathrm{NbS}}}^{t=1} \frac{B_t - C_t}{(1+IRR)^t} - I_{\mathrm{NbS}} = 0 \tag{4.2}$$

Another financial tool is the payback period (PBP), which is used to assess the time required to recover the initial investment in a project or investment. It represents the length of time, usually in years, it takes for the cumulative cash inflows to equal or surpass the initial investment amount. As shown in Eq. (4.3), it can be calculated by dividing the initial investment by the annual cash flows (B_t–C_t). The PBP is typically compared against a predetermined or decision-maker-specific threshold or target. An NbS project is implementable if the calculated PBP is shorter than the predetermined threshold; otherwise, the investment may be perceived as less desirable.

$$\mathrm{PBP}_{\mathrm{NbS}} = \frac{I_{\mathrm{NbS}}}{B_t - C_t} \tag{4.3}$$

Lastly, the return on investment (ROI) is a financial tool used to evaluate the profitability and efficiency of an investment. It measures the gain or loss generated from an investment relative to its cost, typically expressed as a percentage or ratio. As shown in Eq. (4.4), ROI can be calculated by dividing the net profit by the initial investment cost multiplied by 100.

$$\mathrm{ROI}_{\mathrm{NbS}} = \frac{\sum_{t=1}^{T_{\mathrm{NbS}}} \left(B_t - C_t\right)}{I_{\mathrm{NbS}}} * 100 \tag{4.4}$$

ROI is often used for benchmarking and comparing different investment projects. Given the result of ROI calculations, decision-makers can evaluate and prioritise projects based on their relative profitability. However, it is important to consider environmental project standards, market expectations, and decisionmaker-specific goals when comparing ROI values. For stand-alone NbS projects, ROI should be interpreted within the context of the project and its objectives as different projects may have different return expectations. For instance, if an investor expects that an NbS project would generate 200% returns, then the calculated ROI should be greater than this threshold. Moreover, ROI should be used in conjunction with other financial tools and qualitative factors to provide a comprehensive evaluation of investment performance.

4.2.4 Economic Valuation

Value and price are two different concepts in BCA. The price is the amount that consumers are willing to pay for a good or service on the market, while the economic value is the benefit derived from the good or service (Bonner 2022). Many environmental goods and services, such as those provided by NbS projects, are not traded on markets and, therefore, have no market price. Economic valuation identifies and assigns a monetary value to goods, services, assets, or impacts that are not typically bought or sold in the market. Therefore, it is a valuable tool that quantifies the economic worth or value of environmental goods and services, providing a framework for assessing the economic benefits and costs of various policies or projects.

The total economic value (TEV) is a comprehensive concept used in economic valuation to capture the overall economic values of a resource, good, or service to society (Bonner 2022). It encompasses both market and nonmarket values, including both use values (direct or indirect benefits obtained from the item's consumption or use) and non-use values (values unrelated to consumption or use) as shown in Eq. (4.5).

$$\text{TEV} = \text{Use Value} + \text{Non} - \text{use Value} + \text{Option Value} \tag{4.5}$$

Use value consists of direct use value and indirect use value. Direct use values are the tangible benefits individuals derive from directly using or consuming the item. On the other hand, indirect use values are the benefits derived from the resource without actually "using" the item. For NbS projects, direct use value may include the provision of clean water, while indirect use value may include climate regulation and habitat for wildlife.

Non-use value captures existence value and bequest value. Existence value is the value individuals place on the mere existence or preservation of the item, even if they do not directly use or benefit from it. Bequest value is the value gained from preserving the resource to be passed on to future generations, even if those future generations choose not to utilise the resource itself. Moreover, the options value is the value individuals assign to the future availability or potential use of the item. It captures the benefit of having the option to use or benefit from the item in the future.

TEV is typically estimated through a combination of various economic valuation methods. Considering the ecosystem services provided by the NbS projects, a decision-maker may choose the most appropriate method based on the type of project and other circumstances. The summary of various valuation techniques for NbS for wastewater treatment used in the literature is presented in Fig. 4.3.

4.2.4.1 Contingent Valuation Method

The contingent valuation method (CVM) is a survey-based valuation tool used for placing monetary values on nonmarket goods or services, such as environmental resources, public amenities, or intangible benefits (Carson 2000). It provides insights into the economic value individuals place on goods or services that do not have readily observable market prices. As described in Fig. 4.3, it is commonly applied to value various ecosystem services provided by NbS for wastewater treatment.

CVM involves directly asking individuals or households about their willingness to pay (WTP) or willingness to accept (WTA) compensation for a particular good or service. The following are the steps to calculate the value of NbS for wastewater treatment using CVM.

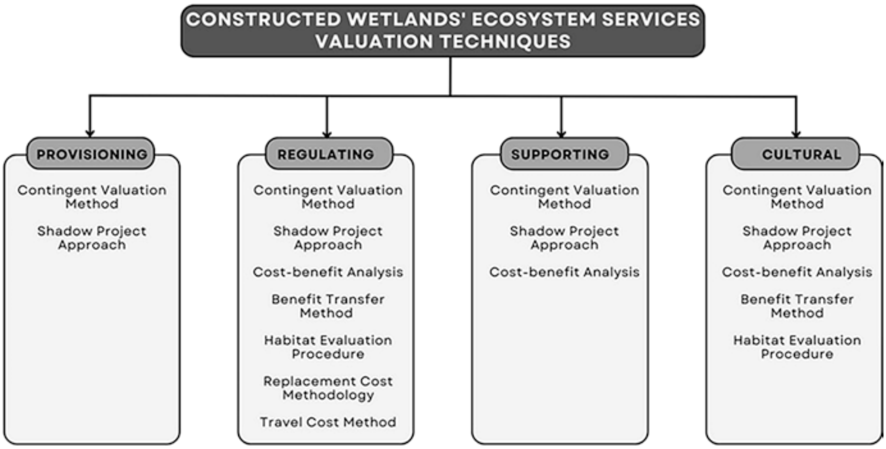

Fig. 4.3 Ecosystem services valuation techniques for nature-based solution for wastewater treatment (source: Agaton and Guila 2023)

Step 1: Define the valuation problem. This includes the identification of the study area where the NbS for wastewater treatment is proposed, what exactly are the ecosystem services being valued, and who is the relevant population. The target population for the survey may include the impact communities, businesses, or other stakeholders within the area.

Step 2: Design the survey questionnaire. This step makes preliminary decisions about the survey, including how it will be conducted, how large the sample size will be, who will be surveyed, and other related questions. The questionnaire should include the following elements:

- Description of the NbS: Briefly explain what is the wastewater treatment method and its positive impacts on the community and the environment.
- Socio-demographic questions: Gather information about respondents' characteristics, such as income, education, sex, age, and other relevant factors influencing the valuation.
- WTP or WTA questions: Ask respondents about their WTP for implementing and maintaining the NbS project or WTA compensation for not having access to it.
- Payment method: Specify how the payment could be made, such as an increase in utility (water or waste) bill, taxes, or a one-time (connection) fee.

Step 3: Conduct the survey. Administer the survey to the selected sample of respondents within the study area. Ensure a well-distributed survey among various demographic groups to achieve representativeness of the target population.

Step 4: Data analysis. Analyse the data to estimate the mean or median WTP or WTA for the NbS. When the dependent variable is binary, indicating whether an individual is willing to pay for a specific environmental service or not, logistic regression could be employed to calculate the WTP or WTA.

Step 5: Calculate the economic value. The economic value of the NbS for wastewater treatment can be calculated by multiplying the estimated mean or median WTP or WTA by the total number of potential beneficiaries within the study area.

It should be noted that CVM has its limitations and potential biases, such as sample, information, hypothetical, and design biases as well as protest responses (Ji et al. 2022; Kalfas et al. 2022). To address these issues, various techniques should be used to improve the reliability of the results, such as the travel cost method or hedonic pricing method. These methods can complement the findings of CVM, provide a more comprehensive understanding of the economic value of the NbS for wastewater treatment, and enhance the robustness of the economic valuation.

4.2.4.2 Shadow Pricing Method

Shadow pricing estimates the monetary value of a good, service, or project that does not have a clear or directly observable market price. It is a valuation method commonly used for activities and products that are not charged, as well as for those that do not have a market value but have a significant role in the protection of the living environment. Hence, it helps management in defining priorities of possible options, taking into account both economic and ecological aspects (Djukic et al. 2016).

Using grey infrastructure or traditional wastewater treatment technology such as sewage treatment plant (STP), the total cost of production is the sum of all variable (input) costs and fixed costs. On the other hand, NbS for wastewater treatment with lower economic input and lower consumption of resources provides the same ecosystem services (regulating—wastewater treatment; provisioning—clean water for various purposes) as the STP technology. Shadow pricing can be used to estimate the value of these ecosystem services of the NbS by calculating the cost savings of shifting wastewater treatment technology from STP to NbS.

4.2.5 Identifying the Uncertainties of the NbS Project

Implementing NbS projects faces several uncertainties and challenges. These arise due to the complex and dynamic nature of ecosystems, the involvement of different stakeholders, and the need to balance the technical, environmental, social, and economic objectives of the project. Uncertainty can be defined in the context of risks as events having a negative impact on the project's outcomes or opportunities that have a beneficial impact on project performance. It can arise from both internal and external sources of the project (Perminova et al. 2008). For NbS projects, there are unknown prospects, both favourable and unfavourable economic developments, which may have a significant possible influence on the projects. Some uncertainties can be in terms of financing, supporting policies, social acceptability, and climate change or natural disasters.

NbS projects face financial uncertainties, expressed in cash flow instabilities, insufficiencies, or unpredictability (den Heijer and Coppens 2023). Particularly for NbS projects that involve market-based products, goods, or services, fluctuations in market and prices can affect project revenue streams. In extreme cases, economic downturns or recessions and pandemics can affect funding availability, investment interest, and financial viability of NbS projects. Additionally, the availability of funding from multiple sources, such as international donors, government grants, or private investments, may be uncertain in terms of securing sufficient financial support.

Another challenge in the implementation of NbS projects is the policy uncertainty. This uncertainty refers to the unpredictability of supporting government regulations, laws, or policies. This can arise from changes in political leadership, shifts in priorities, land use, or disagreements over the best approach to address environmental challenges. For instance, political decision-makers tend to prioritise projects that generate short-term tangible outcomes rather than NbS projects that typically need a relatively long time to produce societal benefits. Hence, politicians are often hesitant or even averse to taking the risk to support NbS projects with highly uncertain outcomes (Sarabi et al. 2020). Additionally, evolving environmental standards, policies, and regulations could affect the NbS application process for permits and approvals, which further delay or add complexities to NbS project implementation.

Social acceptance is another critical dimension in planning and implementing policy interventions and wider NbS technology adoption (Sari et al. 2023). Uncertainty in social acceptance refers to the unpredictability or lack of clarity regarding how the local communities and other stakeholders will perceive and support the implementation of NbS projects. Citizen support for NbS projects diverges, with factors of influence including education, race, ideologies, income, attitudes towards environmental affairs, homeownership status, household composition, gender, and length of residence (den Heijer and Coppens 2023). For instance, the local community may not be familiar with the concept of NbS and its benefits leading to scepticism or misunderstandings about the goals and outcomes of NbS projects. NbS projects may be perceived differently in terms of associated risks that raise concerns about potential disruptions to traditional livelihoods, socio-cultural norms and traditions, or land use practices. Furthermore, social acceptance of NbS projects is also hindered by stakeholders' trust in the project proponents or the credibility of the project's goals and benefits to the local community.

Another significant challenge to NbS project implementation is the uncertainty in climate change and natural disasters. This uncertainty refers to the unpredictability of surrounding future climate conditions and their impacts on the effectiveness and outcomes of NbS interventions. The impacts of climate change can vary significantly from regions, countries, or areas in terms of changes in temperature, precipitation, and extreme weather events. Uncertainty about climate change impacts can create challenges in assessing the vulnerability and risk of specific areas or communities, making it harder to prioritise NbS projects. The uncertainty in adaptation and damage costs associated with the impacts of climate change and natural disasters can challenge the implementation and localisation of NbS projects (Agaton and Collera 2022). Also, the ability of ecosystems to adapt to changing climate conditions as some ecosystems may exhibit resilience, while others may be more vulnerable, and less able to cope with the changing climate. This uncertainty can affect the design and implementation of NbS projects, as different scenarios may require different approaches.

4.2.6 Real Options Valuation

In some cases, the financial cost–benefit analysis and economic valuation method do not capture the uncertainties involved in NbS for wastewater treatment projects. For instance, the NPV, which relies on all-or-nothing, now-or-never decisions, does not recognise the value of NbS technological changes before making an investment decision. Also, the WTP does not consider the uncertainty in social acceptability when a certain government policy is imposed. The real options approach (or real options analysis/valuation) addresses these issues by considering the uncertainties in making flexible decisions for irreversible NbS projects. A "real option" is a right, but not an obligation, to undertake a certain project initiative, such as postponing, expanding/contracting, or shutting down/restarting an investment based on any market, technological, and/or economic conditions (Agaton 2022). Hence, this approach is applied to the valuation of projects with highly volatile and uncertain investment conditions. Otherwise, the traditional economic valuation tools are more appropriate for stable or less flexible investment conditions.

Real options valuation is an extension of the NPV by incorporating the identified uncertainties of a project and flexibility in the decision-making process. Among the valuation models include the closed-form Black–Scholes model, developed by Black and Scholes (1973) and Merton (1973), which is the most popular solution with the simplest computation and the easiest conduct of sensitivity analysis. The real options value for an NbS project can be calculated using Eqs. (4.6), (4.7), (4.8).

$$\mathrm{ROV}_{\mathrm{NbS}} = Ve^{-\delta(T_{\mathrm{ROV}}-t)}N(d_1) - I_{\mathrm{NbS}}e^{-r(T_{\mathrm{ROV}}-t)}N(d_2) \tag{4.6}$$

$$d_1 = \frac{\ln\left(\frac{V}{I_{\mathrm{NbS}}}\right) + \left(r - \delta + \frac{1}{2}\sigma^2\right)(T_{\mathrm{ROV}} - t)}{\sigma\sqrt{T_{\mathrm{ROV}} - t}} \tag{4.7}$$

$$d_2 = d_1 - \sigma\sqrt{T_{\mathrm{ROV}} - t} \tag{4.8}$$

where V is the value of free operating cash flows (sum of the discounted benefits minus costs as described in Eq. 4.1), δ is the opportunity cost of delaying the NbS project, $T_{\mathrm{NbS}} - t$ is the time to expiration of the option or the real options valuation period, I_{NbS} is the NbS investment cost, r is the risk-free interest rate, and $N(d)$ is a cumulative normal probability density function.

$N(d_1)$ represents the cumulative standard normal distribution function of the variable d_1, which determines the probability that V will exceed the I_{NbS} at the end of $T_{\mathrm{NbS}} - t$. $N(d_2)$ represents the cumulative standard normal distribution function of the variable d_1, which determines the present value of the expected V at the expiration of the option $T_{\mathrm{NbS}} - t$. Meanwhile, σ^2 is a parameter measuring the volatility of the V, which is measured as the variance of the continuously compounded rate of return over a time interval of length one. For NbS projects, this parameter represents any uncertainty, such as regulatory changes, technological advancements, market conditions, or changes in wastewater treatment requirements, which may have potential impacts on the future cash flow V of a project.

In the Black–Scholes model, the volatility (σ^2) is a crucial input parameter that represents the expected future fluctuations of V as a result of the uncertainties. There are various methods to calculate the volatility depending on how the uncertainties affect V, such as historical volatility (geometric Brownian motion, mean reversion), implied volatility (Newton–Raphson method), generalised autoregressive conditional heteroskedasticity (GARCH) models, exponentially weighted moving average (EWMA), Poisson jump process, and others.

One of the most commonly used methods is the geometric Brownian motion (GBM), which is applied to, for instance, uncertainties in fuel and electricity prices, commodity prices, demand and supply, and financial assets. It is a continuous-time stochastic process that assumes the logarithm of the asset's price follows a Brownian motion with drift. The GBM model for the evolution of V over time is given by Eq. (4.9).

$$dV = \mu V dt + \sigma V dW \tag{4.9}$$

where dV is the change in V over a small time interval dt, V is the present value of cash flows of the NbS project, μ is the drift or expected return per unit of time, σ is the constant volatility of the returns per unit of time, and dW is a Wiener process or Brownian motion, which represents random noise or uncertainty in the movement V over time. The first term μVdt represents the deterministic growth component of V, which is proportional to the current price of V and the expected return μ over a small time interval dt. The second term $\sigma \cdot V \cdot dW$ represents the stochastic or random component of the movement of V, which is proportional to the current price V and is multiplied by the random Wiener process dW (representing the randomness and volatility in the model).

The augmented Dickey–Fuller (ADF) test is applied to determine whether a time series has a unit root. A unit root implies that the time series is non-stationary, which means its statistical properties, such as the mean and variance, are not constant over time. To calculate σ, the time series data of the returns or historical prices of the identified uncertainty of the project should be obtained first. Then, transform the data by taking the logarithmic or simple differences between consecutive values or prices. Check for the stationarity of the time series data using the ADF unit root test.

The null hypothesis of the ADF test is that the time series has a unit root (it is non-stationary). If the returns of the time series are stationary, calculate the volatility using traditional methods like the sample standard deviation or other methods (EWMA, GARCH, etc.). Substitute the calculated volatility in Eq. (4.6) to compute the real options value (ROV_{NbS}) of the project.

4.2.7 NbS Project Implementation Using Economic Analysis under Uncertainty

The results of BCA provide decision-makers insights on whether to implement an NbS project or not. Considering the uncertainties in implementing an NbS project, the real options valuation extends the NPV offering more flexibility in making investment decisions. For instance, if a decision-maker utilises the real option to wait, defer, or postpone the implementation of an NbS project, there would be three investment decisions, as presented in Fig. 4.4.

The red line represents the NPV of an NbS project. Using the BCA rule, the decision-maker should implement the project only if the pay-off, V, or the future net cash flows exceed the investment cost, from point V^{NPV} and beyond. Otherwise, the implementation of the project will only generate losses as $V < I$.

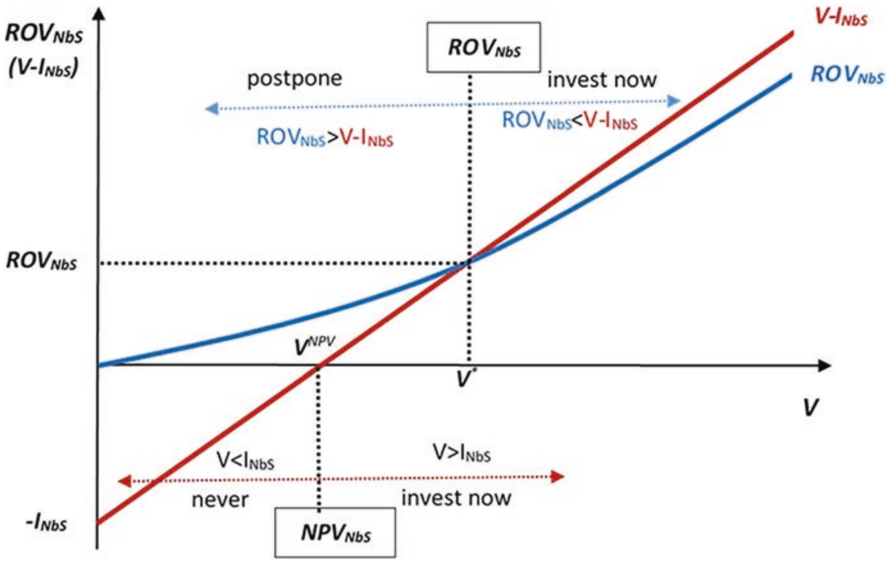

Fig. 4.4 Comparison of investment decisions between real options value and net present value. Note: *ROV* real options value, *V* present value of cash flows, I_{NbS} present value of investment costs, *NPV* net present value (source: Agaton 2022)

The blue curve represents the real options value, ROV, of an NbS project. Using the real options rule, a decision-maker may either postpone the energy transition project or implement the project immediately. For instance, at point V^*, the project can be implemented using the NPV rule. However, a decision-maker can postpone the project as the ROV of waiting is higher than the value of immediate implementation with NPV_{NbS} (or $V – I_{NbS}$). Postponement takes advantage of gaining more information concerning the uncertain environment and avoiding being stuck in a loss-making, irreversible NbS project.

Therefore, real options valuation provides three decision options for the implementation of an NbS project:

$$\begin{cases} \mathrm{NPV}_{\mathrm{NbS}} < 0, \mathrm{ROV}_{\mathrm{NbS}} \leq \mathrm{NPV}_{\mathrm{NbS}} & \text{not implement} \\ \mathrm{NPV}_{\mathrm{NbS}} \geq 0, \mathrm{ROV}_{\mathrm{NbS}} \leq \mathrm{NPV}_{\mathrm{NbS}} & \text{implement immediately} \\ \mathrm{ROV}_{\mathrm{NbS}} > 0, \mathrm{ROV}_{\mathrm{NbS}} > \mathrm{NPV}_{\mathrm{NbS}} & \text{postpone implementation} \end{cases}$$

From this rule, an NbS project should only be implemented if the NPV > 0 and there is no value in waiting ROV = 0 or postponing is not worth the wait than immediate implementation ROV < NPV. If NPV < 0 and ROV < NPV, then the project should be rejected. Lastly, the project implementation should be postponed if (a) NPV < 0 but ROV > 0, or (b) NPV⩾0 and ROV > NPV. It should be noted that, besides waiting or postponing, there are other decision options for real options valuation, such as terminating, expanding, stopping and reoperating, switching, and others. A decision-maker should decide what type of real option is applicable and appropriate to the NbS project.

4.3 Case Study of Constructed Wetlands in Bayawan City, Philippines

This section presents the application of the methodology discussed above in the case of constructed wetlands (CWs) as an NbS to wastewater treatment in a residential area in Bayawan City, Negros Oriental, Philippines. The following subsections provide a brief background of the construction of the CWs project, the result of contingent valuation for the WTP of the residents for the CWs, a sample calculation of benefit–cost analysis, the challenges and uncertainties in the implementation of the CWs project, and the application of real options valuation integrating the identified uncertainties of the CWs project.

4.3.1 Background of Constructed Wetlands in Bayawan City

The CWs projects in Bayawan City were outcomes of the first International Symposium on Low-Cost Technology Options for Water Supply and Sanitation that occurred in Bohol in September 2004. The Local Government Unit (LGU) of Bayawan City had their delegates attend the symposium and a team of German and Filipino experts afterwards visited Bayawan City to quickly assess the sanitary conditions in specific zones. There were two potential sanitation solutions eyed for the city: a CW for domestic wastewater treatment in a peri-urban resettlement area and a dry sanitation concept for less populated rural areas. The first option was deemed suitable for the city.

The project's planning began in February 2005, and the construction phase was carried out by the City Engineering Office from May 2005 to August 2006. The CWs became operational in September 2006 and have remained continually functional since then. The project is located in Bayawan's peri-urban area, which was utilised to move residents who had previously lived in coastal informal communities without access to safe water and sanitation services. The relocation site, also known as the Fishermen's Gawad Kalinga Village, has 676 houses. As of September 2009, each house in the area was occupied. The village is situated along the boulevard of Bayawan City near the coastal area. The CWs were built in front of the village (see Fig. 4.5).

The requirement for efficient wastewater treatment and the consideration of space restrictions led to the decision to incorporate both vertical and horizontal vegetated soil filters into the CWs' design. To create the filter, native reed plants called "tambok" (*Phragmites karka*) were used. These plants were grown at a nursery on the relocation site.

The overall cost of building the constructed wetland was around 160,000 EUR, which included project investment costs as well as labour and consulting fees. The Bayawan City municipal administration covered the majority of the project costs through a World Bank loan. Through the LGU of Bayawan City's partnership with German organisation GTZ Water and Sanitation, they were able to secure funding for the soft components of the project, such as the international consultant, organising workshops, engaging the community, and socially preparing for the project's implementation. The GTZ provided the required technical assistance for the completion of the project. Further, the project's annual operation and maintenance costs are estimated to be around 3500 EUR composed of 3000 EUR labour and 500 EUR utilities. These expenses are covered by the city government. The households in the Fishermen's Gawad Kalinga Village are not charged with any amount for the operation of the wastewater treatment facility, but they are accountable for their individual electricity and water usage charges.

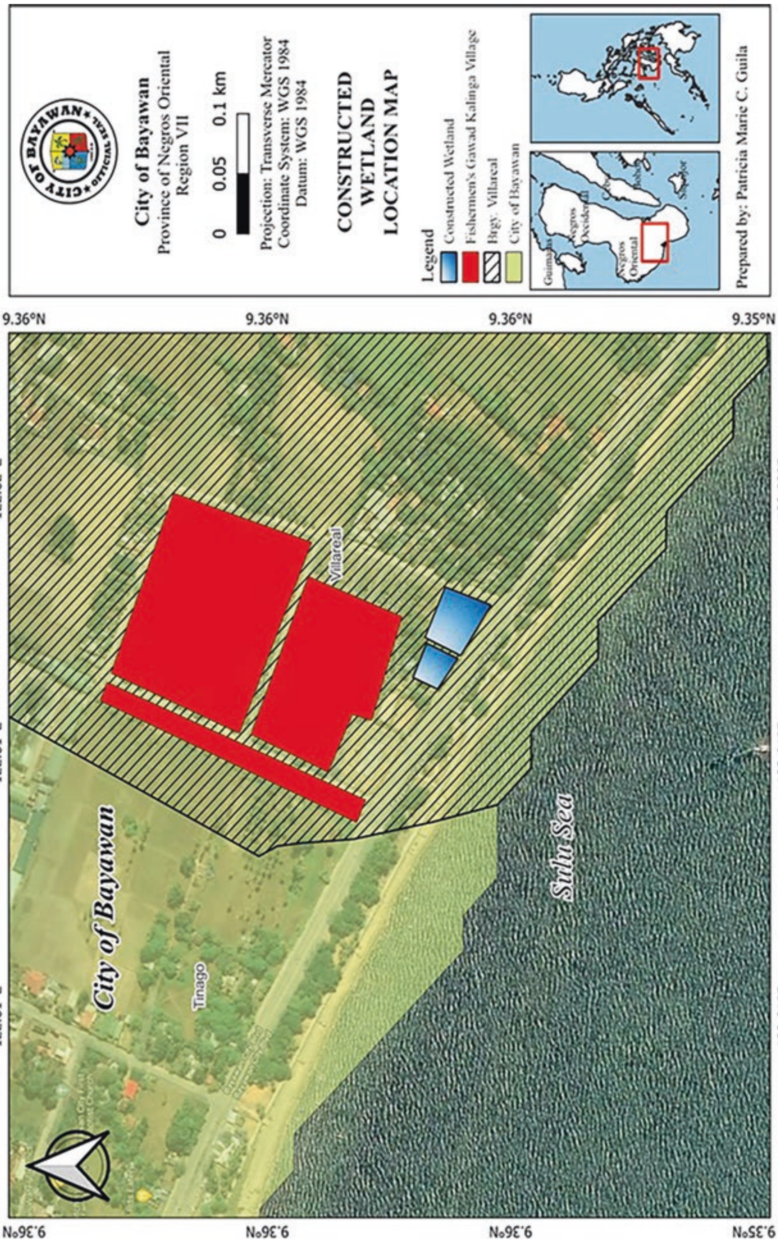

Fig. 4.5 Location map of constructed wetland in Fishermen's Gawad Kalinga Village, City of Bayawan (source: Guila 2023)

4.3.2 Economic Valuation of Constructed Wetlands

The WTP of the village residents was collected using a survey questionnaire (available on the website: https://doi.org/10.30852/p.18686; Asia-Pacific Network for Global Change Research (APN-GCR) project for 2021–2023 titled "Integrated Assessment of Existing Practices and Development of Pathways for the Effective Integration of Nature-based Water Treatment in Urban Areas in Sri Lanka, the Philippines and Vietnam"). The questionnaire was divided into seven (7) sections: a summary and objectives of the study; informed consent to participate in the survey; respondents' socioeconomic backgrounds; awareness of the presence of CWs in their community; the ecosystem services offered by the CWs; the WTP for the CWs; and the challenges and success factors in the implementation of the CWs project. The data collection involved ten (10) enumerators who are proficient in speaking English and the local language. A total of 270 respondents were gathered from a population of 750 households.

Initially, all respondents were aware of the presence of CWs in the village. Between 50% and 95% of the respondents acknowledged the ecosystem services offered by the CWs, including provisioning services (water supply for the community garden), regulating services (wastewater treatment, water purification), supporting services (habitat formation), and cultural services (tourism, education and research, and aesthetic). More than 96% of the respondents were willing to pay for these ecosystem services of CWs composed of 224/226 females and 36/44 males. As shown in Table 4.1, the mean WTP of respondents is 2.88 ± 3.94 USD with a maximum of 6.20 ± 15.39 USD and a minimum of 1.34 ± 3.21 USD.

Currently, there are 750 households in the Fishermen's Gawad Kalinga Village connected to the services of CWs. Therefore, the estimated economic value of ecosystem services provided by the CWs to the community amounts to a mean of 2160 ± 2955 USD annually.

In terms of shadow pricing, the CWs in Bayawan City have a capacity of 180 cubic metres, which can be filled up with domestic wastewater three times daily. This is equivalent to 197 thousand cubic metres of treated wastewater annually. With a shadow price of 4 cents USD per cubic metre (based on the septage fee collected by Bayawan Water District), the economic value of provisioning and regulating services of CWs is estimated at 7884 USD annually.

Table 4.1 Willingness to pay (in USD) of the selected residents of Fishermen's Gawad Kalinga Village for CWs (source: Guila 2023)

	n	Mean ± SD	Median
WTP	258	2.88 ± 3.94	1.11
Max WTP	234	6.20 ± 15.39	2.22
Min WTP	239	1.34 ± 3.21	0.44

4.3.3 Benefit–Cost Analysis of Constructed Wetlands Project

In the benefit–cost analysis (BCA), there were three (3) cases considered. Case 1 describes the perspective of a private investor who is only looking at the financial aspect of the NbS project. Cases 2 and 3 describe the perspective of the society (or LGU), which considers the economic (societal) benefits and costs of the project. Parameter estimations for the BCA are summarised in Table 4.2, while all calculations are presented in Appendix A.

The CWs project costs 180,000 USD, composed of the initial project investment, consultation fees, and construction labour. Annual operations and maintenance costs of 4000 USD, including salary and utilities. Currently, the project generates no revenues, and therefore the project is run and subsidised by the local government. Considering the value of ecosystem services of CWs, the community's mean WTP is 2160 USD per year, while the shadow price is 7884 USD per year. Hence, the total economic value of the ecosystem services of CWs is 10,044 USD per year. The valuation period for the project is 15 years, which is the same period for the lease given by the LGU to the temporary residents of the village. The discount rate is 0% based on the social discount rate set by the National Economic Development Authority.

The results of BCA, particularly the net present value (NVP) for the three cases, are summarised in Table 4.3. In Case 1, the NPV of the project is −210 thousand USD. This implies that the project generates losses from the perspective of a private investor; hence, the investment decision is not to implement the project.

In the second case, the economic value of ecosystem services offered by the CWs to the community is considered and integrated as project benefits in Eq. 4.1. Despite the benefits, this value cannot recover the huge cost of investment, resulting in a negative NPV of −134,129 USD. Still, the project seems to be not profitable; hence, the LGU covers these costs to keep the operations of CWs running.

Considering a generous donor that will fund the project, Case 3 yields a positive NPV of 45,971 USD. This implies that the project is feasible considering the community's WTP for the CWs, its shadow price, and the donation that covers the cost of the project.

Table 4.2 Parameters for benefit–cost analysis of constructed wetlands

Parameter	Description	Unit	Value
I_{NbS}	Project investment cost	USD	180,000
C_t	Annual operations and maintenance cost	USD/year	4000
B_t	Annual revenue from the project	USD/year	0
WTP_t	Mean WTP for CWs	USD/year	2160
SP_t	Shadow price of CWs	USD/year	7884
B_t	Total economic value from WTP and SP	USD/year	10,044
r	Discount rate	%	10
T_{NbS}	NbS project valuation period	years	15

Table 4.3 Results of benefit–cost analysis of constructed wetlands

	Net present value	Decision
Case 1—without ecosystem services value	−210,424 USD	Not invest
Case 2—with ecosystem services value	−134,029 USD	Not invest
Case 3—with project donor and ecosystem services value	45, 971 USD	Invest

4.3.4 Uncertainties of Constructed Wetlands Project

Despite the successful implementation of the CWs in Bayawan City, several challenges and problems have surfaced that jeopardised the project's long-term viability. These challenges, which range from foul smells and poor maintenance to the effects of flooding and other natural calamities, highlight the complexities of maintaining such NbS to wastewater treatment. While the project has had substantial success in improving sanitation and wastewater management in the area, these problems underscore the importance of continual evaluation, adaptive management, and resilience planning to ensure the project's sustainability and resilience.

Residents of Fishermen's Gawad Kalinga Village have expressed their concern regarding the foul smell that originates from the constructed wetland in the area. This problem poses issues not only for the people who live there but also for the environment. The residents experience discomfort, distress, and annoyance as a direct result of the odour, which contributes to the public's refusal of, or social unacceptability of, the constructed wetland. This putrid odour, unless well managed, may be an indication of an improperly managed wetland system, which may hurt the local ecosystem as well as well-being, particularly the public health of the people.

In addition, the CWs of Bayawan City suffer from poor or improper maintenance, which may be the result of many issues that also present obstacles to the wetland's overall effectiveness. Proper maintenance efforts can be hampered by a lack of resources, such as financial resources and skilled manpower. In addition, the lack of in-depth understanding knowledge and training linked to the maintenance of such a system may result in neglect or the implementation of procedures that are not suitable or improper for the constructed wetland. Inadequate community engagement or involvement may also lead to a lack of incentive for properly maintaining the space. The lifespan of the wetland system can be shortened by improper maintenance, which can also drive up the costs connected with its repair or replacement.

Finally, natural disasters such as typhoons and earthquakes are cited as challenges to the constructed wetland. Flooding caused by extreme typhoons can overwhelm the capacity of the wetland, limiting its ability to treat wastewater, which could contaminate the surrounding environment and endanger the health of the residents. Furthermore, earthquakes can cause physical damage to the CWs, impairing its operation and potentially necessitating costly repairs or even replacement of parts of the system.

4.3.5 Real Options Valuation of Constructed Wetlands Under Uncertainties

Considering the challenges and uncertainties of CW implementation, this study applies the real options valuation as discussed in Sect. 4.2.6. The real option to wait/defer/postpone the implementation of the project is applied under the uncertainty in social acceptability. The parameter estimations for the real options valuation are summarised in Table 4.4.

The implementation of the project costs 180,000 USD, which is similar to the NPV calculation. The total discounted cash flows for the duration of the project are 225,971 USD, equivalent to the summation of net benefits discounted to present value at a 10% discount rate. In the options valuation, a decision-maker is given 10 years to decide whether to immediately implement the project or postpone the implementation to a later period within 10 years. However, the postponement incurs an opportunity cost of 10% of the project value annually. Considering the uncertainty in social acceptance of CWs, the economic value of the project may increase/decrease relative to the WTP of residents for the project. Since there is no existing historical data for WTP, we assumed a 20% volatility based on the range of WTP of residents to the CWs. Substituting the estimation parameters to Eq. (4.6), the calculated real options values of CWs are summarised in Table 4.5. The results are compared with NPV, and the decisions are concluded based on NbS implementation decisions in Sect. 4.2.7.

The results showed that if the NbS project is implemented now, the investment has an NPV of 45,971 USD, implying a decision to accept the project. However, we consider here the value of flexibility to postpone the implementation of the NbS

Table 4.4 Estimation parameters for the real options valuation of constructed wetlands

Parameter	Description	Unit	Value
I_{NbS}	Project investment cost	USD	180,000
V_{NbS}	Total discounted cashflows	USD	225,971
T_{ROV}	Decision (waiting) period	years	10
δ	The opportunity cost of waiting	%	10
r	Discount rate	%	10
σ	Volatility in public acceptance	%	20

Table 4.5 Real options valuation of constructed wetlands under various uncertainties

	NPV	NPV decision	ROV	ROV decision
$\delta = 0$	45,971 USD	Invest	157,825 USD	Wait
$\delta = 10\%$	45,971 USD	Invest	23,600 USD	Invest now

project (termed as a real option to wait). At $\delta = 0$, there is no opportunity cost of waiting. The real options valuation results in a project value of 157,825 USD, which is relatively higher than NPV. This implies that waiting to implement the project incurs higher returns than implementing it immediately. Another interpretation for this is that the investor LGU or project planner is willing to give up the ROV of 157,825 USD and get the NPV of 45,971 USD to implement the project now.

At $\delta = 10\%$, there is an opportunity cost, which is 10% of the expected annual cash flows. This can be attributed to the lost opportunities to benefit from the ecosystem services provided by CWs. The real options valuation results in a value of 23,600 USD, which is lower than the NPV. This means that postponing the implementation of the NbS project incurs losses, resulting in a lower project value. Therefore, the more optimal decision is to immediately implement the project to avoid the losses from waiting. In other words, the investor, LGU, or project planner should give up the ROV of 23,600 USD to get the NPV of 45,971 USD by implementing the project now.

Under uncertainty in social acceptance, immediate implementation of NbS projects is optimal if we only consider the opportunity cost of waiting. Otherwise, the project planner should postpone because the WTP is uncertain and expected to increase over time with the increase in residents' acceptance of the NbS project. This highlights the advantage of using real options valuation over traditional methods, as it gives additional value to the flexibility in the implementation of a project. To make the project implementable at the current period, the identified uncertainties should be minimised by proposing policies that support the implementation of NbS projects, securing external funding to finance the initial investment of the project, considering the lost opportunities to benefit from the ecosystem services of NbS projects, involving all relevant stakeholders in the decision-making process, and providing other sources of revenues to make the project viable and sustainable in the long run.

4.4 Conclusion

Economic analysis plays a crucial role in the establishment of NbS projects for wastewater treatment projects. Considering the complexity of NbS as an environment-friendly and more sustainable water treatment technology, as an ecosystem, and the uncertainties in its implementation, traditional economic analysis does not seem sufficient. This chapter presented an integrated economic analysis framework that captured these complexities. The real options valuation of NbS projects integrated the ecosystem services valuation in benefit–cost analysis and was complicated by the uncertainties in project implementation.

The proposed economic analysis framework was validated using the case study of constructed wetlands, an NbS to wastewater treatment, in Bayawan City, Philippines. A survey was conducted on 270 household representatives of

Fishermen's Gawad Kalinga Village who benefited from the constructed wetlands. The results found that the residents are aware of the NbS project and its benefits and are willing to pay for ecosystem services (provisioning, regulating, supporting, and cultural) provided by the constructed wetlands. However, the mean willingness to pay ranging from 1.34 ± 3.21 USD to 6.20 ± 15.39 USD accounted for the mean economic value of 2160 USD annually. Using the shadow pricing method, the provisioning and regulating services from constructed wetlands resulted in an economic value of 7884 USD. The total economic value of constructed wetlands from both methods accounted for 10,044 USD. The NPV of constructed wetlands is 45,971 USD, which was only viable with the presence of external funding for the construction of the project. Considering the uncertainty in social acceptance and the flexibility to postpone the implementation of the project, the project value significantly increased to 157,825 USD, making it viable in a later period if there are no opportunity costs. Otherwise, it is better to implement the project immediately to avoid the opportunity losses (ROV = 23,600 USD) from waiting.

The findings of the case study provided recommendations to make the NbS projects viable through policies that support the implementation of NbS projects, finding sources of funding and financing mechanisms, stakeholder involvement, and generating revenues from the project. While the case study in Bayawan City simplified the proposed economic analysis framework, it served its main purpose of providing support, along with the technical, environmental, governance, and social aspects, in evaluating the feasibility of NbS projects. To apply the proposed framework to other NbS projects, a more tailored approach in terms of economic valuation techniques, uncertainty identification, and country/project-specific conditions must be considered.

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Appendix A

Sample Calculation for Benefit–Cost Analysis and Real Options Valuation

This material provides sample excel calculations for the economic analysis of nature-based solution for wastewater treatment using benefit-cost analysis and real options valuation.

Benefit-cost calculation

	Case 1	Case 2	Case 3	Notes
Investment cost	180000	180000	0	
OM cost	4000	4000	4000	
Benefits		10,044	10,044	Based on WTP + shadow price
Discount rate	10%	10%	10%	
0	−180000	−180000	0	
1	−3636	5495	5495	PV_t = (B_t−C_t)/(1+r)^t
2	−3306	4995	4995	
3	−3005	4541	4541	
4	−2732	4128	4128	
5	−2484	3753	3753	
6	−2258	3412	3412	
7	−2053	3102	3102	
8	−1866	2820	2820	
9	−1696	2563	2563	
10	−1542	2330	2330	
11	−1402	2118	2118	
12	−1275	1926	1926	
13	−1159	1751	1751	
14	−1053	1592	1592	
15	−958	1447	1447	
NPV	−210424	−134029	45971	NPV = sum(PV_t)

Real option calculation

	delta=0	delta=10%	Notes
I	180000	180000	
V	225971	225971	V = NPV+I
T	10	10	
rho	20%	20%	
r	10%	10%	
delta	0%	10%	
d1	1.5377	−0.0434	d1 = [ln(V/I)+(r−delta+1/5rho^2)] / [rho*sqrt(T)]
d2	0.9053	−0.6759	d2 = d1 − rho*sqrt(T)
N(d1)	0.9379	0.4827	N(d1) = NORM.DIST(d1,0,1,TRUE)
N(d2)	0.8173	0.2496	N(d1) = NORM.DIST(d2,0,1,TRUE)
ROV	157825	23600	ROV = V*exp(−delta*T)*N(d1) − I*exp(−r*T)*N(d2)

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Chapter 5
Social Acceptability Assessment for Nature-Based Solution for Wastewater Treatment

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Abstract The challenge in treating wastewater has continuously been occurring, aggravated by rapid urbanisation, unsustainable human activities and practices, and population growth. Majority of wastewater globally is yet to be treated, and millions of people still have limited access to safe and clean facilities, resulting in individuals practising unsafe and unsustainable human practices such as open defecation. In the Philippines, the environment is experiencing adverse effects evident in the hydrological and ecological changes in the river systems due to the previous economic conditions coupled with rapid industrialisation. A nature-based solution (NbS) for wastewater treatment, such as constructed wetland (CW), can be an alternative for cities and municipalities in the Philippines. The case of the wastewater facility in Bayawan City, Negros Oriental, is the best example of NbS-CW operating for almost 17 years. With the aim of replication and successful implementation of NbS projects, social acceptability assessment is a crucial support tool to study social acceptance, benefits, barriers, and opportunities as perceived by the stakeholders for implementing NbS projects. Social preparation such as training, seminars, consulta-

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tions, and local government commitment and partnership are also greatly needed to successfully implement, replicate, and adopt NbS technologies and projects in the Philippines.

Keywords NbS replication · Social acceptance · Social preparation

5.1 Introduction

Throughout the years, the issue of wastewater has been an occurring challenge and is being aggravated due to rapid urbanisation, unsustainable human activities and practices, and population growth, where more resources utilised means more wastewater is being produced. As stated by Masoud et al. (2022), majority of wastewater globally is yet to be treated. To further specify, 3.6 billion people globally experience a scarcity of safe water services management. Likewise, the number of people who lack access to basic sanitation still is at 1.9 billion. Aside from that, millions of people still have limited access to safe and clean facilities, which resulted in individuals practising unsafe and unsustainable human practices such as open defecation. In the Philippines, Jalilov (2017) stated that the environment is experiencing adverse effects, which is evident in the hydrological and ecological changes in the river systems due to the previous economic conditions coupled with rapid industrialisation. Moreover, it was reported that in 2017, seven million Filipinos still performed open defecation. That said, the WHO (2017) also stated that the Department of Public Works and Highways (DPWH) asserted that an accumulated amount of more than 78 million pesos is lost due to these conditions.

Given these current challenges, different initiatives have been implemented to combat and resolve such issues. At the global level, the Sustainable Development Goals were developed by the United Nations to serve as a blueprint for countries to achieve "peace and prosperity for the people and the planet, both at present, and in the future" (United Nations 2020). Under these goals, wastewater treatment is covered under SDG #6: Clean Water and Sanitation, which administers various approaches and processes to treat wastewater and enable people to reuse them. In the Philippine context, on the other hand, the Philippine Clean Water Act of (2004) was implemented to create and institutionalise a framework for water quality management. This law prohibits the disposal of wastewater in all bodies of water. In addition to that, the collaboration between local governments is required to co-manage such areas within their jurisdiction (The Philippine Clean Water Act 2004; Guino-o et al. 2009).

Nature-based solution (NbS) refers to the mechanisms that mimic the processes of the natural environment to solve societal problems, such as improving water quality and management. On the other hand, Cohen-Shacham et al. (2016) presented a definition by the International Union for Conservation of Nature (IUCN), which stated that NbS are courses of action established to protect, manage, and restore natural and modified ecosystems. In the case of wastewater, constructed wetlands have been known to be an NbS to treat and improve water quality. Constructed wetlands are also proven to provide various ecosystem services such as biomass and water supply (provisioning services), water purification, and flood and climate control (regulating services), habitat formation and nutrient cycling (supporting services), and recreation and aesthetics (cultural services) (Agaton and Guila 2023).

To achieve a successful implementation of NbS projects, social acceptability is crucial as it provides input from the residents and groups essential in successfully planning for the future of a community (Sowińska-Świerkosz and García 2022). Social acceptability refers to the interdisciplinary approach to comprehend the perceptions of the public towards a certain practice or development (Brunson 1996; Masclef et al. 2020). Moreover, assessing social acceptability and, at the same time, improving the knowledge of stakeholders is extremely important for successful diffusion strategies. However, it was argued that assessing these aspects must be performed in the early stages of the project planning process (Zaunbrecher and Ziefle 2015).

Similar to the Nature4Cities social acceptance method, this social acceptability assessment is an NbS implementation support tool (methodological tool) that studies social acceptance and barriers as perceived by the stakeholders for the implementation of NbS projects (NetworkNature 2021). The social acceptance method by Nature4Cities also uses a questionnaire for quantitative evaluation similar to the social acceptability assessment used in the Asia-Pacific Network project (https://doi.org/10.30852/p.18686). Through this assessment, planning practitioners and decision-makers can easily adopt the methodology to assess and manage the social acceptability of NbS for wastewater treatment by respective stakeholders.

5.2 Methodology

5.2.1 Study Areas

Social acceptability assessment was conducted in two sites in the Philippines, one in Bayawan Gawad Kalinga (GK) Wastewater Facility, Municipality of Bayawan, Negros Oriental, and the other site in the Panguil River Eco Park, Municipality of Pangil, Laguna.

Study Area 1: Bayawan GK Wastewater Facility is the site of the constructed wetland (CW) treating domestic wastewater from the resettlement areas in the City of Bayawan. In 1995, an estimated 750 Informal Settler Families (ISF) lived on the coast, which made them highly exposed and vulnerable to disasters. Furthermore, they had no access to safe water supply and sanitation facilities and thus contributed to the pollution of the coastal waters according to Engr. Antonio S. Aguilar of Bayawan City Engineering Office. Records from the Bayawan City Health Office revealed a significant prevalence of illness and mortality from water-borne infections in these informal settlements (Lipkow and von Münch 2010). To address this health concern, the city government bought a seven-hectare land, now called the GK Fisherman's Village, as a relocation area for the affected families, and installed a constructed wetland for domestic wastewater treatment. From May 2005 to August 2006, the Engineering Office of Bayawan City worked on the project with technical assistance provided by the German Technical Cooperation (GTZ) through its Water and Sanitation Program (Lipkow and Münch 2010). In September 2006, the CW system was officially inaugurated. It has been continuously operated and managed by the Bayawan City Local Government Unit (LGU) until now (see Fig. 5.1, photos taken February 2023).

Before the transfer of the ISFs to the GK Fisherman's Village, continuous social preparations were conducted by the LGU Bayawan to ensure that the residents understood the value of the resettlement areas. As mentioned, the CW (GK Wastewater Facility) has been established since 2006 and now has been handling domestic wastewater from around 700 households. As the first study area for the Asia-Pacific Network for Global Change Research (APN-GCR) project, under the "Integrated assessment of existing practices and development of pathways for the effective integration of nature-based water treatment in urban areas in Sri Lanka, the Philippines, and Vietnam", through the social acceptability assessment, benefits, challenges, and opportunities will be measured as perceived by the local stakeholders in the GK Wastewater facility of the City of Bayawan.

Study Area 2: Panguil River Eco Park is located in Pangil town, situated in the province of Laguna, and covers a total land area of 45.03 km^2 (PhilAtlas 2022). The Panguil River Eco Park (see Fig. 5.2) is an ecotourism destination established last 10 June 2010 as a result of the initiative by the local government of Pangil through the offer of the Laguna Lake Development Authority (LLDA) to be funded by the World Bank. Throughout the years, the eco-park has been a sustainable venture in providing various benefits such as income generation for the municipality and job

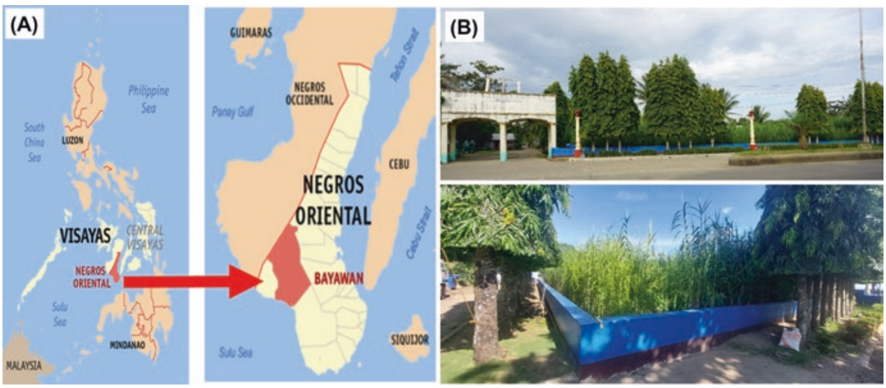

Fig. 5.1 Study Area 1: Philippine map showing the location of Negros Oriental and Bayawan City (**a**) and photos of GK Fisherman's Village CWs (**b**) (Devanadera et al. 2022)

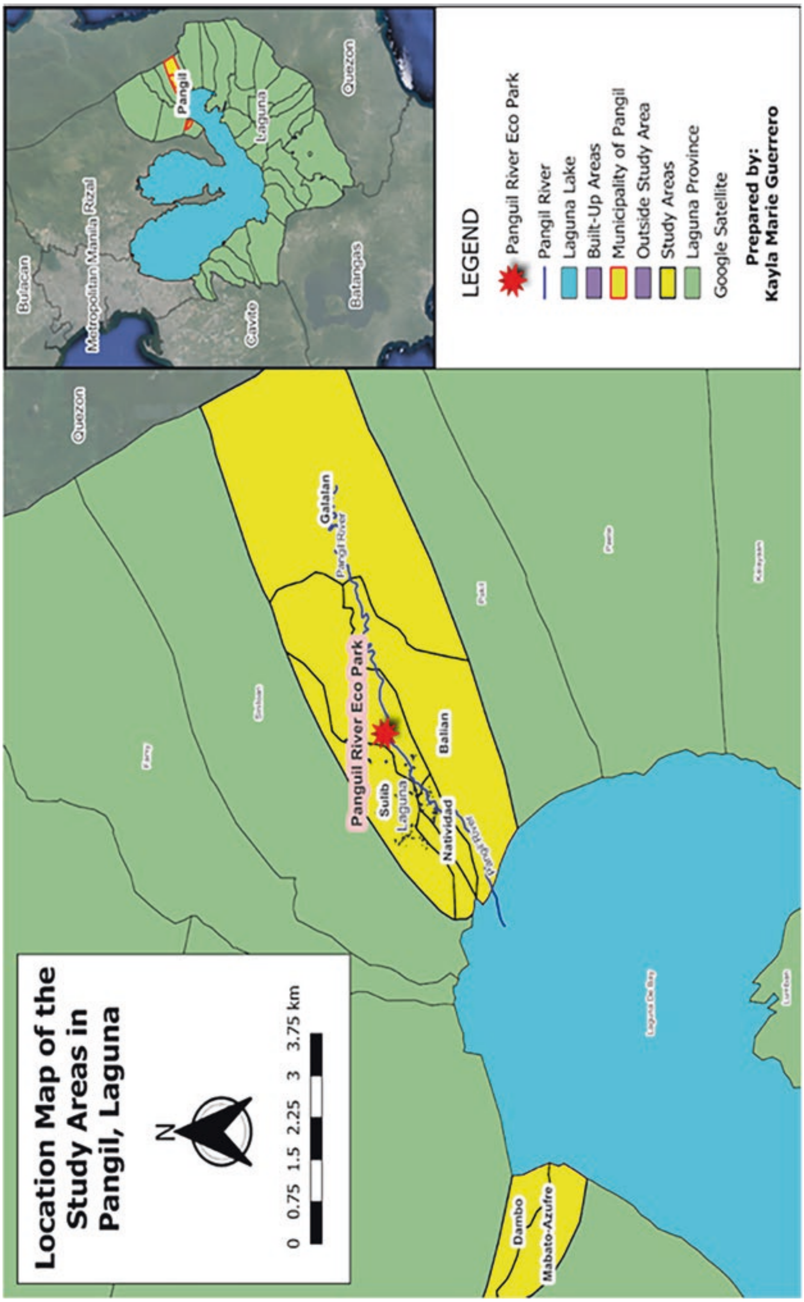

Fig. 5.2 Study Area 2: Location Map of the Study Area—Panguil River Eco Park

opportunities for the residents. In terms of amenities, the area offers cottages, a swimming pool, river tubing, tent rentals, and a pavilion; at the same time, it also covers many notable areas such as Panguil River, *Ambon-Ambon* Falls, *Biak na Bato* falls, and the *Barking Bato*, among others. Moreover, it was stated that it is also considered as a "municipal sanctuary" for different flora and fauna. This site was chosen as it will be the location of an NbS-constructed wetland, where it can handle septage wastewater of around 200–300 tourists/visitors. As mentioned, the CW will be established; thus, an initial/pre-construction social acceptability is conducted to gather the perception of the stakeholders in Pangil.

5.2.2 Survey Instrument and Focus Group Discussion

Social acceptability survey questionnaires were used to measure the awareness, perception, challenges, and opportunities of establishment, replication, and adoption of NbS-constructed wetlands in the treatment of domestic wastewater in the Philippines. The survey questionnaires were drafted based on the following factors affecting social acceptability: (1) level of social acceptability, (2) participation in the operation of CW, (3) perceived level of safety of CW operations, (4) trust in the government's CW operations, (5) perceived benefits of CW, and (6) perceived risk of CW. Two (2) different survey questionnaires were used depending on the appropriateness to the study area. Focus group discussions (FGDs) and key informant interviews (KII) were also conducted with respective barangay (village) leaders and people involved in the operation (LGU). The complete survey questionnaires can be found on the website: https://doi.org/10.30852/p.18686. This site is the Asia-Pacific Network for Global Change Research (APN-GCR) project for 2021–2023 titled "Integrated Assessment of Existing Practices and Development of Pathways for the Effective Integration of Nature-based Water Treatment in Urban Areas in Sri Lanka, the Philippines and Vietnam", in which this study is part of.

5.2.3 Respondents of the Survey

To determine the sample size, a purposive sampling method was used. This technique, also known as judgement sampling, is a non-probability sampling approach that is suggested to be helpful in identifying respondents who can contribute to gathering information to answer the research questions (Graunke 2018). This sampling technique involves determining respondents based on the judgement of the researcher. Creswell (2014) stated that this involves gathering data from individuals or groups that may be insightful for the analysis of the research (as cited by Graunke 2018). For Study Area 1, clustering in the resettlement areas was utilised, while in Study Area 2, the workers in the Panguil River Eco Park, as well as the invited residents from the barangays of Pangil, were gathered to assess their perceptions and acceptability towards the constructed wetlands that will be constructed in the Panguil River Eco Park.

5.3 Case Study Findings

5.3.1 Study Area 1

5.3.1.1 GK Wastewater Facility

Social acceptability of Bayawan City's GK Wastewater Facility measured the six parameters/factors affecting social acceptability. The individual perceptions of the residents towards nature-based solutions and constructed wetlands were assessed based on the level of social acceptability, how they participate in the operation of CW, the level of safety in CW operations, the trust of people in the government in relation to operations, the perceived benefits of CW, and lastly the possible risk having constructed wetlands in their area. As mentioned FGDs and survey were conducted to measure social acceptability in Bayawan City. Three (3) FGDs were conducted, which included (1) block/cluster leaders of the GK Fisherman's Village, (2) Barangay (village) officials and staff in Barangay Maninihon, and (3) Barangay officials and staff in Barangay Villareal, all from the City of Bayawan (see Fig. 5.3).

Representatives from each cluster of the GK Fisherman's Village also participated in the social acceptability survey. It was conducted by SCPW and UPLB as part of the APN-GCR project. Around 94% (254 out of 270) of the survey respondents were aware of the CW and its existence in the village. Table 5.1 shows the

Fig. 5.3 FGDs on social acceptability for wastewater treatment using CWs (from left to right: GK Fisherman's Village Block/Cluster Leaders, Barangay LGU of Maninihon, and Barangay LGU of Villareal in Bayawan City, adapted from Devanadera et al. 2022)

Table 5.1 Survey results on the social acceptability of constructed wetland (GK wastewater facility in Bayawan City[a]

Factors affecting social acceptability	Mean	Verbal interpretation
(1) Level of social acceptability to CWs	4.37	Very High
(2) Participation in the operation of CW	3.49	High
(3) Perceived level of safety of CW operations	4.24	Very High
(4) Trust in the government's CW operations	4.40	Very High
(5) Perceived benefits of CW	4.27	Very High
(6) Perceived risk of CW	2.39	Low

[a]5-point Likert scale range and interpretation (Pimentel, 2010)—very high: 4:21-5.00; high: 3.41–4.20; neutral: 2.61–3:40; low: 1.81–2.60; very low: 1.00–1.80

summary of the survey results on social acceptability of the CW (GK Wastewater facility) in Bayawan City. All factors affecting the social acceptability were recorded to have high to very high values except for the low value on the perceived risk of CW. This means that the respondents have positive acceptance of constructing CW in their village.

The study confirmed that CWs are a cost-effective way of treating domestic wastewater to reduce water pollution, which helps improve the health of the community. Key factors affecting social acceptability according to the result of the FGD, the KIIs, and the survey are adequate preparation, participation, and involvement of the local community, awareness, trust in the implementers, a feeling of safety, and the perceived impacts and benefits to the community. Moreover, through thematic analysis, it was found that the critical aspects for the sustainability and replicability of the CW in the case of Bayawan City are strong political will, policy and funding support, cooperation of the community (social/public acceptance), the existence of a unit responsible solely for managing the operations and maintenance of the CWs, technical knowledge, and availability of land.

In terms of opportunities for improvement of the current and future applications, the study suggested that the generation of more direct benefits, especially provisioning services, which have economic values for the community is essential to ensure the continued interest and support of local decision-makers and politicians. Currently, the CW is perceived by the community as beneficial only for its regulatory service, specifically for wastewater treatment.

5.3.2 Study Area 2

5.3.2.1 Panguil River Eco Park

The Panguil River Eco Park is a potential site for the replication of a constructed wetland for domestic wastewater treatment. The CW will handle the wastewater coming from the visitors/tourists of the eco park. This NbS technology will ensure the protection of river system/waterbody (Panguil River and Laguna Lake) from untreated wastewater discharge.

As part of the social preparation for the establishment of the NbS-CW and to promote the social acceptability of constructed wetlands (Green Filters) among the local communities to secure its successful operation at the Panguil River Eco Park, SCPW conducted another capacity-building activity that focused on nature-based solutions/constructed wetlands and their role in wetland management. The training was conducted in the Panguil River Eco Park. It was composed of lectures and learning sessions about wetlands conservation and management, nature-based solutions, and constructed wetlands/green filters. The social acceptability survey and focus group discussions to determine the perception of local stakeholders were also part of the 3-day training. In addition, there was a section in the training about how to culture effective microorganisms (Bokashi) to ensure adequate supply for the constructed wetland as well as for the use of local communities in their homes. This training is under the "Living Lakes, Biodiversity and Climate Project"—a 5-year global project funded by Germany's Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection under the International Climate Initiative (IKI) with the Global Nature Fund, an NGO based in Germany as the lead organisation.

For the Panguil River Eco Park, social acceptability and FGD were also conducted under the APN-GCR project. The survey questionnaire was adapted and revised based on the appropriateness of the factors affecting social acceptability in the Panguil River Eco Park as a potential site for the establishment of NbS-CW. It was divided into several sections, namely, the socio-demographic profile, ecosystem services in the Panguil River Eco Park, awareness of NbS, CWs, and wastewater, planning participation, individual perceptions on constructed wetlands, willingness to pay (motivations and demotivation), and possible interventions to improve knowledge and awareness. Stakeholder perceptions were determined through the survey and FGDs.

The majority of the local stakeholders were new to NbS and constructed wetland concepts. However, they are very much interested and willing to support the project when they hear the benefits and opportunities from the project. Initial findings from the survey showed that the constructed wetland to be established in the Panguil River Eco Park is accepted by the residents of Pangil, Laguna. There are a few stakeholders who expressed concerns about the safety of the people, economic effects, and some hindrances in the implementation. Local stakeholders also expressed that training and seminars be conducted to improve the awareness and knowledge of the people towards nature-based solutions and constructed wetlands. The utilisation of online materials (i.e. video blogs) for the promotion of the NbS-CW was also suggested. Survey respondents also expressed the need to involve the people in planning to ensure better establishment of the project.

FGDs with the officials from different barangays in Pangil, Laguna, Philippines, including (1) Barangay San Jose and Dambo, (2) Barangay Balian, and (3) Barangay Natividad, were also conducted. During these sessions, it became evident that the barangay officials were largely unaware of the concept and functions of constructed wetlands (CW). They expressed that the FGD and learning event on nature-based solutions and constructed wetlands conducted by SCPW were their initial exposure to CW and the first time they learned about the CW establishment project in their municipality.

While their response during the FGD was largely positive, the officials acknowledged several potential risks. They were concerned about issues such as leaks and overflows, particularly during adverse events like storms and floods, the possibility of biological hazards from CW, which may adversely affect community health and cause diseases, and the potential attraction of mosquitoes and flies, which may be brought by CW. Furthermore, some FGD participants highlighted the importance of sustainable maintenance and operations of CW systems, expressing reservations about the government's capacity to ensure ongoing viability. They were worried that inadequate maintenance could lead to project failure or waste.

Despite these reservations, the officials expressed overall support and acceptance for the project's pursuit and establishment within their local government units (LGUs) as a pilot demonstration of the CW technology. They believed that a functional CW example within their community would foster greater appreciation and understanding of the technology, encouraging replication in their respective barangays if resources, funding, and space permitted. They are also considering and asking for the possibility of integrating a constructed wetland with their existing waterways and rivers as a means to further reduce water pollution.

As suggested by the barangay officials, to ensure successful implementation of the NbS-CW project in Pangil, Laguna, they emphasised key factors such as (1) raising public awareness through effective information dissemination campaigns, (2) community involvement, (3) unwavering commitment and support from barangay officials and the municipal LGU, (4) effective waste management, (5) secure funding, (6) robust CW design and construction, and (7) proper operation and maintenance protocols.

Barangay officials also recommended seeking the support of the Sangguniang Bayan or Municipal Legislative Body of Pangil, Laguna, to enact an ordinance that outlines the support, operation, and maintenance of CW systems, which can also contribute to its sustainability. Public hearings and community participation were seen as crucial components of this process. Additionally, they mentioned that establishing a comprehensive waste management system within the municipality, including improvements to the sewerage infrastructure, should be prioritised.

5.4 Conclusions

Through the social acceptability assessment of nature-based solutions for wastewater treatment, benefits, challenges, and opportunities in the implementation and replication of new technologies as perceived by the local stakeholders will be determined. Possible interventions on how NbS technologies and projects can be successfully implemented, such as NbS-CW for wastewater treatment, need stakeholder awareness, consultation, and acceptance. Social preparation such as training, seminars, consultations, and local government commitment and partnership are crucial to successfully implement, replicate, and adopt NbS technologies and projects.

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Chapter 6
Guide to Constructed Wetlands: A Philippine Perspective

Perlie Velasco, Antonio Aguilar, Michaela Dalisay, Cloie Chie Mueca, Joseph Angelo Sabio, Kale Ashley Carurucan, Emel Ken Benito, and Ma. Hazel Castillo

Abstract Part of the Philippines' climate action plan is the utilisation of nature-based solutions (NbS) for water management. Constructed wetland (CWs) is an alternative NbS wastewater treatment system that utilises plants and substrates to treat wastewater. Its effectiveness has been proven in other countries in treating various types of wastewater. However, its adaptation in the Philippines is limited due primarily to the lack of information about CWs guiding the users in its implementation. Thus, this chapter provides a framework for establishing, operating, and maintaining CWs systems treating domestic wastewater in the Philippines. The framework is based on the existing process for establishing and operating wastewater treatment facilities in the Philippines, incorporating the best practices from Bayawan City, where the most successful CWs system in the country is being demonstrated. Nonetheless, while the socio-economic aspect was discussed in detail in the previous chapters, this chapter focuses on the technical aspects. The framework was validated in consultation with government agencies and other relevant organisations through a roundtable discussion, where the final framework was crafted and developed.

Keywords Constructed wetland · Integrated framework · Nature-based solution Philippines

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6.1 Introduction

Wastewater generated from various sources will continue to cause other major environmental problems, such as flooding, water-borne diseases, diminishing water resources, and destruction of biodiversity for health and tourism if not properly and efficiently addressed. The National Economic and Development Authority (NEDA), which is the Philippines' independent socio-economic planning agency, developed the Philippine Water Supply and Sanitation Master Plan (PWSSMP). This national action plan aims to improve access to safe, adequate, affordable, and sustainable water supply, hygiene, and sanitation by 2030, particularly by providing 97% of basic sanitation in the country (National Economic and Development Authority 2021). From this master plan, some important baseline data are summarised in Table 6.1. These data are far from the target of 100% coverage by 2030. The main barriers to attaining these targets are the lack of policy mandating each LGU to collect and treat the wastewater, particularly from domestic sources, and the lack or limited funding and highly technical requirements of the conventional treatment technologies (Mendoza et al. 2017; ARCOWA 2018).

One of the countermeasures to adapt to these barriers is using nature-based solutions (NbS). NbS aims to protect the natural environment and sustain public health and livelihoods (Cohen-Shacham et al. 2016). Natural infrastructures or green solutions, such as healthy forests, wetlands, and river ecosystems, have been shown to give sustainable, cost-effective solutions. For instance, source watersheds can collect, store, and filter water, delivering sufficient flow and water quality to communities downstream. A third of the world's one hundred largest cities get a significant portion of their drinking water from protected forest areas (Dudley and Stolton 2003). Furthermore, natural systems, such as wetlands and lagoons, can treat wastewater before returning it to rivers, streams, lakes, and aquifers at a low cost (Cross 2018). One common type of NbS for wastewater treatment is constructed wetlands (CWs), which remain under-utilised due to the domination of the traditional technology and infrastructures, as well as the lack of knowledge and insufficient support from the government for the implementation of CWs and other NbS. Thus, its enormous potential has not yet been explored in enhancing water availability, improving water quality, and reducing disaster risks and climate change that could significantly

Table 6.1 Estimated coverage sanitation in the Philippines (National Economic and Development Authority 2021)

% coverage	Baseline (2015)	Remarks
Sewerage system services	13%	Coverage of the population in the country, majority in Mega Manila
Septage management programmes	18%	
Septic tank (on-site system)	74%	Coverage of the household in the country, desludging rate every 4 years

contribute to the country's progress towards sustainable development (United Nations World Water Assessment Programme & UN-Water 2018).

6.2 Effectiveness of Constructed Wetlands for Wastewater Treatment

Constructed wetlands (CWs) are engineered systems to simulate the physical and biological treatment processes occurring in natural wetlands. Other terms used for CWs are bioremediation and reed beds. The first known experiments on the potential use of CWs for wastewater treatment were in 1952 in Germany, and the number of CWs studies became substantial in the 1990s as the application expanded to treat different kinds of wastewater. CWs have been adopted since, particularly in developed countries, and would require intensive pilot-scale studies to be accepted in developing countries (Hoffmann et al. 2011).

Figure 6.1 summarises the various configurations of CWs systems, which can be utilised separately, in series (i.e. French CWs where VSSF are in series) or hybrid (i.e. HSSF followed by VSSF), while Table 6.2 provides the description for each type. Moreover, Table 6.3 summarises the major components or factors affecting the treatment effectiveness of CWs. These are then used in the design considerations of CWs for wastewater treatment.

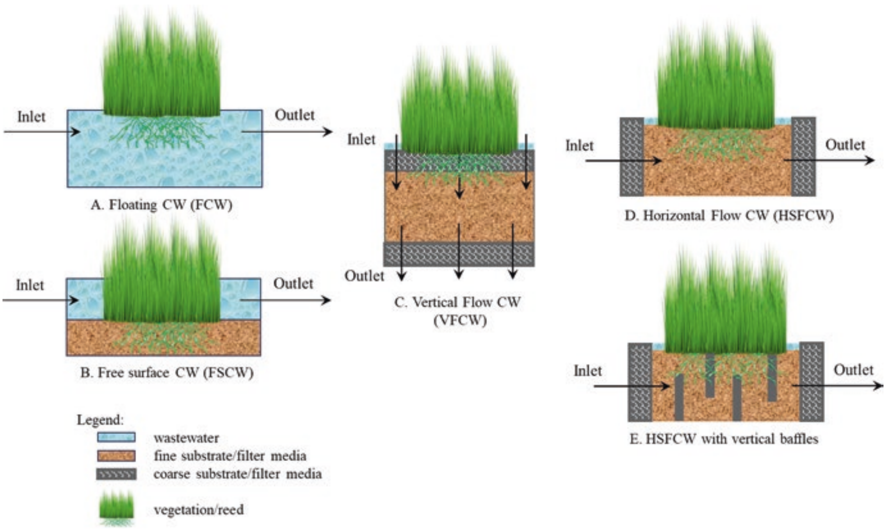

Fig. 6.1 Types of CWs configurations (Parde et al. 2021)

Table 6.2 Comparison of the types of CWs configurations

Type of CWs	Advantages	Disadvantages	Performance	References
Floating	– Useful in the removal of phosphates and nitrogen – Biomass that will be harvested can be used for fuel, animal feeding, and fertiliser – Easy desludging – No cost for substrates – No clogging – Easy access to air diffusers	– Low removal for BOD and COD – Biomass harvesting can increase O&M costs	– In full scale, the removal of respective pollutants amounted to 90%, 90%, 99.8%, 92.5%, and 86.4% for TP – In the lab-scale, the treatment efficiency amounted to 79% of chemical oxygen demand (COD), 88% of biochemical oxygen demand (BOD), and 65% of the total dissolved solid	Parde et al. (2021), Vymazal et al. (2021)
Free Surface	– Heavy metals are effectively treated – Wide range of vegetation can be used – Helpful for flood prevention and shoreline erosion – Waterproofing is not always used – Aerobic condition helps with plant growth – Wastewater exposure to sunlight helps destroy pathogenic bacteria and viruses	– Birthing grounds to mosquitos – Large land area requirement – High plant density requirement – Low phosphorous removal – Requires protection from public access	– Has been observed with up to 86% TKN, 93% oil content, 80% COD, and 88% BOD removal – Phosphorous removal is reported up to 41% only – Mean removal efficiency for trace metals (iron 53%, copper 45%, zinc 52%, and lead 52%), BOD and COD (50%–60%), TSS (70%–80%), and nitrogen (50%–65%)	Parde et al. (2021), David et al. (2022)

Table 6.2 (continued)

Type of CWs	Advantages	Disadvantages	Performance	References
Vertical	– Nitrification capacity – Less space requirement – High efficiency in removing BOD, COD, and bacteria – Nutrient removal at shorter hydraulic retention times (HRTs) (in a few hours)	– Limited denitrification – Clogging – Wastewater inside the CWs is heterogenous (unlike horizontal, which is homogenous)	Pilot-scale treating food processing wastewater with the removal of nitrogen (94%), BOD (96%), and TSS (94%)	Hoffmann et al. (2011), David et al. (2022), Parde et al. (2021), Vymazal et al. (2021), Waly et al. (2022)
Horizontal	– Better denitrification – Effective in treating organics, suspended solids, microbial pollution, and heavy metals	– More land area requirement compared to vertical flow CWs – Long-term saturation of bed creates limited opportunity for aeration, causing limited removal of ammonia – Low removal of phosphorous – Pre-treatment needed to avoid bed clogging – Due to the large surface area, horizontal CWs are much more prone to evaporation in areas with hot climates	Studies conducted in Spain and South Africa on raw wastewater showed that horizontal CWs could be utilised for the removal of pharmaceuticals and personal care products (PPCPs)	Hoffmann et al. (2011), David et al. (2022), Parde et al. (2021)

Table 6.3 Components affecting the effectiveness of CWs

CWs Components	Description	Design consideration	References
Vegetation	Vegetation aids with nutrient removal which usually occurs in the root zone	The vegetation's capacity and tolerance to the pollutants should be considered. Also, proper environmental conditions of the vegetation should be met to ensure survival and increase nutrient removal efficiency	Parde et al. (2021), Sijimol and Joseph (2021), David et al. (2022)
Substrate	Substrates are linked to other components of the CWs, such as sizing and the hydraulics	The substrate should support the vegetation and the microbial organisms' growth. The type of substrate should also be considered since it affects the pollutant removal efficiency based on factors such as hydraulic conductivity, porosity, and pollutant adsorbing capacity. Most of the removal of nutrients occur at the topmost layer of the substrate. However, there are cases such as for the removal of PCCPs, 0.3 m depth of the tank is enough for adsorption. The type of substrates also affects the lifespan of the CWs. In some cases, artificial substrates extend lifespan of the CWs	Sijimol and Joseph (2021), David et al. (2022), Waly et al. (2022)
HRT	HRT is the time the wastewater stays inside the tank or contact time	Depending on the pollutants that need to be removed, HRT should be sufficient enough to ensure chemical reactions and microbial activities occur in the substrate. For example, denitrification requires shorter HRTs compared to nitrification	David et al. (2022), Waly et al. (2022)
HLR	Hydraulic loading rate (HLR) is the volume of wastewater applied per unit area	HLR should be maintained at 2–30 cm/day to prevent clogging in the CWs. Additionally, HLR is related to HRT and that HLR should be set so that there is enough interaction between wastewater and the substrate	David et al. (2022)

6.3 Guide Framework for CWs Implementation in the Philippines

In the Philippines, CWs for wastewater treatment are not yet well adopted due to limited or lack of knowledge on their operation and effectiveness (Velasco et al. 2022). Thus, through the Asia-Pacific Network for Global Change Research (APN-GCR) project funding, an integrated framework was developed to guide establishing and operating CWs for wastewater treatment in the Philippines, with performance and impact assessments. Ultimately, the framework aims to provide the benefits of

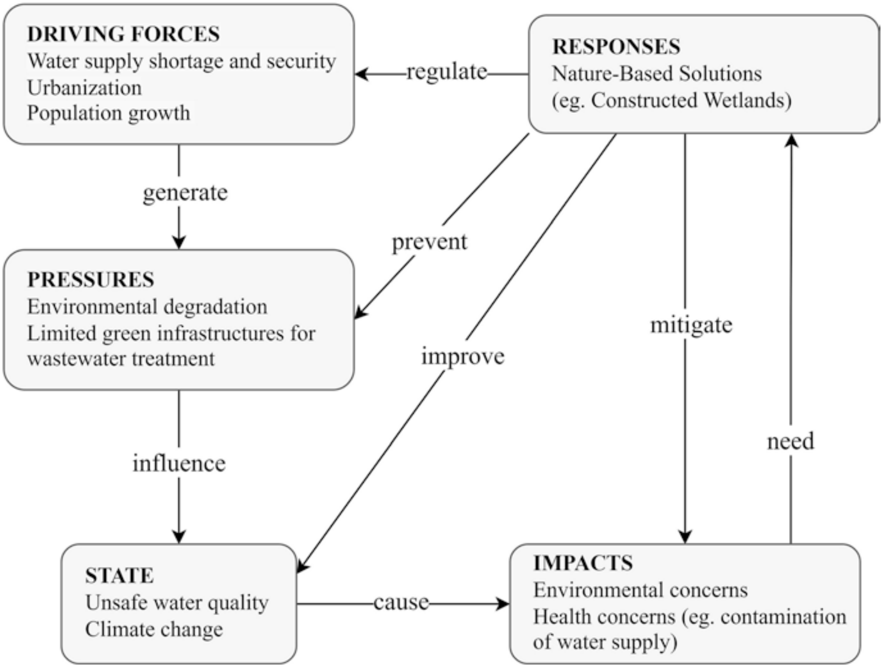

Fig. 6.2 Driver-pressure-state-impact-response (DPSIR) framework for CWs

CWs or other NbS in the country to address various issues, such as resilience to climate change and other water-related disasters and preservation and enhancement of water resources quality and availability.

The driver-pressure-state-impact-response (DPSIR) framework given in Fig. 6.2 suggests some general insights on the impacts of CWs, such as regulation of the driving forces, prevention of pressures, and improvement of the status quo, given the challenges on water supply and security, such as environmental and public health concerns. Ultimately, water resource degradation may be prevented, and health and environmental concerns related to water quality can be mitigated.

The final guide shown in Fig. 6.3 was developed based on various existing frameworks in the Philippines for establishing and operating a wastewater treatment facility. The experiences and practices of Bayawan City, Negros Oriental, Philippines, with their CWs systems treating domestic wastewater from the Gawad Kalinga Fishermen Village, were also incorporated in the guide. Information and data were collected and qualitatively analysed from the articles in the literature and Engr. Antonio Aguilar, the main person in charge of the said CWs in Bayawan City. The framework also focuses on the implementation for (i) new construction—step 1 to step 11 (yellow- and blue-coloured boxes) and (ii) existing CWs for further evaluation or retrofitting—step 8 to step 11 (blue-coloured boxes). It should also be noted that the last step should always be incorporated into the CWs system to promote its implementation.

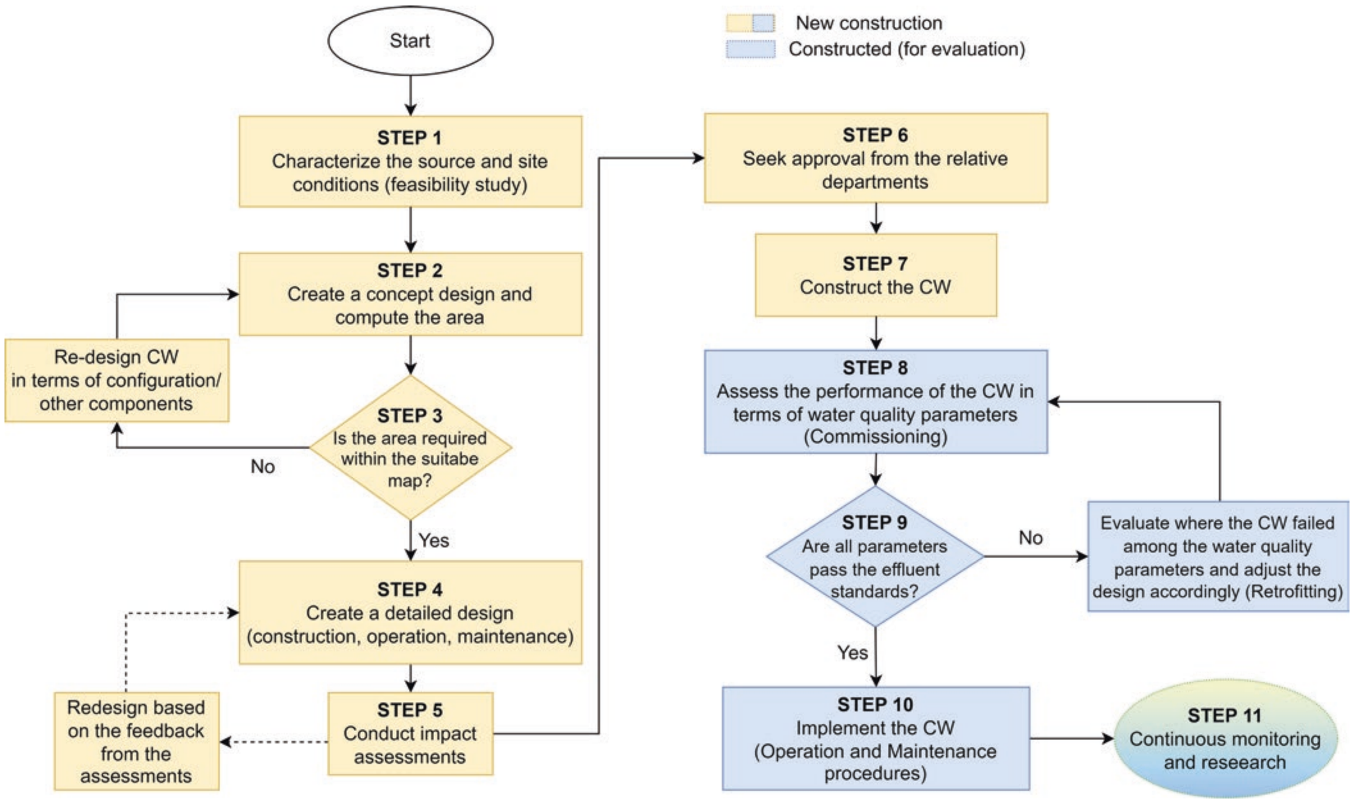

Fig. 6.3 Guide framework for the establishment and implementation of CWs in the Philippines

Table 6.4 List of agencies and organisations present in the consultative meeting

Group	Name of agency/organisation
National government offices of the Department of Environment and Natural Resources (DENR)	Mines and Geosciences Bureau (MGB)
	River Basin Coordinating Council (RBCO)
	Biodiversity Management Bureau (BMB)
	Forest Management Bureau (FMB)
Other national government agencies (NGAs)	Philippine Nuclear Research Institute (PNRI)
	Bureau of Soils and Water Management (BSWM), Department of Agriculture (DA)
	Department of Public Works and Highways (DPWH)
	Department of Interior and Local Government (DILG)
	Laguna Lake Development Authority (LLDA)
Local government unit (LGU)	Bayawan City Engineering Department
Private and non-government organisations	Society for the Conservation of Philippine Wetlands (SCPW)
	Philippine Water Partnership (PWP)
	Metropolitan Waterworks and Sewerage System (MWSS) Corporate Office (CO)
Universities	University of the Philippines Los Banos (UPLB)
	Technological Institute of the Philippines (TIP)
	De La Salle University (DLSU)

The developed integrated assessment framework was then validated through a meeting consultation with representatives from various agencies and organisations, held at Wynwood Hotel, Ortigas, Pasig City, on 7 October 2022. Individuals from National Government Agencies (NGAs), private institutions, academe, and other civil society organisations (CSOs) attended the consultative meeting. The complete list of organisations and government agencies is summarised in Table 6.4. The framework was presented in the meeting, and all comments and feedback were noted. Thus, the final framework presented in Fig. 6.3 was the revised version based on this meeting. Each of the steps in the guide is discussed in the succeeding subsections.

6.3.1 Site Survey (Step 1)

The standards in the Philippines related to wastewater treatment are defined in the DENR Administrative Order No. 2016-08 (DAO 2016-08) and No. 2021-19 (DAO 2021-19). The main parts of these standards used for the guide are summarised in

Table 6.5. The Water Body Classifications (Section 5 of DAO 2016-08) are set forth and assessed by the DENR-Environmental Management Bureau (DENR-EMB), where the classes of water bodies are based on their usage and the required water quality parameters. For sewage treatment, the significant parameters are BOD, faecal coliform, ammonia, nitrate, phosphate, oil and grease, and surfactants. Provided in Fig. 6.4 is a sample worksheet for personal water quality monitoring. It should be noted that the national standard has prescribed a manual for water quality planning and monitoring (EMB Memo Circular 2008-008), which is usually done by government agencies or accredited third-party water testing laboratories. The official website for these standards can be found at this link: https://emb.gov.ph/laws-and-policies-3/.

For siting the most suitable locations for CWs, Chap. 3 of this book provides the detailed methodology for suitability mapping of CWs in selected provinces in the Philippines as case studies. The required site conditions suitable for CWs are summarised in Table 6.6. Comparing the weights of each criterion, distance to water

Table 6.5 Related wastewater management standards in the Philippines

Administrative Order	Description
DAO 2016-08	– Water Body Classification: Classes of water bodies based on their usage (Sect. 5) and the required water quality parameters (Sect. 6)
	– Significant Parameters: Required water quality parameters for evaluation per sector or wastewater source (Sect. 7)
	– General Effluent Standard: Required water quality parameters of effluent before allowed for disposal (Sect. 7)
DAO 2021-19	Updated Guidelines for Water Body Classification and Effluent Standard of DAO 2016-08 of the following parameters: ammonia, phosphate, sulphate, faecal coliform, copper, and boron
EMB Memo Circular 2008-008	Effluent Quality Monitoring Manual: monitoring plan, effluent sampling methods and quality control, and flow measurement

Sector (DAO 2016-08 PSIC Code, Table 8):	Sewerage (37000)							
Significant Parameters[a]	Unit	Method[b]	Untreated Water (In)	Treated Water (Out)	Removal efficiency, % (In-Out)/In*100	DAO 2016-08 Effluent Standard A, B, C, D, SA, SB, SC, SD	Pass / Fail	Remarks
Ammonia as NH_3-N	mg/L							
BOD	mg/L							
Fecal Coliform	MPN/100mL							
Nitrate as NO_3-N	mg/L							
Oil and Grease	mg/L							
Phosphate	mg/L							
Surfactants (MBAS)	mg/L							

[a] Other parameters can be added based on DAO 2016-08
[b] Possible references: EMB Memo Circular 2008-008 or any edition of Standard Methods for the Examination of Water and Wastewater

Fig. 6.4 Sample worksheet for the CWs monitoring (for certain significant parameters based on DAO 2016-08)

Table 6.6 Site conditions for suitability mapping of CWs

Criteria	Suitability description	
	High suitability	Low Suitability
Land cover	Open or barren	Forest land
Slope	0–8%	>50%
Soil type	Clay or clay loam	Mountainous land or hydrosol
Distance to water bodies	≥190 m	<190 m
Distance to coastlines	≥200 m	<200 m
Distance to Protected areas	≥350 m	<350 m
Distance to Built areas	≥270 m	<270 m
Distance from active fault lines	≥500 m	<500 m

bodies is considered the top priority due to its effect on the nearest discharge and its environmental impact on the water body. Other hazard maps that should be considered are flood, storm surge, tsunami, volcanic, and liquefaction. These hazard maps can be quickly estimated from the Philippine Institute of Volcanology and Seismology (PHIVOLCS) found at this site: https://www.phivolcs.dost.gov.ph/index.php/gisweb-hazard-maps. In addition to these criteria, a site visit and consultative meetings with the Mayor of LGU, and/or its representative(s), and the residents of the barangay(s) where the CWs will be located should be done not only for inquiries but also to engage them in the implementation of CWs.

6.3.2 Conceptual Design to Detailed Design (Steps 2–4)

The critical design components for CWs are established in Sect. 6.3 of this chapter. These are footprint area, vegetation, and substrate or filter media. Various CWs configurations (Fig. 6.1) will also provide different removal efficiencies depending on the types of wastewater to be treated and the required effluent standard for safe disposal. However, this guide provides the design and operating conditions for hybrid CWs since this is the established and proven effective system in Bayawan City, Philippines, which is the model CWs system for this guide. Nonetheless, other CWs configurations should be explored and studied, particularly the French CWs (VSFCWs in series), since this is expected to have a lower area requirement. Table 6.7 summarises the recommended components for hybrid CWs based on the design of Bayawan City.

After having the conceptual design (Step 2), the required area can be checked with the suitable map generated in Step 1. If there is not enough footprint area for the CWs, additional treatment would be needed, and technical consultations from experts (from NGOs or state universities) would be beneficial to provide options, and any changes should be documented. Otherwise, if there is an available area, the production of a detailed design could start. It is almost always the case that the vegetation and filter media would not be the limiting factor for the CWs design, except for cost consideration, particularly for the filter materials used. The detailed design

Table 6.7 Recommendations for CWs conceptual design based on Bayawan City, Philippines hybrid CWs system

Component	Description
Surface area	(i) 0.1 $m^3/m^2/d$ (HSFCWs) and 0.2 $m^3/m^2/d$ (VSFCWs) for hybrid CWs—Bayawan City (2022) for 185 m^3/d (750 households) with 1900 m^2 VSFCWs and 900 m^2 HSFCWs (ii) 0.02–0.3 $m^3/m^2/d$ (David et al. 2022)—to avoid clogging and to ensure enough contact time for treatment)
Vegetation	(i) Checklist: – Grow in natural wetlands or riverbanks – Local, indigenous species – Can tolerate acidic pH – Deep-rooted and strong rhizome/root system – High biomass or stem densities – Has ultimate use (such as animal feed, handicrafts) (ii) Commonly used vegetation: – Vetiver – Napier – *Phragmites karka* (currently used in Bayawan City) – *Phragmites australis* (common reed)
Filter Media	(i) Used in layers or combination: – Soil – Sand – Gravel – Organic materials such as mussel or oyster shell (ii) Depth depends on the rooting depth of the vegetation and its replacement (root depth in a year if vegetation is annually replaced)
Other design considerations	(i) High-density polyethylene (HDPE) liners—additional protection from a leak when the integrity of the concrete base of CWs breaks (ii) Pre-treatment or primary treatment before CWs—for the case of Bayawan, the septage will go through the anaerobic baffled reactor (ABR) before the VSFCWs (iii) Use of pumps and header tanks to distribute the wastewater at the top of VSFCWs (iv) Storage area for the effluent for monitoring and reuse purposes (irrigation of non-edible plants, firefighting, and construction purposes)

of the Bayawan City CWs can be found on the APN project website (https://doi.org/10.30852/p.18686), which can be used as a guide in providing the needed information for the design of CWs. Further, some photos and details of their CW design can be found as well in Jegatheesan et al. (2023) and Velasco et al. (2022).

6.3.3 Impact Assessments and Approval from Relevant Departments (Steps 5–6)

In the Philippines, any projects involving government funds and/or the public and environment before construction would require an Environmental Impact Assessment (EIA). The EIA would ensure that all the concerned stakeholders will

Table 6.8 Other related environmental permits and issuing agency in the Philippines

Environmental permit	Issuing agency
Compatibility with the Existing Land Use	LGU
Proof of Authority over the Project Site	Land Owner
Water Rights Permit	National Water Resources Board (NWRB)
Permit to Operate—Air Pollution Source Equipment	DENR-EMB
Discharge Permit	DENR-EMB
Permit to Cut/Ball Out Trees	DENR-EMB
ROW Permit	Land Owner
Hazardous Waste Registration	DENR-EMB

be involved in the execution of the project at the earliest stage possible. Further, EIA is one of the requirements for the Environmental Compliance Certificate (ECC), one of the environmental clearances needed before project construction. On the other hand, DENR-EMB classifies projects as significantly environmentally critical or not based on EMB Memo Circular No. 2014-005. The CWs project is considered under Category B, but would only need to provide an Initial Environmental Examination (IEE) checklist, a smaller study than an EIA. Only the IEE will be required if the volume to be treated is between 30 and 5000 m^3 (if <30 m^3, no ECC is required, if >5000 m^3, EIA is required for ECC). Aside from the ECC, other environmental permits would be required, as shown in Table 6.8.

Aside from these environmental permits, social acceptability, economic, and financial assessments should also be provided to ensure the CWs' sustainability. The details for the social and economic assessments for CWs are discussed in Chaps. 4 and 5, respectively. Community engagement is highlighted in these chapters as well.

6.3.4 Implementation of CWs (Steps 7 to 10)

Once the environmental, social, and economic assessments are successful, the construction of the CWs can proceed. Like any wastewater treatment facility, a commissioning of one year should be done to evaluate the performance of the CWs system before the actual operation. If it is proven that the CWs system works efficiently and effectively after commissioning, the full operation of the system can commence. Wastewater Discharge Permit should be applied yearly (online through the EMB website). The sample worksheet shown in Fig. 6.4 can also be used to assist in the personal assessment of CWs for continuous monitoring and research. If the CWs system fails within the commissioning period, the system should be reevaluated, particularly the hydraulics part. Further, if issues are not identified, it is highly recommended to seek the assistance of experts from NGOs and universities, and any changes should be documented.

The operation and maintenance of the CWs can be patterned from the Bayawan City CWs Manual (uploaded in the APN project website: https://doi.org/10.30852/p.18686). Troubleshooting of some common problems they have encountered with their CWs system is also provided in the manual. It is highly recommended that the nearby communities be involved in the construction, operation, and maintenance of the CWs system, particularly since the technical requirement in implementing CWs is not that complicated compared with other conventional wastewater treatment technologies.

6.3.5 Continuous Monitoring and Research (Step 11)

The inclusion of continuous monitoring and research is the recommendation of the stakeholders during the consultative meeting. Thus, the end of the framework should be open-ended and not "END". Aside from monitoring the technical soundness of CWs (in terms of water quality assessment), their impact on the public and the environment should also be quantified.

For the impact assessment, the framework for assessing the benefits of implemented NbS developed by Watkin et al. (2019) can be adapted (Jegatheesan et al. 2023). In the selection of benefits of an NbS intervention, Watkin et al. (2019) categorised the impacts into three components: water, nature, and people. This chapter only focuses on water-related indicators. Thus, the impacts to be considered revolve around surface and groundwater quality and water storage and reuse. Nevertheless, these indicators can only be analysed if pertinent data are available to evaluate the impact of an NbS. For each indicator, performance is determined by specific equations that utilise the available data, providing a numerical value for its impacts. The equations used in the evaluation of CWs compare variables between a case study region with an NbS and a comparative area without the NbS or a case study area before the NbS was implemented. Moreover, standards values or literature values, as well as other case study areas with exceptional results, can also be used in comparison to an area of study in assessing the impact of implementing an NbS. Hence, the gravity of the indicators may be assessed through these values and evaluated how greatly the impacts vary upon the implementation of the NbS (Watkin et al. 2019). Table 6.9 summarises the quantitative impact assessment of the mentioned indicators of CWs. As mentioned, this assessment only includes the impact of CWs on water. Other impact assessments that can be added are the socio-economic and ecological aspects.

Overall, CWs can have a beneficial or negative impact on the environment. In comparing two study areas with and without CWs, the impact score in one area must be substantially greater than the other area without CWs to obtain a high-value impact. On the other hand, indicators that are similar or the same for two areas of study indicate no variances in indicators or CWs benefits. Meanwhile, if standard values are used for the comparison, a high value will be obtained if the value in the area of study is close to considered exceptional values from the literature or other

Table 6.9 Impact assessment of CWs for water (Watkin et al. 2019)

Indicator	Equation
Effluent and groundwater quality	$W_1 = 100\ [(W_{i,R} - W_{i,A})\ /\ W_{i,R}]$ W_1—water quality pollutant concentration (units may vary) i—individual pollutant R—raw wastewater concentration (influent to CWs) A—treated wastewater concentration (effluent from CWs)
Water storage and reuse for irrigation (following the Department of Agriculture Administrative Order No. 2007–26)	$W_2 = 100$ W W_2—impact of CWs on water storage and reuse (%) W—is the time duration that irrigation needs were met by CWs (# days/365)
Groundwater recharge	$W_3 = 100\ [(R_a - R_b)/R_a]$ W_3—quantitative impact of CWs on groundwater recharge R_a—average recharge in Area A with CWs (metres/year) R_b—average recharge in Area B without CWs (metres/year)

case studies, which means that the impact of CWs is highly beneficial as it lives up to these given standards. Generally, the higher the value of each indicator, the greater the advantage in that area will be, and thus, a more evident impact of the intervention.

For the next step of the analysis, each indicator value that is calculated is converted to a corresponding value, for instance, if $W \leq 20\%$ = score is 1.0; if $20\% < W < 80\%$ = score is between 2.0 and 4.0; and if $W \geq 80\%$ = score is 5.0. The average of all the indicator scores is used to determine the CWs' grades. Further, if the stakeholders believe some indicators are more valuable than others, assigning weights to the indicator scores is optional. However, stakeholders should develop weighted criteria based on the value of each indicator's contribution to the community. After all the scores from the various indicators have been weighted, averaged, and combined to produce a single numerical number, the CWs' grade consolidates all of the impacts considered (Watkin et al. 2019). The assessment outcome will be CWs' grade particular to the case study, with grades ranging from 0 to 5, with 1 indicating little to no benefits, while a value of 5 suggests multiple advantages. Table 6.10 gives a complete description of each CWs grade for each corresponding score.

After conclusions of the performance and impacts of the CWs have been established, the analysis is to be finished by making appropriate recommendations for all the chosen indicators, particularly those that resulted in low scores. These recommendations can further improve the assessment of its impacts through instructions on how to involve stakeholders better, monitor, gather, and analyse data, and track the benefits of CWs to ensure that they continue to be beneficial in the future, maximising their potential. After all, the main goal for the entire assessment framework is to improve and develop a more efficient system for wastewater treatment, particularly to promote sustainability for the protection of the environment.

Regarding further research, the recent review paper of Vymazal et al. (2021) provided a comprehensive recent research perspective for CWs treating various

Table 6.10 CWs grading system (Watkin et al. 2019)

CWs grade	Description	Grade number
Very poor	CWs do not provide any benefits; re-evaluation is necessary	0-1
Poor	CWs provide very few benefits; improvements may be required; re-evaluation may be necessary	1-2
Good	CWs provide some added benefits; some improvements may be required	2-3
Very Good	CWs provide added benefits; minor improvements may be required	3-4
Excellent	CWs provide at least 80% more benefits; continue with regular maintenance.	4-5

Table 6.11 Recent research perspective for CWs (Vymazal et al. 2021)

General topic	Research perspective
Wastewater source and types	Removal efficiency treating wastewater from various industrial sectors, such as glass and aluminium production, dyes, pulp and paper, and emerging pollutants, such as pharmaceuticals, personal care product, pesticides, food additives, abusive drugs, fire retardants, nanoparticles, and cyanotoxins
Filter media	Use of waste materials, such as bricks, rice husk, wood chips, oyster shells, rubber, plastic pipes, water bottles
Vegetation	Comparison of different species or their combination, particularly on their performance on nutrient removal, ultimate use (circular economy), biomass accumulation
Floating wetlands	Long-term performance analysis, economic analysis, particularly on biomass harvesting, suitability of various macrophyte species
Microbiology	Relationship of microbial composition with other factors such as vegetation species, wastewater type, filter materials, use of aeration
Greenhouse gas emission	Factor affecting high amounts of nitrous oxide emissions (such as vegetation and configuration of CWs) and their mitigations
Benefits	Economic analysis or life cycle analysis of the biomass for energy source, the potential for biodiversity conservation with economic value, ultimate effect as carbon sink or source
Sustainability	Integration of microbial fuel cells to CWs for electricity generation, stable long-term performance, evaluation as green infrastructure in urban environment, role in sponge cities, circular economy analysis, reuse of effluent for irrigation

types of wastewater. These are summarised in Table 6.11. The paper also highlighted that studies on pilot- or large-scale CWs systems to evaluate their long-term performance are highly relevant to improving the utilisation of CWs for wastewater treatment.

6.4 Conclusion

NbS are sustainable wastewater treatment approaches that address traditional treatment technologies' highly technical and costly requirements. One such solution includes CWs. However, CWs remain underutilised in the Philippines as a wastewater treatment technology partly due to the lack of a technical reference for its design and continuous usage. This chapter addresses this gap by developing an integrated framework to guide local stakeholders and government agencies in the Philippines in establishing and operating CWs for wastewater treatment. The integrated assessment framework was developed by incorporating the best practices of Bayawan City LGU in Negros Oriental, Philippines, from using hybrid CWs. Specifically, the framework covers new and existing CWs, which is divided into five major steps: (1) site survey to determine the necessary type and suitable location of CWs; (2) conceptual and detailed design, where the required dimensions, vegetation, and substrate, among other design requirements, are established; (3) assessment of the CWs' environmental, social, and economic impact and compliance with government permits; (4) construction and initial assessment of the facility's performance; and (5) operation and continuous monitoring of the CWs' performance using appropriate indicators or similar benchmark area. The integrated assessment framework was developed with consultative meetings with representatives from national government agencies, private institutions, academe, and other civil society organisations. To further improve the guide, it should be tested on other pilot- and large-scale CWs in the Philippines. Moreover, translating the guide into a user-friendly and open-access toolkit would efficiently replicate and upscale the CWs, particularly for domestic wastewater treatment in the country. This work hopes to contribute to the current global effort of lessening the effects of climate change at the communal level by applying sustainable water treatment technology.

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Chapter 7
Guide to Green Roofs for Wastewater Treatment: A Vietnam Perspective

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Abstract Green roofs can be defined as "contained" green spaces on top of artificial structures and are considered a nature-based solution to prevent several environmental and socio-economic problems associated with urban sprawl and climate change. A green roof system contains a high-quality waterproofing membrane and root barrier system, a drainage system, filter fabric, a lightweight growing medium, and plants. Green roof systems can be modular layered systems already prepared in trays, including drainage layers, growing media, and plants, or each component of the system can be installed separately on top of the structure. With its inherent strengths, green roofs have been applied more and more widely in urban areas. This chapter shows significant information such as basic elements, pollutant removal mechanisms, and benefits associated with green roofs, as well as offer technical

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instructions to install a green roof system and operation and maintenance procedures that ensure the longevity of the system. Using this guide, the users know how to select the type of plant, prepare materials, etc., to install a green roof system. Besides, the users also get a more comprehensive understanding of implementation and maintenance issues.

Keywords Charcoal · Green roof · Growing media · Nature-based solution · Oyster shells · Vernonia elliptica · Trumpet vine

7.1 Introduction

Green roof is one of the innovative architectural and urban development options based on sustainable development concepts that can be utilized to increase urban green areas, improve environmental quality, and generate sustainable urban development. Additionally, green roof improves building insulation, lowering heating and cooling costs and resulting in cost savings. The structure of green roof system is entirely or partially covered by vegetation and has multiple layers such as waterproofing, drainage, insulation, plant growth, and active plant layers (Shafique et al. 2018). The main components of the proposed green roof system have been illustrated in Fig. 7.1. Green roofs are classified into extensive, intense, and semi-intensive (Fig. 7.2). The differences between these types are designs of vegetation layer. Extensive green roofs are simpler, lighter, and thinner (depth of 60-200 mm) and are usually planted primarily with moss, herbs, and grass. While intensive green roofs have a depth of 150–400 mm and are planted with shrubs and trees (Fernandez-Cañero et al. 2013).

Green roof is a technique that benefits the environment by optimizing energy use, absorption of air pollutants, runoff regulation, controlling the heat island effect, and enhancement of urban ecology. Green roof flora minimizes building heat absorption by reflecting or deflecting solar radiation and evapotranspiration. The

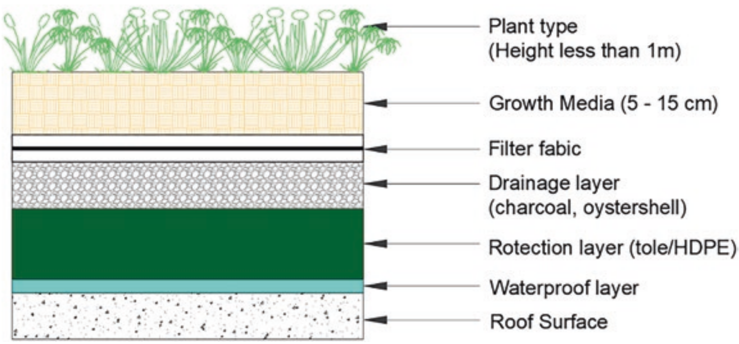

Fig. 7.1 Components of green roof system

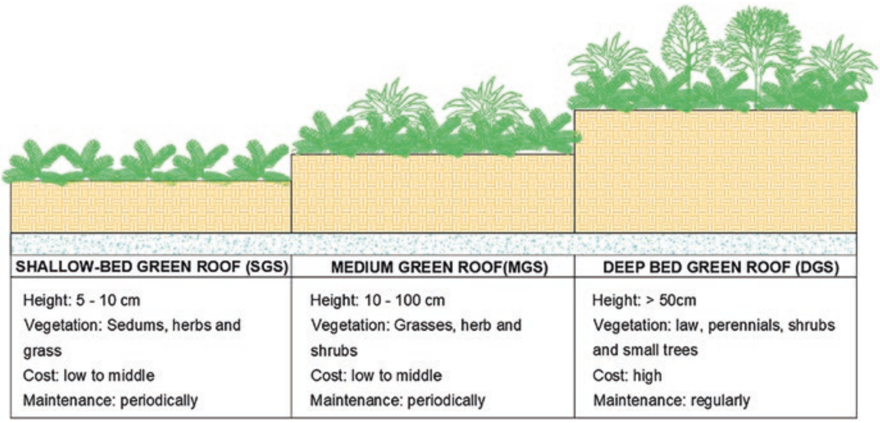

Fig. 7.2 Types of Green roof

growing substrate works as a physical barrier to control proximal temperature and as many drainage layers to keep moisture in the plant. Green roofs with varying substrate depths, drainage networks, and plants function as urban ecosystems on top of conventional roofs; as a result, additional layers are added to the roof surface for better insulation, preventing heat penetration into the building envelope and lowering ambient rooftop temperature. Apart from these benefits, green roofs do not require extra land beyond the building footprint because they are placed on otherwise empty roof space. Building roofs are estimated to cover 80% of impervious surfaces in metropolitan areas. The ability to construct green roofs on existing building roofs without the need to acquire new land area, in addition to their ability to significantly reduce runoff volume and decrease peak discharge, makes green roofs a valuable nature-based solution. They have the potential to absorb hazardous fine dust particles from the air, which can aid in human comfort in heavily developed metropolitan areas. In metropolitan regions, the air generally contains small dust particles, which makes the urban environment unpleasant. Green roofs serve to mitigate air pollution in two ways. To begin, the plants collect tiny air contaminants via stomata. The annual average concentrations of fine particles in the world are measured at 30–55 g/m^3 (PM2.5) and 5–33 g/m^3 (PM10) (Jurado et al. 2023). According to Speak et al. (2012), a green roof with a 19 ha area could eliminate up to 230 tons of PM 2.5 and PM10. This technology also demonstrates that green roofs can assist in decreasing habitat loss in urban settings. Green roofs also encourage urban leisure activities. It encourages animals by enabling them to congregate in green spaces. It aims to convert impermeable surface areas into natural green spaces, which can provide significant environmental advantages in metropolitan settings. Green roofs have a pleasant impact on city dwellers by minimizing air and noise pollution. Green open areas catch the eye and have attempted to bring people together for roof gardening. Green roofs also increase the value of a home. Green roofs can also provide potential for urban agriculture. They can grow many veggies and make civilization self-sufficient in food production: irrigated tomatoes, green beans, cucumbers, peppers, basil, and chives for green roof food production.

Green roof systems have been widely employed nowadays owing to their ecological and economic benefits. A benefit–cost analysis incorporating a social dimension, on the other hand, is still lacking. Thus, quantifiable estimations of their costs and benefits are required to encourage the application of green technologies for sustainable development. The investment costs are determined by a variety of factors, including location, labor costs, green roof type and material, and so on. It is commonly assumed that a green roof does not require frequent irrigation or fertilizer; nevertheless, for the best advantages in drought conditions, watering and fertilization are required. These roofs must also be properly and regularly maintained in terms of plant growth, drainage, and substrate in the systems to extend the used time. In addition, when the installation of green roof systems is improper, there is a great risk of roof leakage and structural failure. As a result, adequate studies should be conducted on various components of green roofs (e.g., weight and storage capacity) to minimize leaks and adverse impacts on structures such as seepage walls and decay walls.

7.2 Instruction for Installing Green Roof Systems

7.2.1 Preparation of Materials

Material layers that support plant growth are considered one of the most important design parameters due to their strong impact on the performance of green roofs in terms of vegetation, physical and biochemical processes, hydrodynamics, wastewater treatment, and other functions. The porous media act as pollutant adsorbents and provide an environment for macrophytes to grow. Soil, sand, and gravel have been commonly used for green roofs; besides, some other materials, as shown in Table 7.1, can be considered. Materials applied in green roofs must be high performance (e.g., lighter, high absorption capacity, long life).

Table 7.1 Characteristics of media used in green roof systems

Medium	Diameter (mm)	Density (kg/m^3)	Porosity (%)	References
Cobble	80–100	270	49	Sheng et al. (2007)
Oyster shell	200–500	250	88	Li et al. (2010)
Coconut Shell	10–20	600–800	15–25	Parjane and Sane (2011)
Charcoal	9–10	180–220	38	Vo et al. (2018)
Ceramsite	8-15	1130-1150	50-60	Cheng et al. (2014)
Mussel shell	90–140	2620	87–89	Geng et al. (2022)

7.2.2 *Plant layers*

Plants, or macrophytes, cover the material layer's surface and create a green space. The root system of the plant may help with physical filtration, avoid clogging, absorb nutrients and metals, and serve as media for microorganisms that are linked to it. It has been demonstrated that plants have a substantial impact on how green roof systems remediate pollutants.

According to Table 7.2, the mentioned plant species suitable for green roofs should have the following characteristics: easy to grow, thriving in harsh conditions (rain/storm in winter and high temperature in summer), capable of treating wastewater, having a long life, and good coverage (green area).

Table 7.2 Characteristics of selected plants

Names	Characteristics
Vernonia elliptica	
	• Perennials, vines, climbers, grown for foliage, evergreen. • Height of plants: 60–120 cm. • Length of leaves: 6–10 cm long. • Density: 46 plants/m^2.
Campsis radicans	
	• High-climbing, aggressively colonizing woody vine. • Fairly heat, cold, drought tolerance, no serious insect or diseases. • Height range from 6 to 12 m, flowers can grow up to 8 cm long; leaves grow up to 10 cm in length. • Density: 28 plants/m^2.
Tristellateia australasiae	
	• Climber, vine and liana. • Fast-growing for fences, pergolas, trellises, and vertical greening of buildings. • Be trained as ground cover; suitable for gardens, parks, or roadsides.
Hedera helix	
	• Evergreen perennial climbing vine that attaches to bark of trees, brickwork, and other surfaces by root-like structures that exude a glue-like substance to aid in adherence.

7.2.3 Design Parameters

The selection of acceptable plant species and substrates as growing materials, the evaluation of the best hydraulic parameters, and the establishment of optimum operating conditions all contribute to the optimization of the removal processes in natural-based solutions. It is crucial to determine the best design parameters for green roofs in order to achieve high levels of pollutants removal while making optimum use of the available space. However, high hydraulic loading rate (HLR) values, on the other hand, speed up filtration and will slow down hydraulic retention time (HRT), which will reduce the amount of time the wastewater will be in contact with the microbial biofilm and plant roots. So, it is anticipated that the removal of pollutants will be reduced by excessive HLR (especially with the pollutants that are more easily washed out). Table 7.3 lists the key parameters for each study in terms of substrate, plants, and operational factors (HLR, organic loading rate (OLR), and HRT), differentiating between pilot and laboratory studies. Thereby, the optimal design value for HLR is in the range of 1.6–5.0 $m^3/m^2/d$ and OLR is 480–1500 $gCOD/m^2/d$.

Table 7.3 Design parameters of a green roof system

Size	Area (m^2)	Media	Design parameters			References
			HLR ($m^3/m^2/d$)	OLR ($gCOD/m^2/d$)	HRT (h)	
Pilot-scale		Soil, sand, small rock	2.60–4.00	300–600	23–30	Vo et al. (2018)
Pilot-scale		Soil, sand, small rock	3.40	490	NA	Van et al. (2015)
Pilot-scale	0.72	Clay, coco coir; sand	1.00	60	0.2–0.7	Masi et al. (2016)
Pilot-scale		Sand, organic soil, LECA, PLA	1.60	120	91.2	Zapater-Pereyra et al. (2016)
Lab-scale	3.50	Sand, coarse sand, gravel	0.05–0.11	5.7–15.4	96–48	Fowdar et al.(2017)
Pilot-scale	2.64	Sand	–	10.2	24	Chowdhury and Abaya (2018)
Pilot-scale	2.50	Soil, sand, rocks, gravel	2.47–4.03	210–280	NA	Vo et al. (2018)
Pilot-scale	1.08	Charcoal, oyster shell, Gravel	1.60–5.00	480–1500	72–24	In case study at HCMUT (Vietnam), 2021

7.2.4 A Case Study in Ho Chi Minh City

7.2.4.1 Design Parameters

Two pilot-scale green roof systems are located on the roof of a building at Ho Chi Minh City University of Technology (10°46′31.3″N, 106°39′35.2″E). Therefore, green roofs are exposed to fully natural tropical conditions such as rain, sunlight, and wind. Each system consists of two modules with the same dimension of 1800 × 300 × 170 mm (length × width × height) (Fig. 7.3). The media in a module were arranged as follows: a charcoal layer (length × width × height = 1680 × 300 × 80 mm) on the top and an oyster shell layer (length × width × height = 1680 × 300 × 40 mm) on the bottom. The mass density of charcoal and oyster shells used in this study was 323 and 476 kg/m^{3,} corresponding to the weight in each module of 13.0 and 9.6 kg. Additionally, the module was allocated marginally with layers of rock 1 × 2 inch on either vertical side, which are equal in size (length × width × height = 300 × 60 × 120 mm). *Vernonia elliptica* and *Campsis radicans* were planted in two separate green roof systems with densities of 55 and 37 plants/m^2 and an average initial height of 70 cm.

7.2.4.2 Instruction for installing the green roofs

The installation process of the system is shown in Fig. 7.4. Details are as described below:

Step 1. Select charcoal and oyster shells and wash and dry them

– Caculate the volume of charcoal and oyster shells required.
– Carry out the preliminary processing: rinse with clean water to remove the dirt from the charcoal and oyster shells. Then let them dry out in the sun.
– Weigh to determine the dry weight of charcoal and oyster shells to be placed into the system.

Step 2. Plant selection. Wash the soil and put the plant in a pot to be adapted to tap water.

Selected plants are brought back from the field or a nursery, and the soil from the root is removed. Wash the roots with clean water and then put them in a pot in order to be adapted to the water environment for about 1–2 days before putting them into the green roof system.

Step 3. Installation of the tray, pump, pipe, and electrical systems.

– Install pipes that connected the inlet tank, wastewater pump, and modules.
– Install the electrical system to operate the pump.

Step 4. Adding oyster shell to the tray

– Calculate the weight of oyster shells that need to be put into the system.
– Weigh and place the oyster shells into the green roof system to the required height.

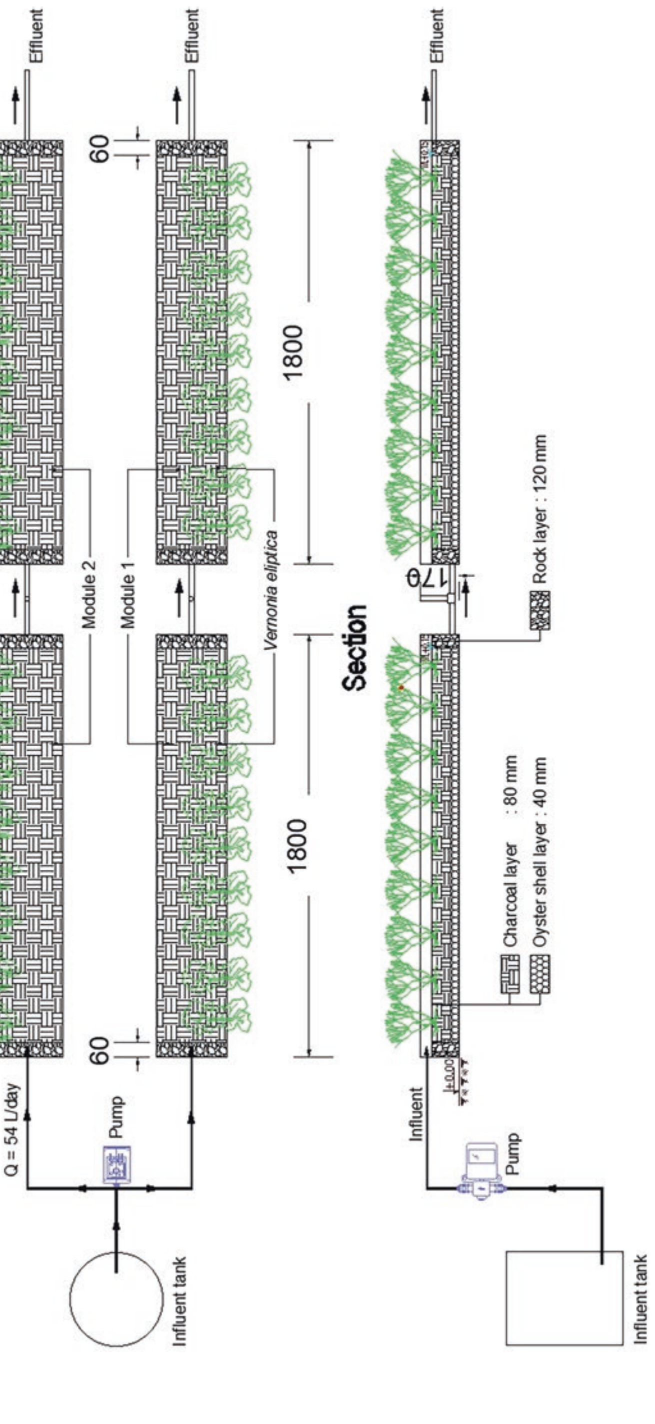

Fig. 7.3 Schematic diagram of the green roof system

Fig. 7.4 Green roof system installation process

Step 5. Adding charcoal to the tray

- Calculate the weight of charcoal that needs to be put into the system.
- Weight and place the charcoal on top of the oyster shell layer to the required height.

Step 6. Adding rocks to the tray

- Calculate the weight of rock that is needed to be placed into the system.
- Place the rocks on both ends of each module to the specific height.

Step 7. Adding plants in the green roof system

- Place the plants in the tank at a specified density. The distance between the two plants is about 20 cm.
- After stabilizing, turn on the pump to bring the wastewater to the system with the calculated flow rate.

Figure 7.5 shows the green roof systems after installing completely.

7.2.4.3 Experiment Set-up

The green roof systems were operated under the conditions shown in Table 7.4. Besides, Table 7.5 shows the water quality of the influent and effluent of the systems.

Fig. 7.5 Green roof systems at Ho Chi Minh University of Technology

Table 7.4 Operational condition of green roof system

Stages	HLR ($m^3/m^2/$day)	OLR (gCOD/m^2/d)	HRT (h)	Q (L/d)	Biomass growth (g/d)	
					Wet biomass	Dry biomass
Adaption	0.9	20	144	14	4.43[a] 0.29[b]	1.02[a] 0.13[b]
HLR1	1.6	115	72	17	8.69[a] 0.82[b]	2.10[a] 0.13[b]
HLR2	5.0	345	24	54	11.65[a] 1.65[b]	2.10[a] 0.27[b]

Note: a: *Vernonia elliptica*; b: *Campsis radicans*

Table 7.5 Characteristics of influent and effluent of green roof system

No.	Parameters	Unit	Concentration (Mean ± SD)	
			Influent	Effluent
1	pH	–	6.8 ± 0.2	7.2 ± 0.4
2	Turbidity	NTU	46 ± 15	3.0 ± 2.0
3	TSS	mg/L	52 ± 14	5.0 ± 2.0
4	COD	mg/L	335 ± 35	30 ± 13
5	NH_4^+-N	mg/L	21 ± 12	3.0 ± 0.8
6	TP	mg/L	2.0 ± 0.8	1.0 ± 0.4

7.3 Operation and Maintenance

Everyone involved in a green roof project benefits from routine upkeep. The achievement of the designer's objective, maximizing the ecosystem services offered by the roof, and safeguarding the owner's investment all depend on it. A green roof can be made to require little upkeep, but this is uncommon. Failure to manage a green roof will frequently conceal issues that eventually have unforeseen effects, which may include the death of the majority or all targeted plants. That might nullify any warranties that still apply. Regular maintenance will increase the lifespan of the roofing materials, lessen the frequency and severity of leaks, and lower ownership costs in addition to supporting healthy plants.

7.3.1 Operational Protocols

7.3.1.1 Starting Up of the System

The domestic wastewater is collected and transferred to an influent tank with a volume of 80 L before being pumped into the green roof system through two separate lines. After about 2 months, when the plants had grown up, pruning and collection of pruned biomass was carried out. Replacement of new plants is not required unless the plants have not grown well or died.

7.3.1.2 Operational Parameters

For the influent wastewater of the green roof system, many researches with different operational parameters have been conducted, and Table 7.6 shows the allowable ranges of those parameters.

Besides those water parameters, regularly monitoring cleaning of the system and measuring parameters to see if they are consistent with the indicators stated on the

Table 7.6 Some operational parameters of green roof and wetland roof systems

Type	Operational parameters				References
	HLR (m^3/ha/d)	OLR (kg/ha/d)	NLR (kg TN/ha/d)	HRT (h)	
GR	160–500	48	–	76.8–240	In the case study at HCMUT (Vietnam), 2021
WR	260–400	30–60	15–39	23–30	Vo et al. (2018)
WR	340	36	21	18	Thanh et al. (2014)
WR	340	49	22.5	–	Van et al. (2015)
WR	160	12	5	91.2	Zapater-Pereyra et al. (2016)
WR	247–403	21–28	9–13	–	Vo et al. (2018)

equipment label or not (2 times a week) in order to promptly detect possible causes that could lead to broken equipment and other parameters such as current, voltage, insulation, and noise also need to be recorded for evaluation.

– The noise level for devices submerged in liquid is 70 dB. For equipment installed on open surfaces, the noise level should not exceed 80 dB.
– Allowable insulation for electrical equipment in low voltage grid is <1 MΩ.
– The allowable voltage rise should not exceed 10% of the voltage stated on the equipment label and the voltage drop should not exceed 2A/100 V.
– The current should not exceed the current indicated on the label of the equipment.

7.3.2 Maintenance

Maintenance considerations should be incorporated into the design process of the green roof system, with emphasis placed on identifying potential maintenance issues early on. Maintenance personnel must be prepared to conduct regular inspections and understand that green roofs require a different approach than traditional grade-level landscapes. It is important to maintain a balance between the health of the growing media and the plants to ensure the longevity and effectiveness of the green roof system.

7.3.2.1 Equipment Maintenance

To ensure proper operation of the machine, it is important to check that the input power supply voltage matches the rated voltage of the machine. Regularly cleaning the suction and discharge nozzles is also crucial, as these areas are prone to becoming dirty or blocked, potentially causing the pump head to malfunction. If the water does not flow properly, it may be due to a loose suction head, allowing air to enter and prevent water flow. In such cases, the air release button can be turned by hand to discharge the air and then screwed back on. It is important to avoid exceeding the allowed flow limit by adjusting the flow control knob, as excess tightening may cause damage to the machine. Regular cleaning of the equipment is also recommended to ensure optimal cooling and heat dissipation. Table 7.7 shows some pump failures and solutions to fix them.

7.3.2.2 Caring Plants and Harvesting Biomass

To ensure the optimal growth of plants on the green roof system and maintain its aesthetic appeal, regular care and periodic pruning is necessary. Weeds should be cleared from the system every two months to promote the growth of the plants. Dead plants should be replaced with new ones. Trimming the plants and clearing weeds will require using ladders or chairs to climb to the roof, so it’s important to

Table 7.7 Some common pump failures and remedies

No.	Problem	Causal	Solutions
01	Pump is not working (not rotating)	There is no incoming power supply	Check the power supply, power cable
02	The pump is working but there is a rattling noise	The power source loses phase to the motor Impeller is clogged with hard objects The gear box is missing oil, grease, and possible wear Large foreign objects are trapped into the pump chamber or screw	Check and repair the power supply Remove rigid objects from the impeller Check and add, or change new oil Check for cleanliness
03	The pump works but does not pump the water	Reverse rotation The opening and closing valve is clogged, or damaged The pipe is clogged; Haven't opened the valve yet Tearing of pump diaphragm	Reverse rotation Check for damage and fix it, if damaged, replace the valve with a new one Check for any head loss and repair it Open valve Other changes
04	Pump flow is reduced	Stuck in the impeller, valve, pipeline The water level has dried up The power supply is incorrect Deteriorated equipment	Check and solve again Turn off now Check the power supply Wash and clean with soap or special solution

exercise caution to avoid damaging the plants' root system and to prevent falls (Fig. 7.6).

Remarks: The operation and maintenance processes must be recorded in the equipment monitoring table and equipment history (date of maintenance, number of times the maintenance is carried out, what accessories have been changed, and include their specifications for the ease of follow-up maintenance).

7.3.2.3 Troubleshooting

The purpose of this section is to present a quick guide to the operator in the event of problems and to provide solutions. To fix a problem, one must first understand the system well. Operators need to know the following in order to troubleshoot:

- The role of each part in the system.
- Principles of the processes in the system.
- Unusual factors and phenomena and ability to identify them.
- Options available when a fault occurs.

In essence, to recognize when an abnormal condition arises, it is crucial to understand how the process functions under normal circumstances. Table 7.8 shows some problems in a green roof system.

Fig. 7.6 Taking care and pruning the green roof system

Table 7.8 Some problems that could occur in a green roof system, their causes, and possible solutions

Problem	Cause	Check or monitoring	Solution
No water in the inlet manifold	Pump is turned off/broken	Pipe is clogged/broken	Clean pipes/remove broken pipes and replace with new pipes
Increase in pollutant concentration at the outlet	Hydraulic loading is too high (overload)	Flow rate	Reduce flow rate
Overgrowth of algae	Low coverage of plant Low hydraulic load	Plant density Flow rate	Increase plant density Intercropping with other crops Increase the flow rate
Yellow leaves, slow growth	Low pH Lack of nutrition	pH adjustment Adjust the water inlet distribution line	Adjust the pH at the inlet stream by adding $NaHCO_3$ Install additional water distribution pipes from the start to the end of the tank
No effluent	Turned off/broken	Pipe is clogged/broken	Unclog/unblock Replace the new pipe

To ensure effective green roof maintenance, it is recommended to plan preventive maintenance visits rather than reactive ones. This requires a sound understanding of plant physiology and weed life cycles. Along with addressing common roof problems, the maintenance crew should inspect the waterproofing and other components to ensure their proper functioning. Optimal plant establishment during the first year or two can greatly reduce the long-term maintenance required for extensive roofs, unless a pre-vegetated installation method is employed. A well-designed program should be developed that includes plant establishment and ongoing maintenance requirements.

7.4 Conclusions

This chapter presents comprehensive guidelines for the construction, installation, and maintenance of green roof systems designed to treat septic tank effluents originating from households, institutions, and various facilities. Notably, these green roof systems offer a cost-effective solution with a small footprint, making them an economically viable choice. The replication of such systems carries the potential to mitigate the long-standing issue of septic tank effluent discharge into canals—a prevalent problem in numerous countries. This not only promises substantial improvements in canal water quality but also stands to enhance the overall well-being of nearby communities and bolster biodiversity by fostering healthier aquatic ecosystems. To fully realize these benefits, future endeavors must address several critical aspects, including (i) establishment of governance structures and policies tailored to the application of green roof systems in diverse settings, (ii) cultivation of awareness and community engagement, along with mechanisms for financial participation, (iii) retrofitting of existing septic tanks to divert effluents toward green roof systems, and (iv) design and integration of novel sanitation solutions within buildings, enabling the collection and distribution of wastewater to these green roof systems. By addressing these key elements, we can harness the potential of green roof systems as a sustainable and ecologically sound nature-based solution to wastewater treatment in urban environments.

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Chapter 8
Guide to Floating Treatment Wetlands—A Sri Lankan Perspective

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Abstract Constructed floating wetlands (CFWs) are gaining popularity as a low-cost, sustainable solution for water quality management. CFWs are artificial marshland systems that utilise natural processes to treat wastewater, stormwater, and degraded water bodies. The technology promises to be a game-changer in the field of environmental protection as it effectively removes pollutants, minimises water wasting, and promotes biodiversity. This chapter examines CFWs implementation, including literature studies, design, social acceptance, operation, research and development, and maintenance of CFWs. The implementation process involves site selection, studies, design, permissions, CFWs installation, and management. The site selection process considers factors such as water quality, depth, and flow rate. The site selection process considers water quality, depth, and flow, whilst the design involves choosing vegetation and substrate. During installation, modules are positioned, and vegetation is planted. Once installed, the system is monitored to ensure

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efficient treatment of the target water quality parameters. Maintenance includes pruning, plant replacement, and substrate cleaning. The implementation of CFWs in an area offers numerous benefits, such as the removal of pollutants, reduction in water wastage, and promotion of biodiversity. Scalable, flexible solution for wastewater, stormwater, and urban/agricultural runoff. CFWs provide long-lasting water quality solutions through design, installation, and maintenance.

Keywords Constructed floating wetlands · Sri Lanka · Water quality management

8.1 Introduction

Constructed floating wetlands (CFWs) are artificial wetland ecosystems that are designed to improve water quality in lakes, ponds, and other bodies of water. They are constructed by floating a platform on the water surface, which supports plants and microorganisms that work together to remove pollutants from the water. Figure 8.1 illustrates the design of CFW, where the arrows indicate the wastewater flow.

CFWs use a combination of physical, chemical, and biological processes to improve water quality. The plants on the floating platform absorb pollutants such as nitrogen and phosphorus from water, which are then used for their growth. The roots of the plants also provide a substrate for beneficial bacteria that convert pollutants such as ammonia and nitrite into less harmful substances. The combination of these processes effectively reduces the levels of pollutants in the water. CFWs offer several benefits over traditional water treatment methods. They are cost-effective, require less energy, and are easy to install and maintain. Further, they provide additional benefits such as habitat for wildlife, aesthetic value, and educational opportunities.

CFWs can be designed to meet the specific needs of the local ecosystem. The plants used in the floating platform can be selected based on the water quality requirements and the local climate and environmental conditions. Native species are preferred, as they are better adapted to the local ecosystem and are more effective in improving water quality. CFWs are increasingly being used in urban areas to improve water quality in lakes and ponds. They can be installed in small or large bodies of water and can be designed to complement the surrounding landscape. By improving the water quality and enhancing the local ecosystem, CFWs contribute to the restoration and preservation of natural habitats in urban areas.

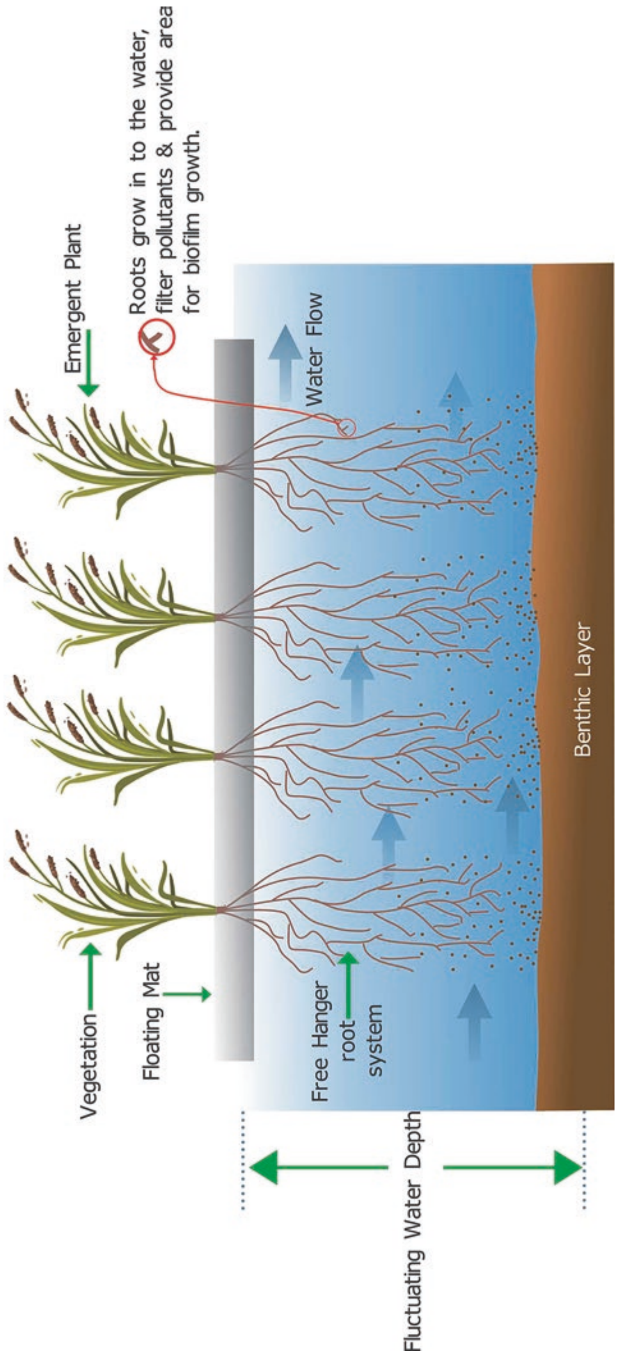

Fig. 8.1 Illustration of a CFW where arrows indicate the wastewater flow through the CFW

8.2 Selection of an Area for the Implementation of CFWs

Before the implementation of CFWs, the selection of a suitable lake or area is an important factor in the process. Figure 8.2 shows a process flow diagram for the implementation of CFWs. It can be accomplished by considering several factors, such as:

- ***Water Quality:*** The water quality of the lake should be assessed before implementing a constructed floating wetland. High nutrient levels, high sediment load, and excessive aquatic plant growth can negatively impact the performance of CFWs. The lake should have relatively low levels of pollutants and nutrient loads (Hudson and Wallis 1998).
- ***Size of the area:*** The size of the lake should be adequate to support a constructed floating wetland. It should also be feasible to cover a sufficient amount of area of the lake with the floating wetland to achieve the desired level of water quality improvement.

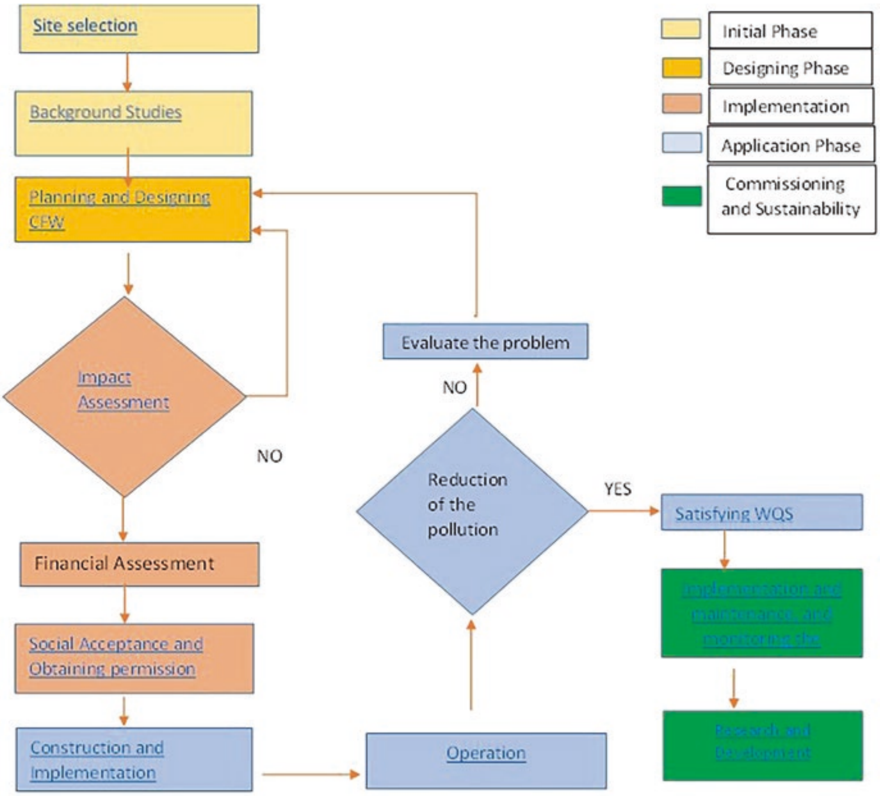

Fig. 8.2 Process flow diagram for the implementation of CFWs

- ***Depth of the Lake:*** The depth of the lake should be such that the bottom is within reach of the plants that will be used in the constructed floating wetland. Typically, CFWs are anchored in shallow water, 3–6 feet deep.
- ***Hydrology:*** The hydrology of the lake is an important factor when selecting a location. CFWs are more effective in lakes with limited water movement. The water current should not be too strong to dislodge the CFWs.
- ***Accessibility:*** The accessibility of the lake is important as the CFWs need to be installed, monitored, and maintained regularly. If the lake is in a remote location, the cost of installation and maintenance may increase significantly.
- ***Community Acceptance:*** Community acceptance is important when implementing a constructed floating wetland project. The project should be communicated effectively and transparently to the local community. Collaboration with local officials and stakeholders before the installation is crucial.
- ***Permits:*** Appropriate permits should be obtained before embarking on any constructed floating wetland project. This typically involves working with local, state, and federal agencies to acquire the necessary documentation for the installation and operation.

Any urban lake such as Kandy and Kurunegala lakes (Fig. 8.3) or suburban lake that is suitable for implementing CFWs should meet the above factors. The weighted score method can be used for the selection of an appropriate area, and the scores can be allocated according to the importance of the factor (see Table 8.1).

Scores and Weights can be given accordingly. For example, for Water Quality (WQ) if the scoring is Perfect = 0; Good = 1; Normal = 3; Bad = 4; and Worst = 5:

- If a particular lake has a bad level of WQ (i.e., Score is 4), then the lake has a weighted score value of 1.6.
- If a particular lake has a good level of WQ (i.e., Score is 1), then the lake has a weighted score value of 0.4.
- The weighted score value of 1.6 indicates a higher impact to select the lake as compared to the value of 0.4.

Fig. 8.3 Satellite images of Kurunegala (left) and Kandy (right) lakes (Source: Google Maps)

Table 8.1 Weighted Score Method for the selection of a suitable lake

Criteria	Weight	Score	Weighted score
Water quality	0.4		
Size of the lake	0.025		
Depth of the lake	0.2		
Hydrology	0.3		
Accessibility	0.025		
Community acceptance	0.025		
Permitting	0.025		
Total	**1.00**		

8.3 Background Studies

8.3.1 Water Quality Monitoring

Assessing the water quality of an urban lake is an important step in determining whether it is suitable for the implementation of CFWs (Hudson and Wallis 1998). Discussed below are the following steps that can be taken to assess the water. As an example, Fig. 8.4 shows the water quality monitoring activity at Beira Lake.

Step 1. Conduct a visual inspection: Look for signs that indicate poor water quality, such as trash, oil slicks, and algae blooms.

Step 2. Measure physical and chemical parameters: Measure physical and chemical parameters such as temperature, pH, dissolved oxygen, turbidity, nitrogen, phosphorus, and heavy metals. These parameters can give an indication of the overall water quality and the potential for supporting aquatic life and other purposes. Table 8.2 (Central Environmental Authority 2019) illustrates that Sri Lankan water quality standards for supporting aquatic life (Category C) and other purposes as mentioned below. Further, Table 8.3 shows the standard methods (APHA 2017) that are used to analyse various water quality parameters.

Step 3. Compare results against the water quality standards (WQS): The comparison of the results with the water quality standards set by the local regulatory agency may provide a better understanding of the overall water quality of an urban lake and whether it meets the requirements for supporting aquatic life and recreational activities.

***Step 4. Monitor water quality over time*:** Regular monitoring of the water quality over time can provide a better understanding of the seasonal changes and long-term trends in the water quality of an urban lake. Once established that the lake is polluted, CFWs can be constructed to reduce or remove the pollutants from the lake.

Fig. 8.4 Lake water quality monitoring at Beira Lake

Table 8.2 Water quality standard measurements (Central Environmental Authority 2019)

No.	Parameter	Unit	Category A	Category B	Category C	Category D	Category E	Category F
1	Colour	Pt mg/l, max	20	–	–	100	–	–
2	pH	–	6.0–8.5	6.0–9.0	6.0–8.5	6.0–9.0	6.0–8.5	5.5–9.0
3	DO at 250 °C	mg/l, minimum	6	5	5	4	3	3
4	BOD_5 at 20 °C	mg/l, max	3	4	4	5	12	15
5	COD	mg/l, max	10	10	15	30	–	40
6	NO_3-N	mg/l, max	10	10	10	10	–	10
7	PO_4-P	mg/l, max	0.7	0.7	0.4	0.7	–	–
8	Chloride (Cl)	mg/l, max	250	–	–	250	600	–
9	CN	mg/l, max	0.05	0.05	0.05	0.05	0.05	0.05
10	F	mg/l, max	1.5	–	–	1.5	–	–
12	B, total	µg/l, max	–	–	–	–	500	–

(continued)

Table 8.2 (continued)

No.	Parameter	Unit	Category A	Category B	Category C	Category D	Category E	Category F
13	Oil/grease	µg/l, max	100	–	100	100	–	300
14	Anionic surfactants as MBAS	µg/l, max	1000	1000	1000	1000	1000	1000
14	Total coliform	MPN/100 ml, max	10,000	10,000	–	10,000	–	–
16	Faecal coliform	MPN/100 ml	500 des 1000 max	500 des 1000 max	–	–	–	–

Notes: Category A shall be water that requires simple treatment, for drinking; Category B shall be bathing and contact recreational water; Category C shall be water suitable for aquatic life; Category D shall be water source that require to undergo general treatment process, for drinking; Category E shall be water suitable for irrigation and agricultural activities; Category F shall be water with minimum quality but does not fall into categories A–E

Table 8.3 Testing methods for various water quality parameters (APHA 2017)

Characteristics	Unit	Method of test
Biochemical oxygen demand (BOD)	mg/L	Incubation for 5 days at 20 °C (APHA 5210B)
Colour	Hazen units	Platinum cobalt colour scale (ASTM D1209)
Dissolved oxygen (DO)	mg/L	Winkler method or Iodometric method (APHA 4500-O A
Chloride (as Cl)	mg/L	Ion chromatography (APHA 4500-Cl–D)
Nitrate (as N)	mg/L	Ultraviolet spectrophotometric method Colorimetry (APHA 4500-NO_3)
Fluoride (as F)	mg/L	Selective ion electrode method (APHA 4500-F-E)
Cyanide (as CN)	mg/L	Cyanide ion-selective electrode (APHA 4500-CN)

8.3.2 Sociological Studies

Studying the social impacts before the implementation of CFWs is crucial. Human interferences are significantly high in urban lake areas where man-made water pollution may cause the effectiveness of CFWs. In this matter, identifying the sociological and community interferences for an urban lake can be followed in several steps:

Step 1. Conduct a sociological analysis*:* Analyse the social factors that affect the urban lake. These factors may include the demographics of the surrounding community, the cultural and economic factors, and the political climate. Understanding these factors will help identify the potential sources of interference.

Step 2. Conduct a community analysis*:* Analyse the attitudes and behaviours of the community towards the urban lake. This may involve conducting surveys or interviews with community members to understand their perceptions of the lake, their use of the lake, and any concerns they may have about the lake. The questionnaire used can be found on the APN project website: https://doi.org/10.30852/p.18686

***Step 3. Identify potential sources of interference**:* Based on the sociological and community analyses, identify the potential sources of interferences that could be impacting the urban lake. These may include pollution from nearby businesses or residential areas, overuse of the lake for recreational activities, or cultural attitudes that do not prioritise conservation efforts.

***Step 4. Develop strategies to address interferences**:* Once the potential sources of interferences are identified, develop strategies to address them. This may involve working with local government agencies, community organisations, or businesses to reduce pollution or limit recreational activities in the lake. Conducting public education campaigns may also help to change cultural attitudes towards conservation and environmental stewardship.

8.3.3 Biological Studies

Plant and animal components of the water bodies where CFWs will be applied may affect the water quality. Biological species around the lake should be scientifically studied before the implementation. Biological studies help to identify animal and plant species in the urban lake area where CFWs will be applied. The following steps can be followed when conducting a biological study:

Step 1. Determine the site: Determine the location of the urban lake of interest.

Step 2. Identify organisms: Identify various types of organisms that inhabit the lake. These may include fish, macroinvertebrates, algae, bacteria, and other small aquatic creatures.

Step 3. Identify the pollutants: Collect samples of water from different areas of the lake using a water sampler. Take note of the water temperature, pH, and other physical characteristics of the water. Further, analyse the water samples for chemical pollutants such as pesticides, heavy metals, planktons, and other toxic substances that may affect the health of the organisms living in the lake.

Step 4. Evaluate the biodiversity: Conduct a biodiversity assessment of the lake by observing and identifying various species that live in and around the lake. Use specialised tools such as nets, traps, and magnifying glasses to catch and study individual specimens. A genetic analysis of the samples can also be performed to identify different species that are present in the lake.

Step 5. Study the organism's behaviour and ecology: Study the behaviour and ecology of the organisms in the lake. Observe their mating habits, feeding habits, and their overall interaction with the environment.

Step 6. Record and report: Compile the findings into a comprehensive report outlining the research methods, results, and conclusions. The study should also include recommendations for protecting and preserving the health of the urban lake and its inhabitants.

8.3.4 Climatological Study

The climate of the area causes the pollution load, water level fluctuations, and other variations of the water bodies. The climatology of the area decides the effectiveness, stability, and durability of the CFWs. The steps that can be followed to conduct a climatological study are as follows:

Step 1. Define the study area: Identify the appropriate urban lake area. Obtain a map of the area and identify the boundaries of the lake, the surrounding urban areas, and any other features that might impact the climate of the area.

Step 2. Collect climatological data: Collect data on temperature, precipitation, wind speed, humidity, and other relevant climatological variables. Such data can be obtained from local weather stations or meteorological organisations. An ample amount of data from a sufficiently long time would be required to capture seasonal and annual variations.

Step 3. Analyse data: Collected data can be analysed using statistical software. Identify the mean, median, and range of each variable. Plot the data to identify trends and patterns.

Step 4. Identify climate drivers: Identify the primary drivers of the climate in the urban lake area. This might include local weather patterns, geography, and human activities such as urbanisation or water management practices.

Step 5. Correlate climatological data with lake measurements: Collect data on water quality, depth, and temperature of the lake. Analyse this data alongside the climatological data to identify any correlations between the lake and the surrounding climate.

Step 6. Interpret results: Once the data analysis is complete, interpret the results considering the study area and climate drivers. Identify any significant changes in the climate of the area that might impact the lake or its ecosystem and recommend any mitigation measures that might be needed.

8.3.5 Modelling

Modelling of lake is crucial for the future planning stages. Modelling can be done in two ways: physical modelling and computer-based modelling. Figure 8.5 shows the depth analysis and modelling of Kandy Lake by computational model.

- ***Physical modelling procedures:*** Collect data on the lake area, shoreline shape and composition, and surrounding land use. Conduct a bathymetric survey to measure the depth and contours of the lake bottom (Pu et al. 2011). Identify the locations of wastewater inlets and outlets and estimate the volumes and flow rates of incoming and outgoing water. Use this data to create a physical model of the lake using scaling techniques and material simulations.

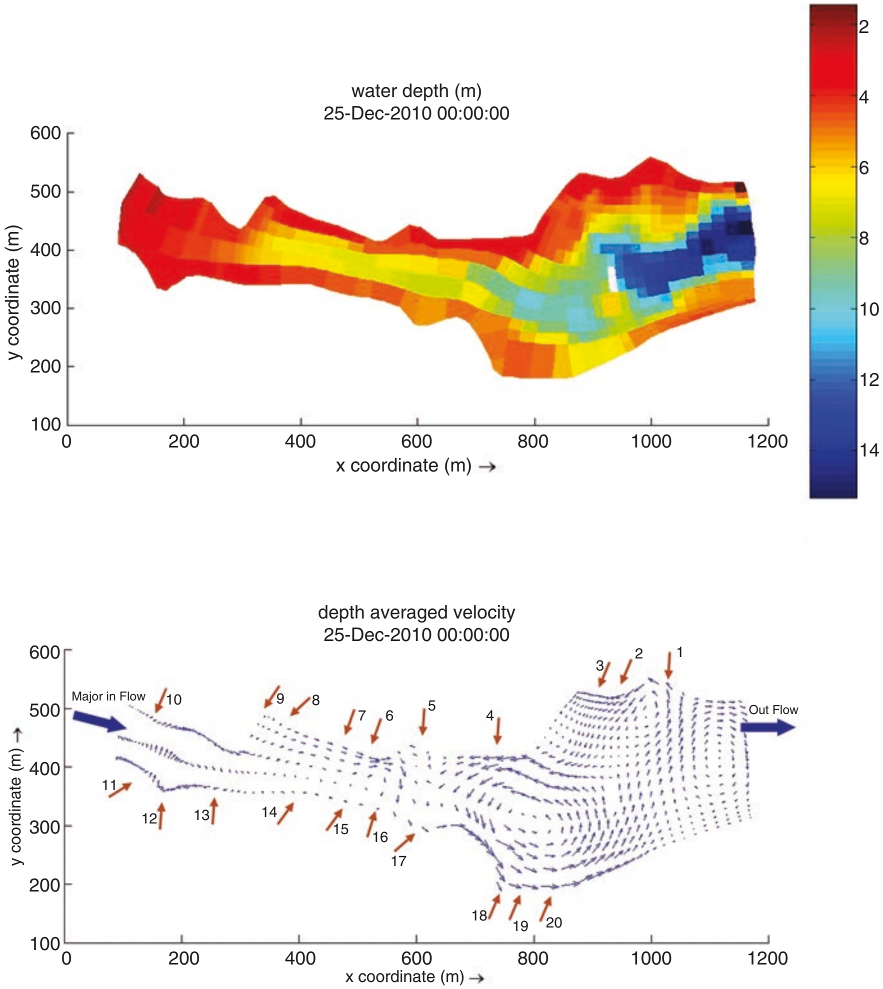

Fig. 8.5 Depth analysis and modelling results of Kandy Lake by computational model (Pu et al. 2011)

- ***Computer-based modelling procedures*:** Collect data on the lake area, shoreline shape and composition, and surrounding land use by Google Maps or other appropriate software. Input this data into hydrodynamic modelling software, such as MIKE 21, DHI, TELEMAC, or UNTRIM. Use the software to create a 3D model of the lake and simulate the flow of water and transport of pollutants (Ananda 2019). Input data on the location and flow rates of wastewater inlets and outlets. Simulate the flow of pollutants and water flow.

8.4 Designing and Planning

Before the implementation steps, the CFWs should be designed and planned with the aid of specialists and previous experiences with the CFWs. The most significant design factors (Ranaweera 2011) include (i) plant selection and coverage, (ii) growth media, (iii) area of the lake, and (iv) methods for achieving buoyancy of the CFWs setup. Further, some of the general aspects and specific factors to be analysed (Ranaweera 2011) are discussed below:

- ***Conduct a water quality analysis and flowrates of lake wastewater (WW) inlets****:* Before selecting areas where CFWs can be applied, it is important to assess the water quality of the lake inlets. Factors such as nutrient levels, dissolved oxygen content, pH, and algae growth should be evaluated to determine the effectiveness of using CFWs as a solution. Assess the extent and types of pollution: Identify the main source of pollution in the lake, whether it is from agricultural runoff, stormwater runoff, ageing septic systems, or other sources.
- ***Depth analysis****:* Selection of proper depth regarding root development is an important factor. Selection and maintenance of proper water depths are vital both for preventing the plants from anchoring and, thus, losing the privilege of water fluctuation resistance and for providing an adequate root cover over the water column. The root depth varies greatly according to plant species and water/wastewater characteristics.
- ***Identify potential locations****:* Areas where CFWs can be applied to control pollution, include the shallow or stagnant areas of the lake where water quality is poor, where vegetation is limited or non-existent, or areas with a lot of runoff.
- ***Evaluate local ecosystems****:* Ensure that the CFWs will not have adverse effects on the ecosystem and do not contain any invasive species. It is important to consider the types of plants and animals already present in the lake, as well as the location's natural systems, in order to preserve biodiversity and environmental equilibrium.
- ***Consult local authorities and experts****:* It is highly recommended to consult with local lakeshore associations, environmental organisations, and government agencies to ensure that the use of constructed CFWs is safe and appropriate for the particular lake or body of water being targeted.

8.4.1 Selection of Plants

The suitability of the plants used for CFWs varies according to the local context and, therefore, should be assessed (Sanjeewani et al. 2022). There is no suggested method for selecting plants in floating treatment wetlands in Sri Lanka. The plant selection is instrumental for the success of the floating treatment wetlands. When selecting plants for a constructed floating wetland, the following criteria can be used.

- ***Systematic Review:*** Plants are selected from systematic reviews of previous knowledge used for previous studies on CFWs.
- ***Preliminary Screening:***

  1. Tolerance to water conditions: Plants should be able to thrive in the wetland environment, which can include fluctuating water levels, high levels of nutrients, and low oxygen levels. Look for plants that are adapted to the local climate and environmental conditions.
  2. Ability to absorb nutrients: Plants play an important role in removing nutrients from the water, therefore, choose plants that have a high capacity to absorb nutrients such as nitrogen and phosphorus. Look for plants with high biomass and fast growth rates.
  3. Root structure: Plants with dense root systems can help to stabilise the floating platform and provide a substrate for beneficial bacteria that can break down pollutants in the water.
  4. Aesthetic value: Consider the visual appeal of the plants when selecting them. Plants that have attractive foliage or flowers can enhance the aesthetic value of the constructed floating wetland.
  5. Non-invasiveness: Select plants that are not invasive and can coexist with native plant species. Invasive species can negatively impact the local ecosystem and reduce the effectiveness of the constructed floating wetland.
  6. Native species: Native plant species are preferred as they are well-adapted to the local ecosystem and can provide a more effective solution for improving water quality.
  7. Seasonal variations: Consider the seasonal variations in the plant's growth cycle and ensure that a mix of species is used to provide continuous nutrient uptake throughout the year. In Fig. 8.6, it shows the plants that can be used for CFWs that are fitted with selection criteria.

- ***Weighted scoring:*** According to the selection criteria, scores are assigned. This approach provides a systematic and transparent way to evaluate and compare the identified criteria.

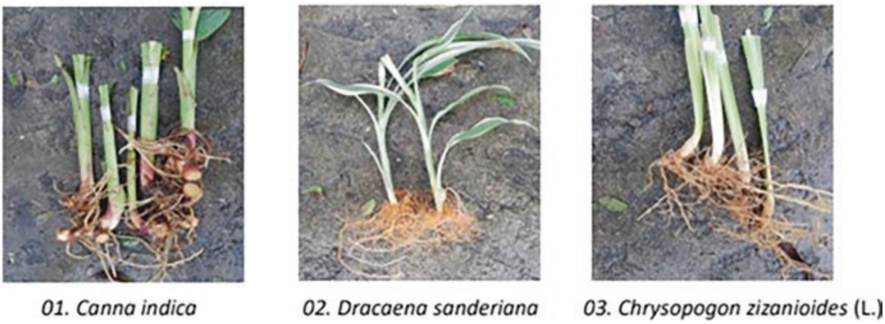

Fig. 8.6 Types of plants can be used for CFWs

8.4.2 Components of CFWs Floater

The components and materials used for the construction of CFWs are summarised in Table 8.4. Figure 8.7 shows the materials used to prepare the CFWs.

8.4.3 Designing of Rafts

CFWs design should be designed for buoyancy (see below calculations). In Fig. 8.8, it shows the plan view and top view of the CFWs.

Unit weight of saturated coir = 0.86 g / cm ^{3}

- Weight of unit length in PVC pipes = 7.63 g / cm.
- Total weight of the floater = $(180 \times 2 + 120 \times 2) \times 7.63 = 45.78$ kg.
- Total weight of the coir = $10.20 \times (120.2 \times 10.2) \times (180.2 \times 10.2) \times 0.86 = 139.5$ kg.
- Weight of the PVC net = 1 kg.
- Weight of the plants = 4 kg.
- Total weight of the model = 190.28 kg.
- Submerged height = H.
- Diameter of the PVC pipe = 10.2 cm.
- By the Archimedes theorem = $H \times 1.2 \times 1.8 \times 1000 \times 9.81 = 190.28 \times 9.81 = 8.81$ cm (< 10.2 cm).

Table 8.4 Components and materials of the CFWs model floater (Ranaweera 2011)

Components	Materials
• A net used to maintain the vegetation controlled • Growing medium for plants • Anchoring concrete cubes (150 mm × 150 mm × 150 mm) • Vegetation	• PVC / bamboo pipes as floaters • Coconut coir as a growing medium • Geo textile membrane • PVC net or netmade from the plant called Ichonocarpus frustescens (Kiri wel) • PVC bends • Binding wires • Plants

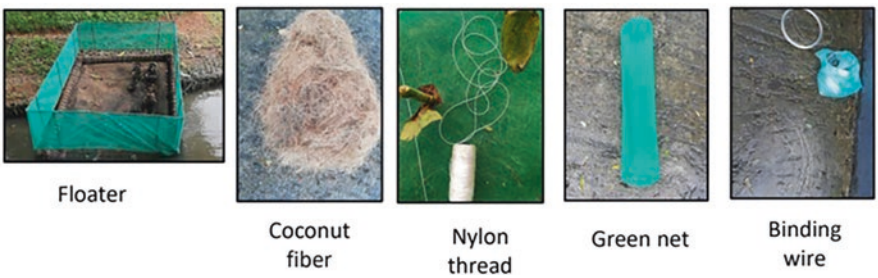

Fig. 8.7 Materials for the CFWs

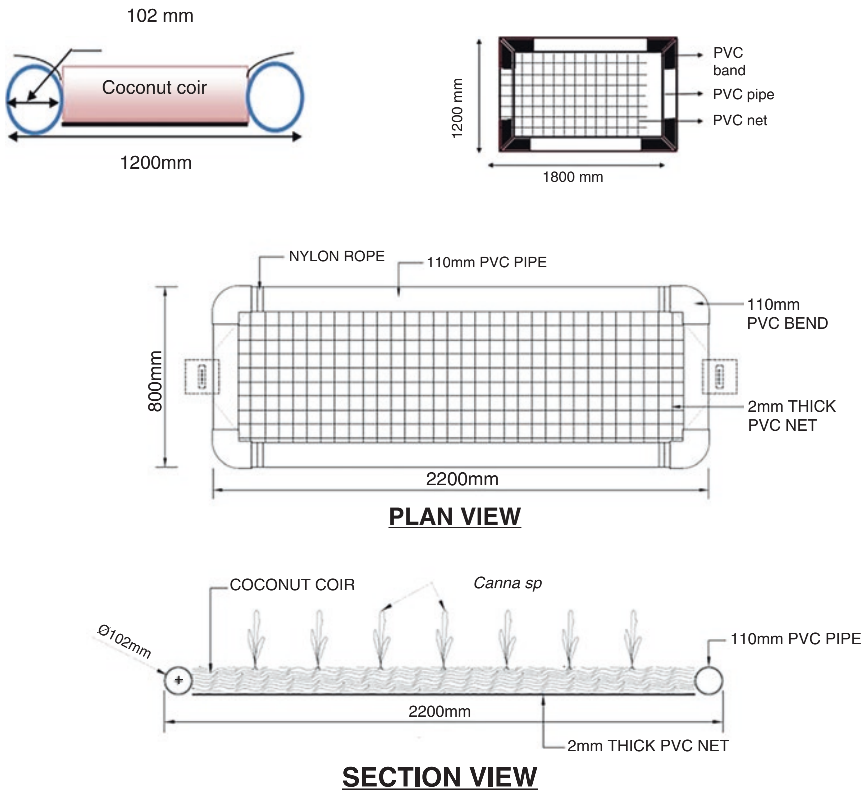

Fig. 8.8 Design of CFWs

8.4.4 Planning of Implementation

Before the implementation, a proper implementation plan should be identified. It consists of proper site selection, amount calculation, and CFWs location identification. The general steps for the CFWs implantation are (i) selecting zones of the lake, (ii) deciding on the number of CFWs, (iii) estimating the total surface area of CFWs, and (iv) connecting and anchoring of CFWs. Implementing areas should be decided based on previous studies. CFWs should not cover more than 30% of the area of urban lake. The number of rafts can be varied with lake water quality and other lake conditions. Rafts can be connected with each other or can be anchored separately.

8.5 Impact Assessment

An impact assessment study (IAS) is a structured process for considering the implications for people and their environment of proposed action whilst there is still an opportunity to modify. There are two types of impact assessment studies: Environmental Impact Assessment and Social Impact Assessment.

8.5.1 Environmental Impact Assessment

Environmental Impact Assessment can be performed using the following steps:

Step 1: Define the scope and purpose of the assessment: The first step is to define the scope and purpose of the assessment. This involves identifying the objectives and goals of the floating wetland project and determining the issues and concerns that need to be addressed. It also involves identifying the stakeholders and their interests, as well as any regulatory requirements or guidelines that need to be followed.

Step 2: Identify the potential impacts of the CFWs: The second step is to identify the potential impacts of the CFWs on the lake and its surrounding environment. This involves conducting a thorough review of the literature and existing data on similar projects and their impacts. It also involves an analysis of the specific design and location of the CFWs, and identifying any potential impacts on water quality, biodiversity, shoreline erosion, recreational activities, and other relevant factors.

Step 3: Assess the significance of the potential impacts: The third step is to assess the significance of the potential impacts identified in Step 2. This involves determining the magnitude, extent, duration, and likelihood of the impacts, as well as their reversibility, cumulativeness, and synergistic effects. It also involves comparing the impacts to relevant criteria, such as regulatory standards, benchmark values, or community expectations.

Step 4: Develop mitigation and monitoring measures: The fourth step is to develop mitigation and monitoring measures to minimise or avoid the potential impacts of the CFWs. This involves identifying the most effective and feasible ways to reduce, eliminate, or offset the impacts. It also involves developing a monitoring plan to track the effectiveness of the mitigation measures and to detect any unforeseen impacts or changes over time.

Step 5: Prepare the impact assessment report: The final step is to prepare the impact assessment report, which documents the findings of the assessment and the recommended mitigation and monitoring measures. The report should include a clear and concise summary of the project objectives, the potential impacts, the significance of the impacts, and the mitigation and monitoring measures. The report should also address any public concerns or comments and describe the consultation process with stakeholders and regulatory agencies. The report should be reviewed and approved by relevant authorities before the construction of the floating wetlands.

8.5.2 Social Impact Assessment

Social Impact Assessment is an important component of the impact assessment study of an urban lake (Jinadasa et al. 2019). The following steps can be used to carry out the social impact assessment:

Step 1: Identify the Goals and Objectives: The first step in conducting a social impact assessment for a constructed floating wetland project is to identify the goals and objectives of the project. These goals and objectives help to guide the assessment and ensure that it is focused on the most important aspects of the project. Some potential goals and objectives for a floating wetland project in an urban lake might include:

- Improving water quality in the lake.
- Enhancing biodiversity in and around the lake.
- Educating the public about the importance of wetlands and water quality.
- Providing a recreational amenity for the community.

Step 2: Identify the Stakeholders: The next step is to identify all stakeholders who are likely to be affected by the project. This includes both individuals and groups who will benefit from the project, as well as those who may be negatively impacted. Some potential stakeholders for a constructed floating wetland project in an urban lake might include:

- Residents who live near the lake and use it for recreation.
- Environmental groups who are concerned about the health of the lake and its ecosystem.
- Local government officials who are responsible for maintaining the lake.
- Business owners who may benefit from increased tourism or property values.
- Wildlife and plant species that live in or around the lake.

Step 3: Assess the Potential Impacts: Once the goals and stakeholders have been identified, the next step is to assess the potential impacts of the floating wetland project on each stakeholder group. This includes both positive and negative impacts, such as:

- Positive impacts: Improved water quality, increased biodiversity, increased recreational opportunities, increased public awareness of environmental issues.
- Negative impacts: Disruption of wildlife habitat, potential for increased noise and traffic near the lake, potential for increased pollution from increased human activity.

Step 4: Develop Mitigation Strategies: After identifying the potential impacts, it is important to develop mitigation strategies to address any negative impacts and enhance any positive impacts.

This may involve:

- Developing signage or educational materials to inform the public about the benefits of the floating wetland and how to use it responsibly.

- Implementing measures to mitigate any potential negative impacts on wildlife or plant species in the lake.
- Working with local government and community groups to develop maintenance and monitoring plans to ensure the project is successful in achieving its goals.

Step 5: Monitor and Evaluate: Finally, it is important to monitor and evaluate the success of the floating wetland project over time. This may involve:

- Conducting water quality tests to assess the impact of the wetland on the lake ecosystem (Hapuarachchi 2019).
- Observing changes in the plant and wildlife communities in and around the lake.
- Conducting surveys or focus groups with local residents and visitors to assess their perceptions of the project and any impacts it may be having on their quality of life.

8.6 Financial Assessment

Financial analysis refers to an assessment of the viability, stability, and profitability of a project. It is performed by professionals who prepare reports with the aid of ratios and other methods. It may consist of several elements, such as profitability, solvency, liquidity, and stability. Also, it depends on past performance, future performance, and comparative performance. By considering these factors, the financial of project implementation could be determined.

8.7 Social Acceptance

In urban and suburban areas, social acceptance is an important milestone to be achieved before the implementation of CFWs because society plays a vital role in the maintenance and protection of CFWs (Jinadasa et al. 2019). The stakeholders are identified through the social impact study as described previously. Once the stakeholders are identified, it is crucial to obtain social acceptance. This can be obtained via Focus Group Discussions. Figure 8.9 shows the conducting of social activities to introduce CFWs models, and Fig. 8.10 shows the conducting of focus group discussions for stakeholders of Kandy Lake, Sri Lanka.

A discussion with lake stakeholders should be arranged, and the objectives of the meeting should be discussed about the capacity building of lake stakeholders.

Fig. 8.9 Conducting school activities to introduce CFWs model

Introducing an action plan for the stakeholders and the formation of the committees, including the stakeholders, to sustain the implementation of CFWs for a long time. Further, seeking approval from authorities and institutions is crucial since most of the urban lakes and wastewater treatment plants are operated under the authority of governmental and non-governmental organisations. Finally, presenting a proper project proposal with an appropriate budget is required to show the effectiveness and benefits of the CFWs for pollution remediation.

Fig. 8.10 Conducting a focus group discussion for the stakeholders of Kandy Lake, Sri Lanka

8.8 Construction

The construction phase can be succeeded if the previous steps are followed properly. This phase is integrated with continuous monitoring, problem solving, and researching CFWs (should be planned to be reliable and safe following relevant engineering standards). Since the measurements in the plan must be precise to satisfy the standards, a qualified contractor must be employed. Furthermore, since issues and problems are inevitable on the site, a person who is well-informed about the plan drawings and goals of the CFW must always be present. Figure 8.11 shows the basic steps in the construction phase.

- A thorough study of drawing plans and specifications must be done.
- Construction plans should have enough information to prepare correct bids and to carry out the project.
- It is advised to have a pre-bid meeting with prospective contractors to go through the project's concept, objectives, and specifications.
- An interpretation and explanation of the design's intent to the operator and the contractor should always be done during a pre-construction conference.
- The required work must be represented to the operator and the contractor through construction plans, specifications, and field layouts.

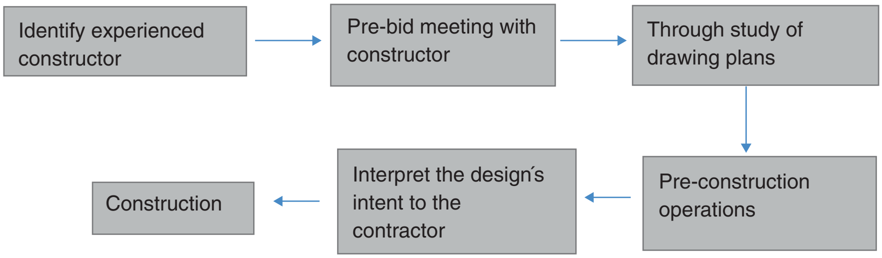

Fig. 8.11 Steps of the construction phase

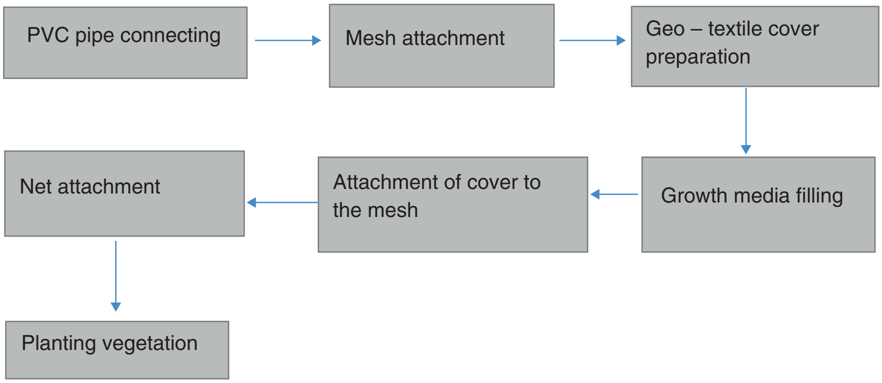

Fig. 8.12 Preparation steps of the CFWs

- Plans can range from being very simple with just a few stakes on the ground to being complex with intricate specifications and plenty of staking due to the significant disparities in conditions and experience.
- To ensure a well-organised and efficient construction project, pre-construction operations should be suitable for the site's size and complexity.

8.8.1 Raft Preparation

In order to construct the CFW units, the following materials and methods will be used. Figure 8.12 illustrates the major steps of the preparation steps of the CFWs.

- **PVC pipe system construction:** A 1200 mm × 1800 mm square frame will be constructed using four pieces of 102 mm of diameter PVC pipes and PVC elbows. This will create a floating base to keep the wetland afloat. Figure 8.13 indicates the preparation of rafts by both Bamboo and PVC.

Fig. 8.13 Preparation of rafts by both Bamboo and PVC

Fig. 8.14 Introducing coconut coir to the constructed rafts

- **Mesh attachment:** A 2-mm hole-size PVC mesh will be cut to the size of the frame's base and attached to the PVC pipes by using wires to create a bed for the growth media.
- **Geotextile cover preparation:** The geotextile will be prepared as a pillow-type cover that fits with the size of the floating frame's inner space volume.
- **Growth media filling:** The geotextile cover will be filled with dry coir pith. Figure 8.14 shows the introduction of coconut coir to the constructed rafts.
- **Attachment of cover to the mesh:** The prepared growth-support pillow will be placed over the mesh and snugly fitted to the PVC frame.
- **Net Attachment:** To protect the CFWs from aquatic animals and other damages coming from the water surface, a net will be installed around the perimeter of the unit.
- **Wetland planting:** Once the unit is constructed, the desired plants with 20 cm of shoots will be planted into the growth media by making cross-cuts of the pillow (4 plants per unit).

8.8.2 Plant Nursing and Planting

There are a few steps to take in order to successfully nurse and plant vegetation in a CFW:

Step 1. Selecting appropriate plants: Choose plants that are native to the region and that will thrive in wetland environments. Some common wetland plants include cattails, bulrushes, water lilies, and sedges. Preparing the floating wetland: Construct or purchase a floating wetland that is appropriate for the size and location of your water body. Make sure the structure is secure and stable.

Step 2. Adding planting material: Fill the planting boxes or baskets on the wetland structure with nutrient-rich soil or substrate. Make sure it is appropriate for the water depth and type of vegetation you will be planting. Planting the vegetation: Carefully plant the vegetation in the soil or substrate. Make sure the roots are fully submerged in the water (20 cm of tillers are planted). These plants should be matured for 2–3 months. Caring for the plants: Monitor the plants regularly for signs of stress or overgrowth. Trim and prune as needed to maintain healthy vegetation.

Step 3. Creating biodiversity: Creating a diverse wetland is essential for a healthy ecosystem. Think about the type of food web preferred by fish and waterfowl living in that water body. Monitoring water quality: Regularly monitor the water quality to ensure the wetland is functioning properly and the plants are healthy. Figure 8.15 shows the CFW after introducing the plants, and Fig. 8.16 shows the introduction of whole CFW units to Kandy Lake.

Fig. 8.15 Introducing plants to the CFWs

Fig. 8.16 Introducing CFWs to the Kandy Lake, Sri Lanka

8.9 Operation, Maintenance, and Inspection

In this phase, CFWs are operated with wastewater, and the removal efficiency should be monitored with regular inspections. Also, the maintenance of CFWs is crucial for the efficient removal of pollutants. Figure 8.17 shows the operation phase procedures of the CFWs.

8.9.1 Operation

In this phase, wastewater passes through the CFWs and pollutants are absorbed by plants as a nutrient uptake. Water Samples are obtained at the water surface and 10 cm from the inlet and outlet to measure the water quality parameters. Check whether there is a reduction in pollution or not. Check whether WQ parameters satisfy Sri Lankan Surface Water Quality Standards or not. If not, the problem should be identified and the design should be redone according to the problem.

8.9.2 Maintenance and Inspection

Proper inspection of the CFWs should be done by specialists or skilled technicians to maintain CFWs in optimal condition. After constructing the floating wetland, the next step is to maintain it. Figure 8.18 shows the maintenance and implementation of CFWs in Kandy Lake, Sri Lanka. This maintenance and inspection phase includes the following steps:

- **Regular Inspection**: Regularly inspect the floating wetland for any damage or signs of wear and tear.
- **Replace Plants**: Replace any plants that are not growing well or have died.
- **Monitor Water Quality**: Monitor the water quality of the lake to determine the effectiveness of the constructed floating wetland in removing pollutants.

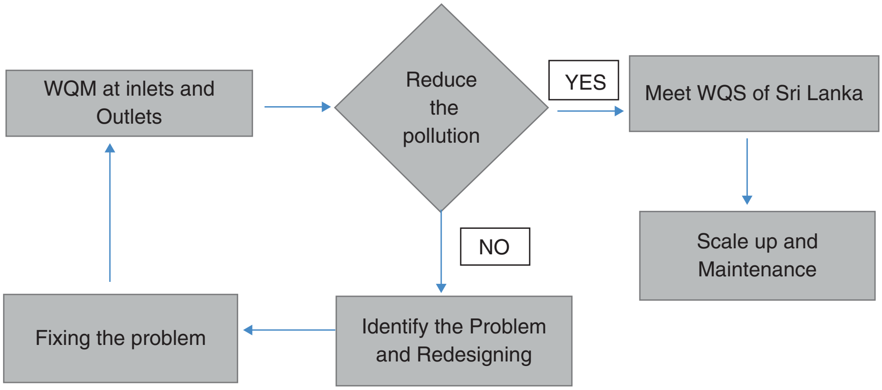

Fig. 8.17 Operational phase of the CFWs

Fig. 8.18 Maintenance and implementation of CFWs in Kandy Lake, Sri Lanka

- **Clean Debris**: Clean any debris that has accumulated on the floating platform.
- **Regular Harvesting**: Regularly harvest the wetland plants to prevent them from overgrowing and to maintain their effectiveness in removing pollutants.
- **Renovate structures.**

8.10 Research and Development

Regular research and development should be conducted after the implementation of CFWs, with the suggested steps:

- **Identify the problem**: Start by determining the specific problem that the CFWs will address. Is it to improve water quality, enhance biodiversity, create recreational opportunities, or all of the above? The problem should be clear and well-defined to guide the research.

Fig. 8.19 Scaling up of CFWs in Kandy Lake, Sri Lanka

- **Research the existing literature**: Conduct a literature review to gather information about similar projects, best practices, and relevant research studies to understand how similar challenges are addressed, as well as to identify gaps in knowledge that a new research could address.
- **Identify the stakeholders**: Determine who will be affected by the CFWs and who holds an interest in the project. This could be the lake management authority, local governments, environmental organisations, community groups, or the general public.
- **Conduct site assessments**: Evaluate the proposed location for the CFWs. Factors to consider include water quality, water levels, fluctuating water levels, sunlight, and temperature. This will help you understand the physical conditions that the wetlands have to cope with.
- **Design the CFWs**: With a clear understanding of the problem and the site in place, develop the design of the CFWs. The design should account for factors such as depth, size, shape, planting schemes, and buoyancy. Computer-aided design, modelling, or simulation software can be helpful.
- **Prototype and test the CFWs**: Build a prototype floating wetland system and test it in a controlled environment (see Fig. 8.19). Conduct experiments to study the system's effectiveness in improving water quality, attracting wildlife, and other relevant outcomes. This phase will validate the design and highlight potential issues before the wetlands are launched on the lake.

- **Monitor and evaluate the wetland's progress**: Once the CFWs are installed, monitor and evaluate their ongoing effectiveness. This will help to identify opportunities for future improvements and ensure that the wetlands continue to achieve their intended outcomes.
- **Engage with stakeholders**: Regularly engage with stakeholders, including the local community, policymakers, and NGOs, to ensure that the project goals are understood and supported. Communication and outreach programmes will help to maintain stakeholder buy-in and create a sense of ownership amongst participants.

8.11 Conclusions

Constructed Floating Wetlands (CFWs) are an innovative and environmentally responsible way to address problems with water quality and environmental preservation. This chapter has covered every aspect of the complicated CFW implementation procedure, from choosing the first site to continuous upkeep. CFWs serve as a shining example of sustainability by effectively removing pollutants, reducing water waste, and promoting biodiversity through the use of natural processes. They may be applied to a variety of contexts, from urban stormwater management to agricultural runoff treatment, because of their adaptability. CFWs provide long-lasting water quality improvements with careful design, appropriate installation, and attentive maintenance. Additionally, obtaining community support and continuing research and development efforts are essential for their success. CFWs have great promise in the overall scheme of environmental preservation, and their incorporation into our landscapes has the ability to usher in a new era of cleaner, greener, and more resilient ecosystems.

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Chapter 9
Guide to the Selections of Plants for Floating Wetlands

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Abstract Emergent plants are strategically placed on a floating mat above the water's surface in Constructed Floating Wetlands (CFWs). This arrangement facilitates their growth and establishment in deeper waters, with the uptake of nutrients and the creation of a microcosm with biofilm to enhance the mineralization, in addition to aesthetic appearance and ecosystem. Screening suitable emergent plant species is crucial as it affects the effectiveness of removing pollutants and maintaining the overall health of the ecosystem. The criteria include the availability of plants in the country to ensure local adaptation, the non-invasive nature of plants to prevent disruption of aquatic ecosystems, preference for terrestrial growth for better control and biomass accumulation, preference for perennial life cycles to enable controlled biomass harvest and efficient nutrient removal, and adaptation to submerged conditions for effective nutrient absorption. The plant selection process follows three steps, literature review, preliminary screening process, and weighted scoring as per the criteria. Based on the weighted score, the most suitable plants can be selected.

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Keywords Constructed Floating Wetland · Plant selection · Urban lake · Sri Lanka

9.1 Introduction

A Constructed Floating Wetlands (CFW) is a nature-based system designed to function as a floating wetland, integrating features from constructed wetlands and conventional retention ponds (Headley and Tanner 2012; Yeh et al. 2015). This hybrid system is particularly effective in the restoration of water bodies affected by eutrophication. Unlike traditional wetlands, CFWs employ emergent plants that are strategically placed on a floating mat above the water's surface. This arrangement facilitates their growth and establishment in deeper waters, thus:

- Allowing them to uptake nutrients from the water column, similar to the hydroponic mechanism (White and Cousins 2013).
- Providing a significant surface area for the growth of biofilms (Borne 2014; Tanner and Headley 2011), which effectively removes excessive nutrients from the water and filter sediments (Tanner and Headley 2011; Winston et al. 2013).
- Releasing oxygen and exudates and creating oxidative microcosm (Masters 2012).

Incorporation of ornamental plants within floating systems enhances not only the visual aesthetics of the site but also the overall ecological well-being (Chen et al. 2009). These plants provide nesting and breeding habitats for fauna and serve as fish habitats, thus promoting biodiversity and supporting ecological equilibrium (Weragoda et al. 2010).

Choosing suitable emergent plant species is crucial for CFWs as it affects the effectiveness of removing pollutants and maintaining the overall health of the ecosystem (Li and Guo 2017). Different plant species have different degrees of capacity in CFWs because of their distinct morphological and physiological characteristics, including nutrient absorption efficiencies, growth rates, and root types, underscoring the importance of selecting the most suitable plants for successful CFW design and implementation (Pavlineri et al. 2017; Wang and Sample 2014). Figure 9.1 shows a schematic diagram of CFW.

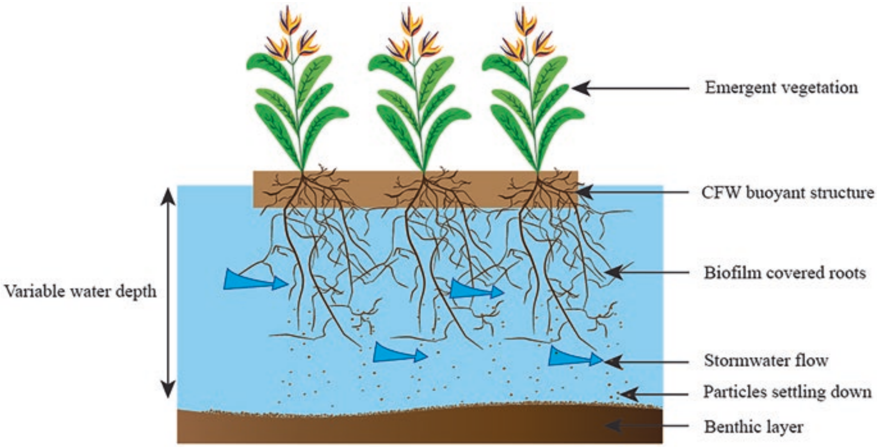

Fig. 9.1 Schematic diagram of constructed floating wetland

9.2 Importance of Plants in CFWs

Emergent plants in CFWs serve as the key component in the purification process. They have distinct abilities to directly absorb excess nutrients/pollutants from the water and act as natural filters. They indirectly contribute to the breakdown and transformation of pollutants by providing a favourable site for biofilms. There are many more factors enhanced by plants. The existing research on emergent vegetation in CFWs is relatively limited compared to constructed wetlands, the importance of these plants should not be underestimated.

In the floating bed system of CFWs, plants have a significant impact on both the chemical and physical aspects of the water. They can alter factors like pH, temperature, and dissolved oxygen, thereby creating a favourable environment for enhancing water quality. Additionally, the presence of plants inhibits the growth of algae by competing for essential nutrients and light, thereby reducing the risk of eutrophication.

Roots play a crucial role in the nutrient uptake and pollutant transformation process. In CFWs, macrophytes are suspended in floating mats, allowing their roots to remain in constant contact with the water. This arrangement enables efficient absorption of dissolved pollutants and provides a large surface area for beneficial biofilm formation. The biofilm, in turn, facilitates the biochemical transformation of contaminants, aiding in their removal from the water column.

The mat of old roots of plants in CFWs create anaerobic/anoxic conditions that promote the growth of denitrifying bacteria, which can convert nitrate into harmless nitrogen gas, effectively reducing nitrate levels. Furthermore, these roots act as traps, capturing fine suspended particulates that would otherwise remain in the water. Moreover, microbes living on the surface of plant roots play a crucial role in removing nitrate through a process called dissimilatory nitrate reduction to ammonium. They can remove up to ten times more nitrate than the plants themselves, contributing significantly to the overall purification process.

The efficient nutrient uptake and assimilation by CFW plants are influenced by various factors, such as the characteristics of the wastewater, plant species, and seasonal variations. Plants allocate resources to below-ground tissues, increase root length, and develop thinner roots to enhance their absorption abilities in response to nutrient availability. Moreover, as plants progress through different stages of their life cycle, nutrients absorbed earlier are remobilized and translocated to different parts of the plant, optimizing nutrient utilization and overall system performance.

Overall, plants in CFWs are central to the purification process, actively removing pollutants from water through direct absorption, facilitating microbial transformation, competing with algae for nutrients, and creating favourable root environments. Their role in maintaining water quality, reducing nutrient levels, and preventing the growth of algal toxins makes them indispensable components of CFWs.

9.3 General Characteristics of Plants Suitable For CFWs

Emergent plant selection is crucial in the process of CFWs. The choice of plants not only affects pollutant removal but also plays a significant role in maintaining the integrity of the local ecosystem (Wang and Sample 2014). Various plant species possess distinct biological properties that determine their suitability for CFWs, including nutrient absorption efficiencies, growth rates, and root types. When selecting plant species for CFWs, it is important to consider both plant-related and non-plant-related factors (Zhao et al. 2012).

9.3.1 Plant-Related Factors

The plant-related factors to be considered in CFW plant selection are as follows:

- ***Native and Non-Invasive Species:*** Native plants are preferred in CFWs as they generally outperform non-native species. They are well adapted to local conditions and pose minimal risk of becoming invasive if they escape from the treatment system (Bi et al. 2019). Native macrophytes have roots that are specifically adapted to thrive in wetland conditions, ensuring their survival and effectiveness in pollutant removal (McAndrew & Ahn 2017).
- ***Herbaceous Perennial Plants:*** Herbaceous perennials are desirable for CFWs because their aboveground biomass can be harvested at the end of the growing season, preventing the release of nutrients back into the water. These plants exhibit new growth in the following season, allowing them to continue absorbing nutrients from the water (Chen et al. 2009). Harvesting the aboveground biomass helps maintain nutrient balance and prevents excessive nutrient buildup.

- ***Terrestrial Plant Species:*** Unlike free-floating plants, the growth of terrestrial plants on CFWs can be controlled (Wang and Sample 2014). This allows for better management and facilitates the maintenance of desired plant populations within the system.
- ***Ability to thrive in a Hydroponic Environment:*** CFWs operate as hydroponic systems where plants grow in water without soil. Therefore, selecting plant species that can adapt to and thrive in this hydroponic environment is essential for their successful implementation in CFWs.
- ***Plants with Aerenchyma:*** Aerenchyma refers to air spaces present in the roots and rhizomes of plants (Chen et al. 2009). Plants with large aerenchymas exhibit increased buoyancy potential, which helps them stay afloat on the water surface. Additionally, aerenchyma facilitates the movement of oxygen from the aerial parts of the plants to the roots and rhizomes, effectively aerating these submerged plant parts (Wang and Sample 2014).
- ***Aesthetic Beauty:*** Whilst not directly related to the functionality of CFWs, the aesthetic appeal of the selected plant species can enhance the visual quality of the treatment system. Choosing plants with attractive foliage, flowers, or overall appearance can contribute to the overall satisfaction and acceptance of CFWs in various settings. Figure 9.2 shows the plant species suitable for CFWs.

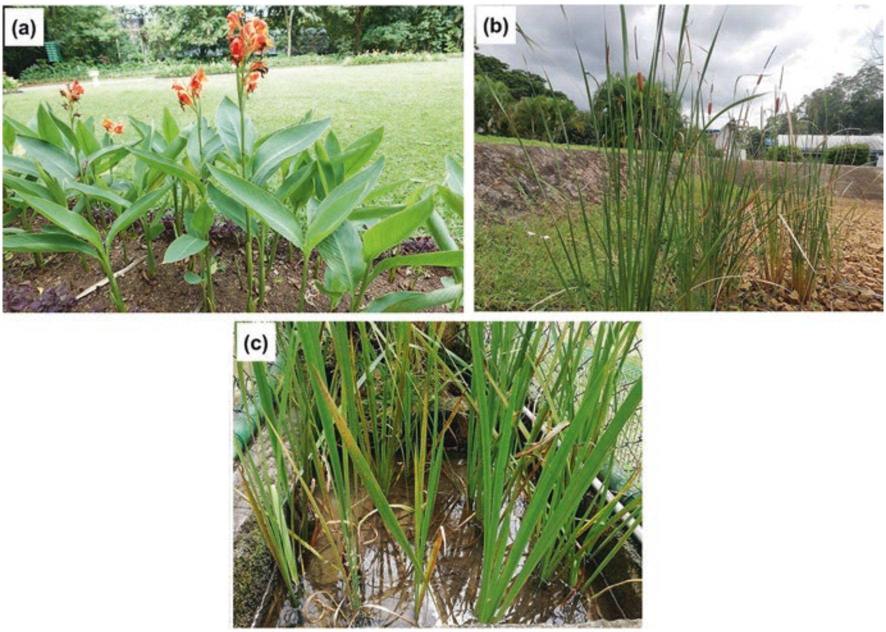

Fig. 9.2 Plant species for CFWs: (**a**) *Canna indica* L.; (**b**) *Typha angustifolia* L.; (**c**) *Acorus calamus* L.

9.3.2 Non-plant-Related Factors

The non-plant-related factors to be considered in CFW plant selection are as follows:

- ***Economic:*** Economic feasibility is an important consideration when implementing CFWs. The total cost of CFWs is influenced by factors such as floating mats, plants, and labour for harvesting and planting (Wang and Sample 2014). Therefore, plant species that exhibit luxuriant growth and produce substantial aboveground biomass are advantageous. Harvested biomass from economically viable plants can be used for various purposes, including composting, soil amendments, anaerobic digestion to produce methane, volatile fatty acid (VFA) production, and animal feed. Furthermore, combining harvested plant biomass with solidified manure can increase the nutrient content, thereby offering additional benefits in agriculture (Sooknah and Wilkie 2004).
- ***Social acceptability:*** Public acceptability is important for the successful implementation of the CFW. The customs, traditions, beliefs, and values of local people have to be considered in the selection of plants.

9.4 Plant Selection Process

The plant selection process is shown in Fig. 9.3. The following three steps can be followed in the plant selection procedure:

Step 1. Systematic review: The systematic literature review on CFWs involves a structured approach to gathering information on objectives, plant species used for previous research, plant selection criteria, and scoring parameters under each criterion. Figure 9.4 shows the major steps of plant selection criteria. The process includes defining the research objective, choosing a relevant search engine, determining keywords, conducting a search, collecting and categorizing relevant studies, extracting data, organizing and analyzing the data, identifying patterns and trends, and synthesizing the findings. By following these steps, a comprehensive and structured analysis of research studies on CFWs can be conducted, highlighting important insights and knowledge gaps in the field.

Step 2. Preliminary screening: This process involves refining information from a systematic review and follows a hierarchical key with five stages. For example, the preliminary screening process aims to select plant species suitable for Sri Lankan conditions, which is described in Fig. 9.5. Only plant species that fulfil all five requirements will be chosen. The selection criteria are based on ecological considerations and CFW requirements. The criteria include the availability of plants in Sri Lanka to ensure local adaptation, the non-invasive nature of plants to prevent disruption of aquatic ecosystems, preference for terrestrial growth for better control and biomass accumulation, preference for perennial life cycles to enable controlled biomass harvest and efficient nutrient absorption, and adaptation to submerged conditions for effective nutrient absorption and treatment in CFWs. By following this

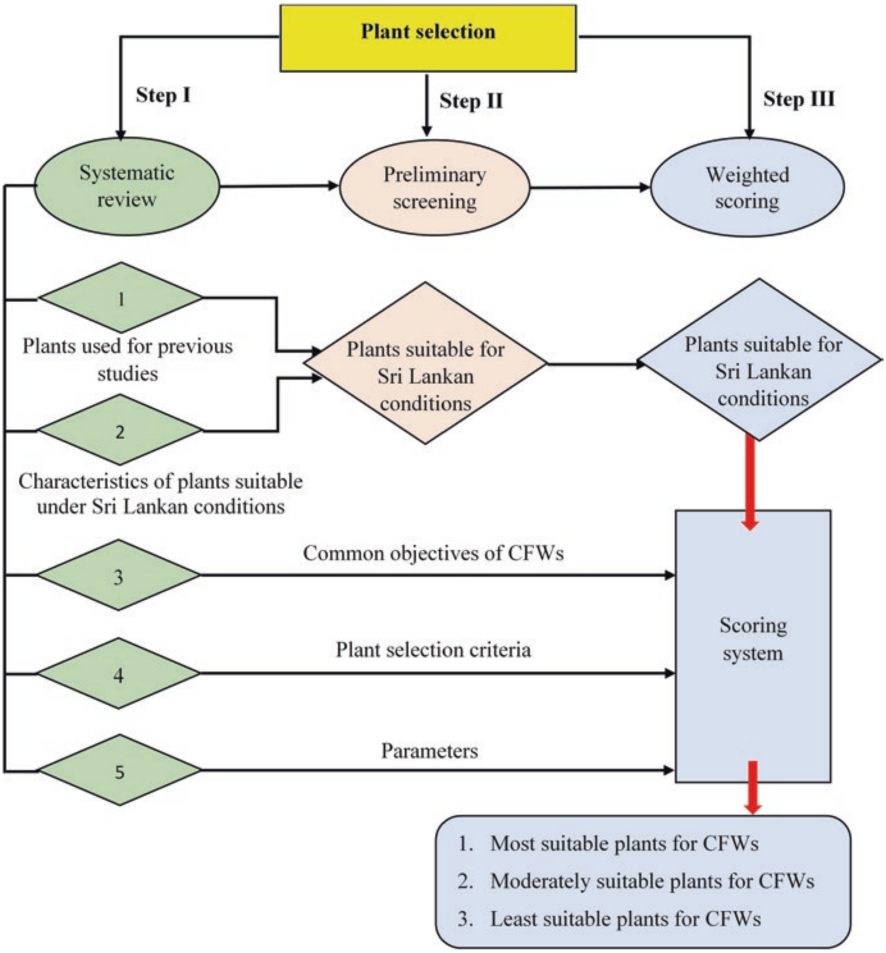

Fig. 9.3 A flow chart for selecting plants for CFWs

systematic screening process, the selected plant species will meet all five requirements, ensuring their suitability for CFWs in Sri Lankan conditions.

Step 3. Weighted scoring: In this third stage of plant selection for CFWs, a weighted scoring system is employed to identify the most suitable plant species for a field study (Table 9.1). The selection process considers common CFW objectives, including lake water quality improvement, biodiversity enhancement, aesthetic value, economic value, and social acceptability. To assess the plant species' suitability, criteria and parameters are identified from the systematic review conducted in the first stage. The assessment involves evaluating nutrient removal efficiency and plant growth for improving water quality, breeding surfaces for benthic organisms and shade provision for fish to enhance biodiversity, flowering and foliage beauty for aesthetic value, income and expenditure for economic considerations,

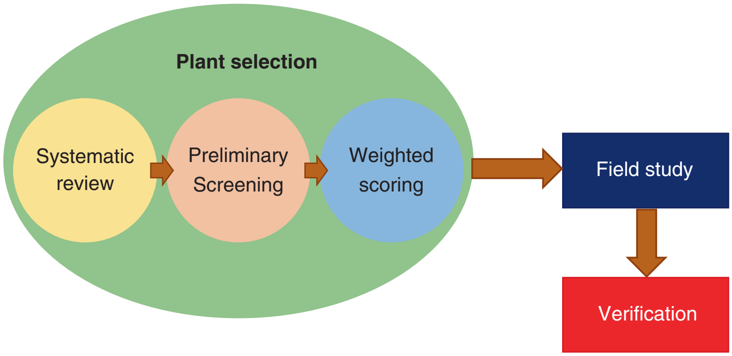

Fig. 9.4 Major steps of plant selection criteria

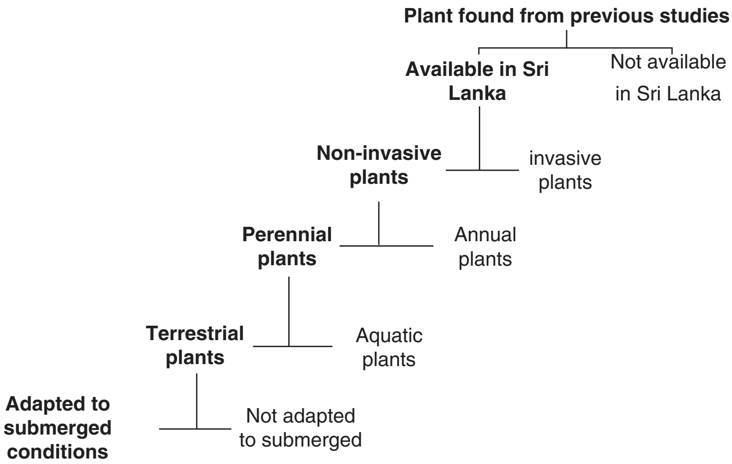

Fig. 9.5 Hierarchical key

and the preference of the local community for social acceptability. Each criterion is assigned a weight based on its relative importance to the overall objectives. Plant species are then scored on a scale of 1–3, indicating their suitability within the identified criteria, with 1 being the least suitable and 3 being the most suitable (Table 9.2). Based on this weighted scoring system, the selection process has identified specific plant species for CFWs. Figure 9.6 illustrates the typical plant species employed in previous studies around the world. These plants have been utilized in various contexts and environments to enhance the performance of CFWs. It is important to note that whilst these plants offer valuable insights, they may not always be the most suitable choices for specific regional conditions.

The plants introduced to the CFWs, as illustrated in Fig. 9.7, have been assessed and ranked according to their suitability scores. Amongst these plants, *Canna indica* L. has emerged as the most suitable species, attaining the highest score, whilst

Table 9.1 Identified common objectives of CFWs, plant selection criteria and parameters

Objectives of CFW	Plant selection criteria	Parameters
Lake water quality improvement	Nutrient removal efficiency	Total Nitrogen (%)
	Plant growth	Total phosphorus (%)
		Plant biomass accumulation (g/m^2)
Increase of biodiversity	Provide breeding ground for benthic organisms	
	Provide shade to cool the water for fish	
Aesthetic contribution to the lake	Flowering	
	Foliage beauty (ornamental plant/not)	
Economic value	Income	Cut flowers/foliage
		For composting
		For soil amendments
		For animal feed
	Expenditure	Operational and management cost (LKR)
		Establishment
Social acceptability	Preference of the local people	

Table 9.2 Scaling of parameters and plant selection criteria (Author)

Plant selection criteria	Parameters	Scores			
		0	1	2	3
Nutrient removal efficiency	Total nitrogen (%)	0%	1%–33.3%	33.4%–66.6%	66.7%–100%
	Total phosphorus (%)	0%	1%–33.3%	33.4%–66.6%	66.7%–100%
Plant growth	Biomass accumulation (g/m^2)	0	1–2000	2001–4000	>4000
Provide breeding ground for benthic organisms		No	Yes(less)	Yes(moderate)	Yes(high)
Provide shade to cool the water for fish		No	Yes		
Flowering		No	Yes		
Foliage beauty (ornamental/not)		No	Yes		
Income	Cut flowers /foliage	No	Yes		
	Composting	No	Yes		
	Soil amendments	No	Yes		
	Animal feed/medicinal value	No	Yes		
Operational and management cost	Market price (LKR)		>200	101–200	0–100

1 LKR = 0.0034 US$

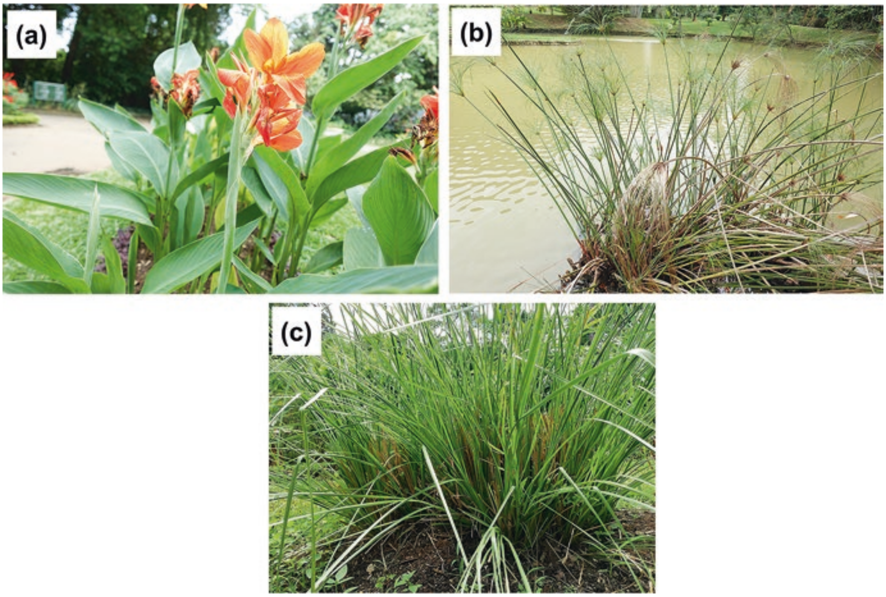

Fig. 9.6 Typical plant species for CFWs: (**a**) *Canna indica* L., (**b**) *Cyperus papyrus* L., and (**c**) *Vetiveria zizanioides* L.

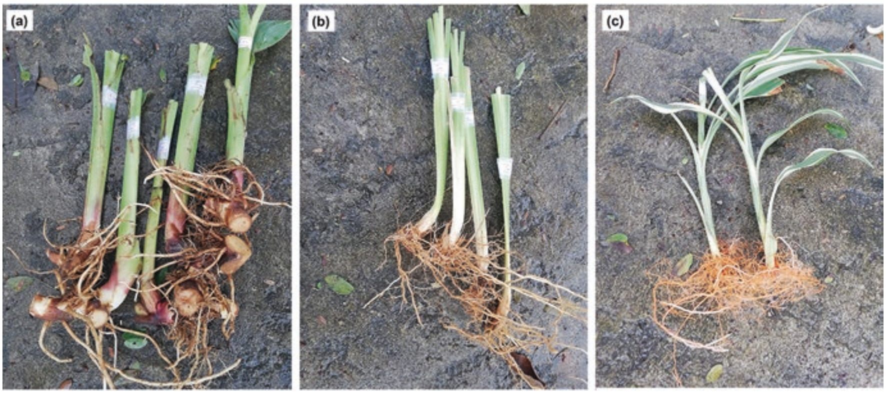

Fig. 9.7 Plants introduced to the CFWs: (**a**) *Canna indica* L., (**b**) *Vetiveria zizanioides* L., and (**c**) *Dracaena sanderiana*

Dracaena sanderiana is considered a moderately suitable option due to its moderate score. On the other hand, *Vetiveria zizanioides* L. has obtained the lowest score, indicating it to be the least suitable choice. Thus, by following this approach, the most suitable plant species can be identified for CFWs based on their total scores, ensuring alignment with the objectives of the study.

Tables 9.3 and 9.4 illustrate our plant evaluation process using *Acorus calamus* L. and *Canna indica* L. as examples. These tables demonstrate how we assess plants

Table 9.3 Weighted scoring for the plant of *Acorus calamus* L. (Author)

Criteria	Level for the criteria	Score
Removal of nitrogen percentage is 38.4%	33.4–66.6%	2 marks
Removal of phosphorus percentage of the plant is 28.9%	1–33.3%	1 mark
Plant biomass accumulation is 3875 g/m^2	2001 and 4000 g/m^2	2 marks
Populating quickly or higher vegetative growth	Provides breeding grounds for benthic organisms—moderate	2 marks
Leaves	Provides less shade to cool the water	1 mark
Produces flowers pleasing appearance	Flowers are not with pleasing appearance	1 mark
Foliage beauty	Plant does not show foliage beauty	No marks
As cut flowers	No	No marks
Use composting	Yes	1 mark
Use as soil amendments	Yes	1 mark
Use as animal feed	Yes	1 mark
Operational cost	No data	No mark
Total score		12 Marks

Table 9.4 Weighted scoring for the plant of *Canna Indica* L.

Criteria	Level for the criteria	Score
Removal of nitrogen percentage is 57.55%	33.4–66.6%	2 marks
Removal of phosphorus percentage of the plant is 58.65%	33.4–66.6%	2 marks
Plant biomass accumulation is 1638.9 g/m^2	1 - 2000 g/m^2	1 mark
Populating quickly or higher vegetative growth	Provides breeding grounds for benthic organisms—high	3 marks
Leaves	Provides less shade to cool the water	1 mark
Produces flowers pleasing appearance	Yes	1 mark
Foliage beauty	Plant show foliage beauty	1 mark
As cut flowers	Yes	1 mark
Use composting	Yes	1 mark
Use as soil amendments	Yes	1 mark
Use as animal feed	No	No marks
Operational cost	60.00 LKR	3 marks
Total score		17 Marks

against specific criteria, such as nutrient removal efficiency and growth, assigning scores based on their performance within these parameters. For instance, *Acorus calamus* L. achieved a nitrogen removal percentage of 38.4%, resulting in a score of 2, whilst *Canna indica* L.'s performance earned it a score of 2 with a nitrogen removal percentage of 57.55%. These scores reflect how well each plant aligns with our criteria. The higher the score, the better a plant meets our objectives for CFWs. These tables provide a standardized and transparent framework for evaluating plant suitability, assisting decision makers in selecting the most appropriate plants for their specific CFW projects.

9.5 Problems with Plant Selection Criteria

Some common challenges with the plant selection criteria are as follows:

- ***Insufficient Data Set:*** One potential risk in the plant selection process for CFWs is relying on a limited number of research publications. This may lead to an incomplete understanding of plant characteristics and their suitability for CFWs. To mitigate this error, it is crucial to conduct a comprehensive literature review that encompasses a diverse range of research sources. By considering a broader spectrum of studies, you can gather a more comprehensive dataset and ensure a more accurate selection of plant criteria.
- ***Evolving Objectives:*** Another mistake that can occur is the selection of static or outdated objectives for CFWs. The field of CFWs is constantly evolving, with new research and advancements shaping the understanding of their objectives. It is important to regularly review and update the objectives based on the latest scientific findings and industry practices. This ensures that the plant selection criteria align with the current state of knowledge and address the most relevant goals of CFWs.
- ***Incomplete Plant Characteristics:*** Inadequate consideration of plant characteristics can be a potential problem in the selection criteria. Whilst you have identified some common characteristics, it is important to acknowledge that there may be other crucial factors to consider. These could include plant root structure, nutrient uptake capabilities, pollutant removal efficiency, and adaptability to specific climatic conditions etc. To address this issue, it is necessary to conduct further research and consult with experts to identify and incorporate all essential plant characteristics relevant to the specific conditions of the CFWs.

Addressing these mistakes and problems in the plant selection criteria for CFWs is crucial for ensuring accurate and effective plant choices. Conducting a thorough and diverse literature review, updating objectives based on current research, considering a comprehensive range of plant characteristics, and actively seeking scientific data will enhance the reliability and success of plant selection in CFW systems.

9.6 Conclusion

The selection of suitable emergent plant species for Constructed Floating Wetlands (CFWs) is vital for effective water purification and ecosystem maintenance. Criteria such as native and non-invasive nature, herbaceous perennials, adaptability to a hydroponic environment, and aesthetic appeal guide the plant selection process. A systematic process involving literature review, screening, and weighted scoring helps identify the most suitable plant species. Amongst these, *Canna indica* L. stands out as a top choice for CFWs, promising effective water quality improvement, biodiversity support, and aesthetic enhancement. These carefully selected plants are key to the success of CFWs in restoring urban water bodies.

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Chapter 10
Guide to Floating Treatment Wetlands—A Vietnamese Perspective

Ngo Thuy Diem Trang, Vo Thi Phuong Thao, Nguyen Chau Thanh Tung, Nguyen Phuong Thinh, Nigel K. Downes, Veeriah Jegatheesan, and Nevelina Pachova

Abstract Constructed floating wetlands (CFWs) have emerged as a promising ecological engineering tool for the restoration of water bodies and have been extensively studied in controlled environments such as mesocosms and laboratories. There is a lack of in situ applications to improve ecosystem health. To address this gap, the project CRRP2021-06MY-Jegatheesan, funded by the Asia-Pacific Network for Global Change Research (APN-GCR), was undertaken. As part of this project, six CFWs were installed in 2022 at Bung Xang Canal in Can Tho City, Vietnam, by the College of Environment and Natural Resources (CENREs) at Can Tho University (CTU). The guide synthesises the knowledge gathered and provides an overview of the operating principles of CFWs. Detailed information on installation, including the official procedure, plant selection, and location, is also included in the guide. Moreover, the guide addresses the challenges that may arise during maintenance and offers recommendations and solutions to ensure the smooth operation of CFWs. The guide is expected to serve as a valuable resource for practitioners and researchers involved in the design, installation, and operation of CFWs for specific water

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resource management purposes and aims to promote the wider implementation of CFWs and contribute to sustainable management and restoration of water bodies.

Keywords Constructed floating wetlands · Eco-friendly technology · Nature-based solutions (NbS) · Sustainable city · Urban landscape · Water management

10.1 Introduction

Constructed Floating Wetlands (CFWs), also termed "planted floating system beds" or "floating treatment wetlands (FTWs)", are a new ecological technology applied for water treatment. In this guidebook, we adopt the term "Constructed Floating Wetlands" (CFWs) since it is the most widely used in the literature. CFWs are man-made structures that provide a medium for aquatic plants to grow above the surface of the water, to grow and develop in waters that are often deep compared to the plants' root systems. The plant roots spread through the floating system and extend down, creating a dense root system with a very large surface area, which creates favourable conditions for microorganisms to adhere and develop (Fig. 10.1).

Constructed floating wetlands (CFWs) are technologies that stand out for their efficiency, ease of installation, and maintenance. The system comprises aquatic macrophytes emerging in a floating structure that keeps the plant roots in direct contact with the effluent regardless of water flow variations over time, allowing the removal of pollutants by various processes (Fig. 10.1). Artificially created floating wetlands have been used with varying success for several applications to date, such as water quality improvement, habitat enhancement, and aesthetic purposes in ornamental ponds (Headley and Tanner 2008).

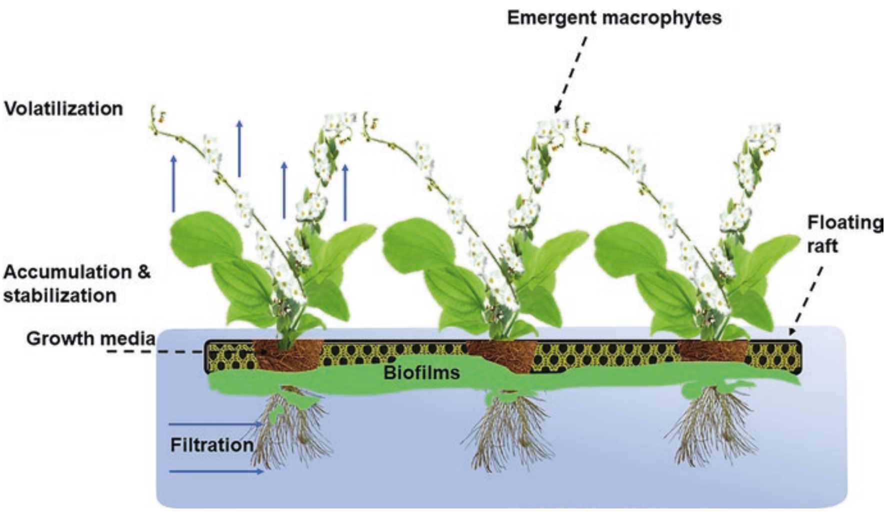


Fig. 10.1 Constructed floating wetlands structure and water purification processes

10.1.1 Applications of CFWs

The application of CFWs to treat wastewater has the advantage of low costs to remove nutrients as well as reducing the cost of maintenance and energy consumption when compared to the conventional centralised treatment of wastewater (Oliveira et al. 2021). Currently, CFWs have been successfully applied to improve water quality (rainwater runoff, domestic wastewater, agricultural wastewater), to improve and provide habitat for wildlife, and to create landscapes in ponds and lakes.

The application of CFWs for domestic wastewater treatment has been widely applied worldwide and is increasingly known in Vietnam. Due to low investment costs, the ease of installation, and low operating and maintenance costs, CFWs offer a sustainable treatment model. Currently, in developing countries, 80% of domestic wastewater from residential areas is discharged directly, without treatment, into receiving water bodies such as urban rivers, lakes, and canals, causing surface water quality to become seriously polluted (World Water Assessment Programme 2009). Therefore, the application of environmentally friendly and low-cost wastewater treatment solutions, for example CFWs, is very necessary for developing countries. A good example of a successfully applied model of CFWs that reduce most organic and inorganic pollutants with a very low treatment cost of US\$0.0026/m^3 of domestic and industrial wastewater in Pakistan is provided by Afzal et al. (2019).

A CFWs with five species of ornamental plants was installed for water treatment and landscaping at Bung Xang canal, Can Tho city of Vietnam (Fig. 10.2), which this guidebook outlines with a cost of only 320,000 VND/m^2 for material used (equivalent to US\$13.95/m^2, 1 USD = 22,946 VND (currency exchange rate in April 2022).

Fig. 10.2 The application model of CFWs at Bung Xang Canal, Can Tho City of Vietnam

10.1.2 Pros and Cons CFWs Applications

The CFWs for wastewater treatment is an artificial ecosystem that simulates a natural floating habitat system. In the early twentieth century, this system was used to mimic the natural habitat of birds and fish breeding grounds. In the 1980s, German scientists designed the modern eco-floating raft and used it for the first time to filter polluted water (Nakamura and Shimatani 1997).

The CFWs are an eco-friendly and sustainable wastewater treatment technique. Basically, this technology is a hydroponic method using artificial aquarium rafts, in which plants grow and use nutrients and organic matter present in wastewater to produce biomass, thereby helping the water environment to become less polluted in an environmentally friendly way (Sun et al. 2009). Some pros and cons of using CFWs for wastewater treatment are presented in Table 10.1.

Table 10.1 Pros and cons of using CFWs for wastewater treatment

Pros	Cons
1. Offers design flexibility: the floating rafts can be sized to fit into any existing space of water body shape such as pond, lake, or domestic sewage drain. Easy to design and to operate. 2. Provide a sustainable pollutant removal system and provide a natural habitat for animals (aquatic animals, insects, birds etc.). 3. The construction of a submerged floating raft on the surface of the pond creates a barrier against the penetration of light into the water surface, thereby limiting the possibility of algae growth. 4. Improved aesthetics: the CFWs can be used to create urban landscapes. 5. Tidal adaptation: the floating rafts can withstand tidal fluctuations as long as they are anchored at the bottom or fastened to the shore. 6. High treatment efficiency: the natural air movement allows the rafts to move over the water surface and this movement adds oxygen to the water to enhance the treatment efficiency. 7. Sustainability: the seedlings of the plants on the floating rafts grow over time, this process is repeated, making the floating raft systems function effectively continuously without interruption over time, especially in the tropics.	1. Occupies a large area of water (because of the biological filtration process, it requires a large planting area). 2. Some contaminants, such as oils and herbicides in municipal wastewater, can affect vegetation and harm microorganisms. 3. In order to achieve maximum treatment efficiency, plants grown on floating rafts need to be harvested periodically to avoid ageing and death of plants, causing re-pollution. 4. Water level is reduced in the low tide, or high evapotranspiration, or drought causing running out of water in the water body, making the rafts unable to float on the water. 5. Pollution because of salinity (i.e. saline intrusion in the water body), eutrophication causes plant death.

10.1.3 Operating Principles

The principles of operation of the CFWs are very simple: the plants on the floating rafts use the nutrients present in the wastewater to produce biomass. Plants provide oxygen through the root system into the wastewater environment, creating favourable conditions for aerobic microorganisms to develop, which contributes to better treatment efficiency. The pollutant removal processes that occur in CFW systems are biosynthesis, deposition, settling, and biofilm metabolism. Sedimentation occurs by the root system, and uptake by plants is the main process for removing phosphorus from wastewater (Pavlineri et al. 2017).

Plants directly uptake pollutants, especially nutrients, from the water using a process known as bio-sorption or bio-uptake. Microorganisms grow on floating rafts and attach to the root systems of the plants. They decompose and consume organic matter in the water. Root systems filter out sediments and pollutants.

Similar to other constructed wetlands with flora, the root systems of the plants below the floating rafts provide a large surface area for the adhesion and growth of biofilms (Fig. 10.1). This creates favourable conditions for the metabolism of organic substances. Microorganisms, phytoplankton, and higher plants (macrophytes) absorb and transport pollutants into the food chain. The suspended organic matter adhered to the biofilm at the root surface is decomposed, becoming food for plankton, larvae, and fish. Finely dispersed suspended solids are settled or precipitated. Aquatic plants also can store carbon dioxide (through photosynthesis), allowing them to remove and convert nitrate and ammonia into nitrogen. These processes prevent or slow down eutrophication and keep the water in balance (Fig. 10.3).

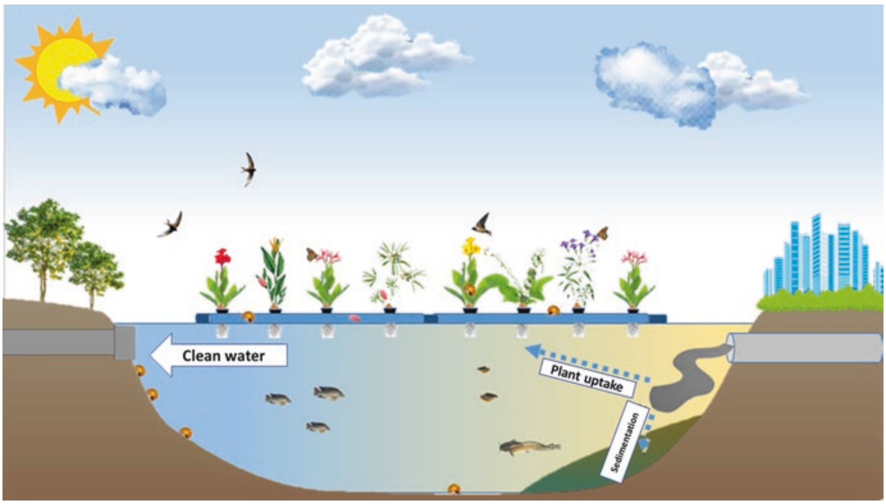


Fig. 10.3 Operating principles of CFWs

10.2 Installation Instructions

10.2.1 Installation Location Survey

10.2.1.1 Surveying the Installation Location of the CFWs

Depending on the purpose of designing the rafts, surveying the location of the raft is conducted accordingly. CFWs for wastewater treatment in urban areas can be applied at the existing ponds, lakes, rivers, and canals in the inner city, for example. Surveying and selecting the placement of the floating rafts is a very important step in the installation process because the appropriate placement of the rafts helps the rafts work more efficiently.

10.2.1.2 Obtaining Permission for Installation of the CFWs

Depending on the location where the floating rafts are to be installed, there will be a specific organisation or agency responsible for the management of the inner-city ponds, lakes, rivers/canals. In urban areas, it is possible that an urban environment company, a Water Supply and Drainage Company, or a Department of Natural Resources and Environment, for example will manage the drainage channels. When agreeing on the location of the rafts, the designer should contact the local authorities for permission of installation of the rafts to be formalised (Fig. 10.4).

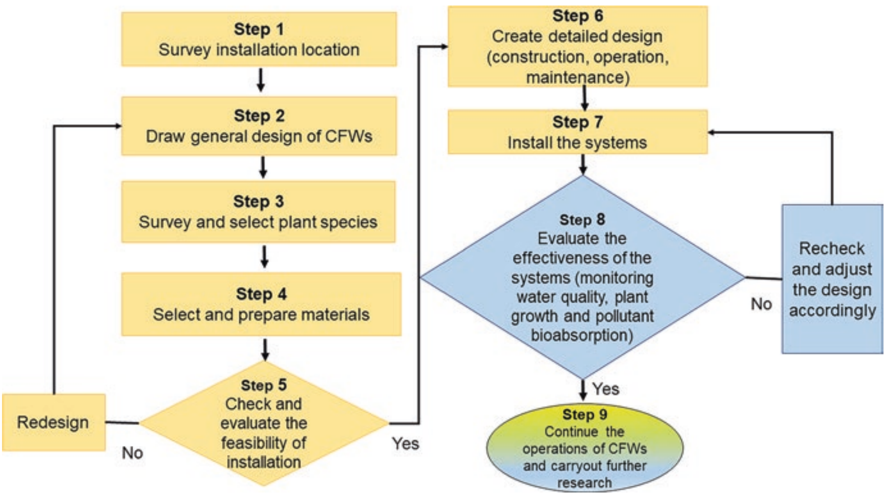


Fig. 10.4 Installation and evaluation steps for the CFWs

10.2.2 Plant Species Selection and Installation Locations

10.2.2.1 Plant Species Selection

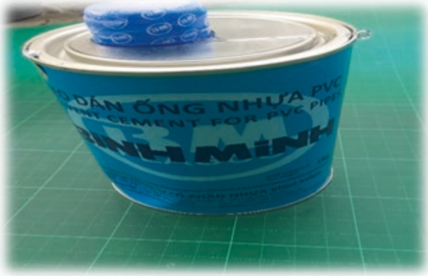
Aquatic macrophytes with emergent growth forms are suitable for selection and growing on the floating rafts. However, it is up to the designer to use the rafts for what purposes they suggest, including the selection of the appropriate species. For example, to create a landscape for the treatment area, choose plants with beautiful flowers or colourful leaves such as *Cyperus alternifolius*, *Canna* sp., *Ruellia tuberosa*, *Heliconia psittacorum*, and *Echinodorus cordifolius* (Table 10.2); if

Table 10.2 Tools and materials used in the design of each floating raft

No.	Tools and materials	Illustrating images
1	The length of a PVC (*polyvinyl chloride)* pipe was l = 2 m, the diameter of the pipe was = 90 mm • Quantity: 07 pipes of 2 m • Function: making frame of floating raft	
2	Plastic trellis mesh size 2 m × 4.5 m, mesh size 1–2 cm • Quantity: 01 grid • Function: fixed stand for planting	
3	Hydroponic baskets: • Quantity: 72 baskets (36 baskets of D57: 65 × 65 × 40 mm; and 36 baskets of 70 × 60 × 40 mm) • Function: support plants standing	

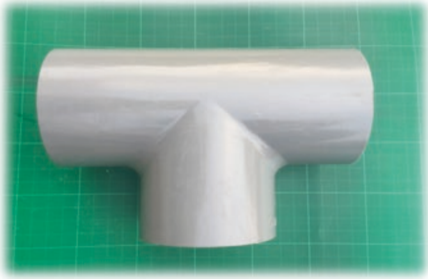
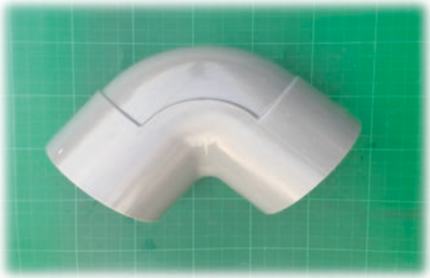
(continued)

Table 10.2 (continued)

No.	Tools and materials	Illustrating images
4	PVC pipe glue • Quantity: 1 jar (0,5 kg) • Function: Fixing PVC pipes and cores	
5	Plastic drawstring 4 T (40 cm) • Quantity: 2 bags • Function: fixing net to the raft frame	
6	Nylon string • Nylon string 3 mm: – Quantity: 2 kg – Function: used to tie the trellis to the PVC pipes • Nylon string 0.5 mm: – Quantity: 0.5 kg – Function: used to tie hydroponic baskets to the net	
7	Pincers, saw, measure • Quantity: one for each • Function: PVC pipe sawing, mesh cutting, nylon string cutting	

(continued)

Table 10.2 (continued)

No.	Tools and materials	Illustrating images
8	Φ90 mm T-shaped PVC core used to connect pipes • Quantity: 2 pieces • Function: connect pipes to form a raft frame	
9	Φ90 mm T-shaped PVC core used to connect pipes • Quantity: 4 pieces • Function: connect pipes to form the raft frame	
10	Coconut coir • Function: used as substrates to fix the plants to the baskets and to support the plants to stand	
11	Aquatic macrophytes • The species (*Cyperus alternifolius*, *Canna* sp., *Ruellia tuberosa*, *Heliconia psittacorum*, *Echinodorus cordifolius*) selected for the design in this guide. • In addition, depending on the purpose of the CFWs application, the designer can choose the appropriate plant species (outlined in Sect. 10.2.2.1)	

choosing plants to collect biomass for reuse as fodder or for composting, choose herbaceous plants such as Vetiver (*Vetiveria zizanioides* or *Chrysopogon zizanioides*), Cattail (*Typha* sp.), Reed (*Phragmites* sp.); or can choose plants that can be harvested and sold, for example *Cyperus alternifolius* (Dell'Osbel et al. 2020). Some designers even choose to plant fruit and vegetable crops such as pumpkin, eggplant, and tomato (Bi et al. 2019).

In addition to the landscape value, it is necessary to pay attention to select plants that have the ability to grow well in wastewater conditions and exhibit a high pollutant treatment efficiency. It should be noted that in order to limit the investment costs to purchase plants and to increase the adaptability of the plants on the CFWs systems, the designer needs to select native species that are available in the area where the CFWs are arranged (Bi et al. 2019). The species (*Cyperus alternifolius*, *Canna* sp., *Ruellia tuberosa*, *Heliconia psittacorum*, *Echinodorus cordifolius*) were selected for the design in this manual based on their common applicability, which were then selected and planted on the floating wetlands in application models. They have been previously applied to treat many types of wastewater and evaluated to be effective in generating high biomass, contributing to the effective treatment of pollution in wastewater (Barco and Borin 2020, Dell'Osbel et al. 2020).

10.2.2.2 Location Selection and CFWs Layout

It is very easy to choose the location to place the CFWs, it can be ponds, lakes, rivers, or canals in the inner city. However, surveying and choosing the location to install the CFWs is a very important step. During the installation process, a suitable installation position will help the CFWs work more efficiently. Selecting the appropriate location to install the CFWs should meet the following criteria:

- The installation location is large enough (note not to obstruct the traffic of boats if the canal serves waterways).
- Near the inlet point of wastewater flowing into the water body (to promote the pollution treatment effectiveness of the plants on the rafts).
- Avoid locations with tree stakes under the water (so that the raft is not entangled at low tide).
- Select locations with full sunlight to ensure photosynthesis of the plants on the rafts.
- If the water body is a river, choose places with weak currents to avoid affecting the rafts.
- It is necessary to pay attention to the concentration of pollutants in the wastewater before placing the rafts (because if the concentration is high, it will affect the vegetation on the raft, thereby affecting the pollution treatment process).
- It is necessary to avoid sources of discharge with herbicide content, which would affect the vegetation on the rafts.

Some locations and placement layouts of rafts in inner-city lakes, ponds, and canals are shown in Fig. 10.5.

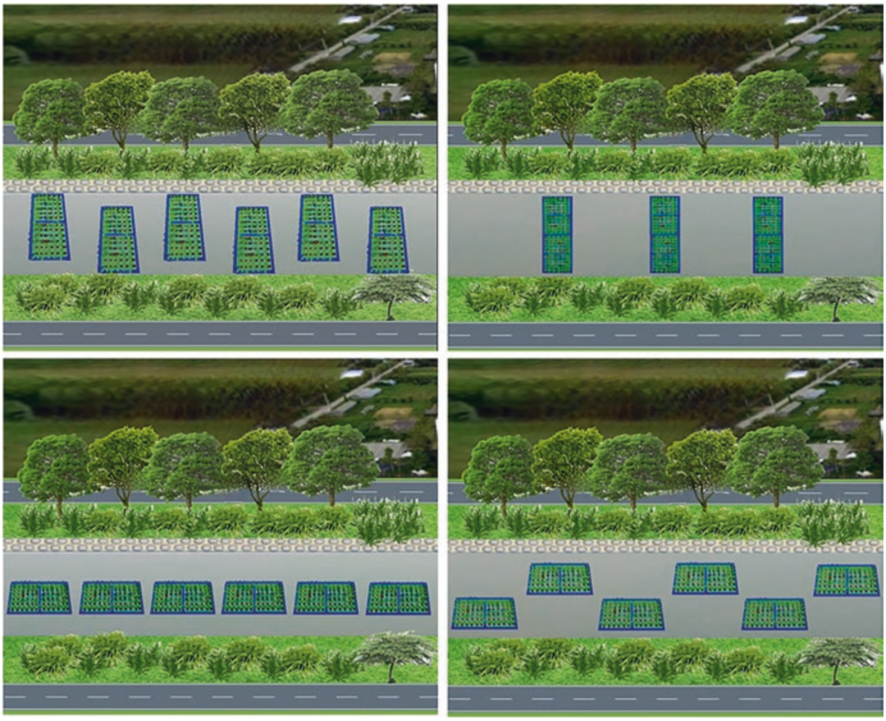


Fig. 10.5 The ways of placing the floating rafts in an urban canal

The depth of the water body selected for installation varies depending on the selected water bodies for treatment and the applied aquatic plant species. The minimum recommended depth of 0.8–1.0 m should be maintained to prevent the macrophyte roots from attaching to the benthic substrate. If the roots attach to the basin bottom, there will be a risk that the floating raft will remain anchored and become submerged when water levels rise again. This could potentially lead to the death of the macrophytes and significant damage to the floating structure (Headley and Tanner 2008). For nutrient-rich water bodies, at a depth of 0.2 m, roots can also be active. However, in nutrient-deficient wastewater such as rainwater, the recommended depth is 0.8–3.0 m because plant roots are capable of growing longer in the absence of nutrients and can grow into lower-bottom sediments.

10.2.3 Design Guidelines

10.2.3.1 Size and Shape of the Floating Rafts

The size and shape and the number of floating rafts do not follow any rigid specifications, depending on the purpose, the location of the installation in the water body, the budget, the available design materials etc. designer may have a suitable CFWs design. Depending on the size of the water body (i.e. water surface area), it is possible to design the appropriate size of the floating rafts, however, it is advisable to arrange the floating rafts with a moderate size for later easy installation and maintenance of the rafts. The recommended raft size in this guide is a length twice the width (Schwammberger et al. 2019), with a length of 4 m and a width of 2 m.

Between 2 PVC pipes of 2 m, there should be a T-shaped PVC core (Fig. 10.6). This divides and supports the PVC pipes when plants' biomass becomes high and heavy.

Materials used to make frames of the floating rafts: There are many types of materials that can be used for the frame of a floating raft for growing aquatic plants as long as it can make the rafts float on the water surface and withstand the weight of the plant throughout their life cycle. The commonly used materials for making floating rafts are: bamboo, foam sheets, plastic bottles/jars, PVC pipes, and coconut coir mats (Sharma et al. 2021) (Table 10.2; Fig. 10.7). However, since the raft is in direct contact with water, it is necessary to choose materials that will not break down when saturated with water. In addition, in tropical climates like in Vietnam, it is important to choose materials with a long life under direct sunlight. There are many commercial products (e.g. carpets) available and floatable; however, PVC pipes or natural floating materials (e.g. bamboo) are reliable and inexpensive alternatives (Pavlineri et al. 2017). The shape of the frame is designed according to the user, it can be rectangular, square, oval, circle, diamond, hexagon, and many other shapes to make it more beautiful.

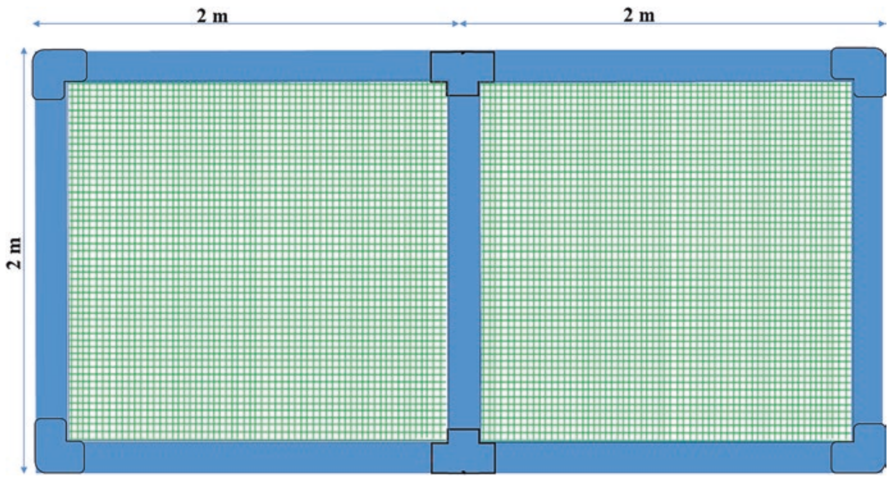


Fig. 10.6 Size of the CFWs with a rectangle shape

Fig. 10.7 Materials that can be used to make the frame of floating rafts

The recommended number of rafts, or total raft area per water surface area, is 5% for optimal nutrient treatment efficiency (Chang et al. 2012). Whereas the density of plants should allow for a total raft coverage of at least 50% (Sharma et al. 2021). In this guideline, the coverage area of the rafts per water surface area was 4.4%, and total plant coverage on each raft was 30% at the initial planting stage, whilst, within 1 month after planting the plant coverage rate increased to 80–90%.

10.2.3.2 Prepare Materials and Tools for Raft Design

The materials used to make the floating raft are presented in Table 10.2. The quantities of materials shown in Table 10.2 were used to design a raft with the dimensions of 4 × 2 m (length × width, respectively) with a total area of 8 m^2.

10.2.3.3 Material Costs for Making a Floating Raft

Materials and cost of materials used to design the floating raft with an area of 4 × 2 m = 8 m^2 are listed in Table 10.3. The total cost of materials used to design the raft was 320,000 VND/m^2 (equivalent to US$13.95/$m^2$, 1 USD = 22,946 VND (currency exchange rate in April 2022).

Table 10.3 Material costs used to design the floating raft (4 × 2 m = 8 m²)

No.	Items/product's name	Unit	Unit price	Quantity	Costs (VND)
1	Ø90 PVC pipes	m	60,000	14	840,000
2	T-shaped core	Piece	47,000	2	94,000
3	I-shaped core	Piece	30,000	4	120,000
4	Plastic drawstring 40 cm	Bag	45,000	2	90,000
5	Plastic trellis net (2 m width)	m	155,000	4	620,000
6	Nylon string (3 mm)	kg	130,000	2	260,000
7	Nylon string (0.5 mm)	kg	110,000	0.5	55,000
8	Glue	0.5 kg	150,000	1	150,000
9	Saw	Piece	40,000	1	40,000
10	Hydroponic basket D57 (6.5 × 6.5 × 4 cm)	Piece	3,000	36	108,000
11	Hydroponic basket (7.0 × 6.0 × 4 cm)	Piece	3,500	36	126,000
12	Pincers	Pair	55,000	1	55,000
Sum					**2,558,000**

Note: 1 USD = 22,946 VND (currency exchange rate in April 2022)

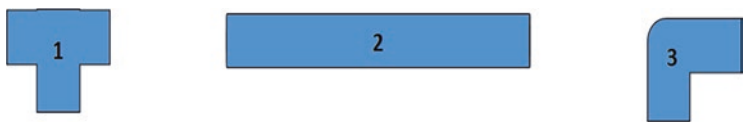


Fig. 10.8 Numbered PVC pipes and joints

10.2.3.4 Steps to Design the Rafts

10.2.3.4.1 Numbered PVC Pipes and Cores

Before installing the raft frame, use a marker to mark the joints (cores) and PVC pipes. In the design of this raft, two types of joints are used: T- and I-shaped joints (Table 10.2; Fig. 10.8). The T-shaped joints are numbered 1, the I-shaped joints are numbered 3, and the pipes are numbered 2 (Fig. 10.8). Each PVC pipe with number 2 has a length of 2 m.

10.2.3.4.2 Placing the Pipes on the Ground and Checking the Size

Choose a dry and flat area, before installation, it is necessary to remove sharp and hard objects on the ground, such as stones, gravels, and woods, to minimise the possible risks of damage to the pipes. Then proceed with the following steps in sequence:

– Place the PVC pipes on the flat ground.
– Double check the length of the pipes.
– Cut the ends of the pipes flat.

– If it is sunny, the pipes should be exposed to the sun to make it easier to glue the pipes because when the pipes absorb heat, the pipes become softer (note: it is necessary to wear gloves when the pipes are hot, to avoid burning your hands).

10.2.3.4.3 Glue the Joints and Pipes to Form the Frame

Step 1**:** Fix the two T-shaped joints marked as number 1 to the centre pipe of the raft (pipes marked with number 2) to obtain product 1 (Fig. 10.9). Since the centre pipe is the pipe that affects the flatness of the raft, this step is very important. After gluing, you must place it on a flat surface to check if the two joints are even, if not, correct them immediately because the glue is not tight at this time, if it is, then proceed to the next steps.

Step 2**:** Glue the two I-shaped joints marked with number 3 and the pipes marked with number 2, resulting in product 2 (Fig. 10.9). One raft needs these 2 products.

Step 3**:** Next, stick the 2 pipes number 2 on the remaining 2 ends of the I-shaped joints cores of product 2, we get product 3 (Fig. 10.9).

Step 4**:** Connect 2 products 3 to product 1, to get product 4, which is a complete 8 m^2 raft frame (Fig. 10.9).

After gluing the final positions, place the raft on a flat surface for final alignment before the glue dries. After checking, wait for about 2 hours for the glue to dry, at this time it is necessary to bring the raft to a shady place to quickly dry the glue and pay attention that the raft is placed on a flat surface.

10.2.3.4.4 Fix the Net to the Raft Frame

After the glue dries, fix the net to the raft frame with a drawstring or plastic tie. The length of the net needs to be about 20 cm longer than the edge of the raft frame so that when fixing the net, it is wrapped around a plastic pipe to increase the surface tension of the net, from which the plants when planted on the net will be stronger.

The net selected to be fixed to the raft is a plastic trellis net (Table 10.2; Fig. 10.10) made from PE (polyethylene) or HDPE (high-density polyethylene), the mesh is diamond shaped, with a mesh size of 1–2 cm. These two types of plastic have properties that make the mesh both flexible and resistant. The hardness is at the right level, and durable over time.

10.2.3.4.5 Fix the Baskets and Place the Plants into the Baskets

Plants are grown in specialised hydroponic baskets, so select the baskets made from PVC materials, synthetic plastics with high heat resistance, and without the need to worry about damage resulting from weather or water. The baskets are fixed to the raft with 0.5 mm small nylon string (Table 10.2), using the nylon string to tie the bottom of the basket in a cross-shaped and leaving the four extra string wires about

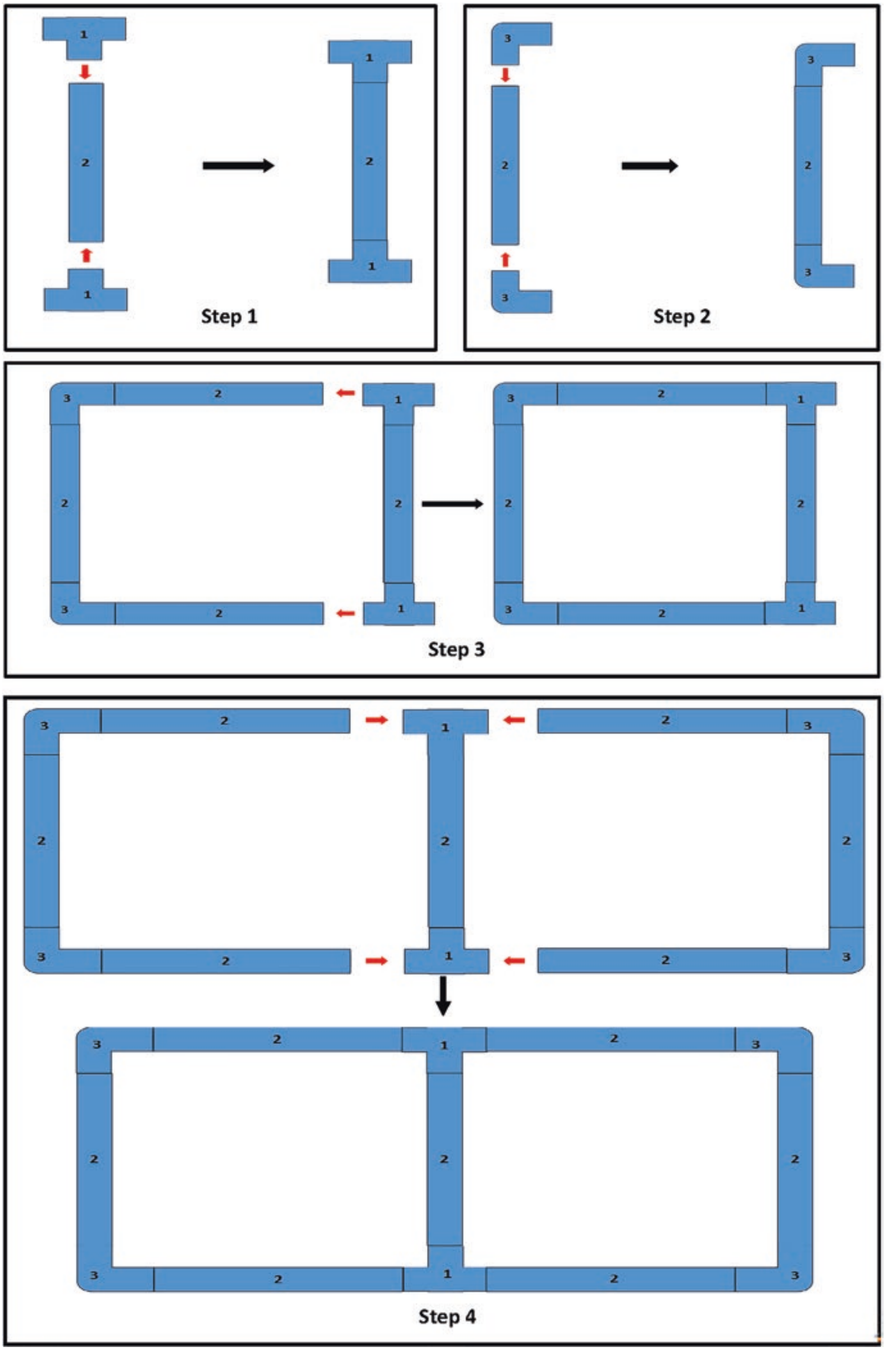


Fig. 10.9 Steps to build the floating raft

Fig. 10.10 The process of fixing the net to the raft frame

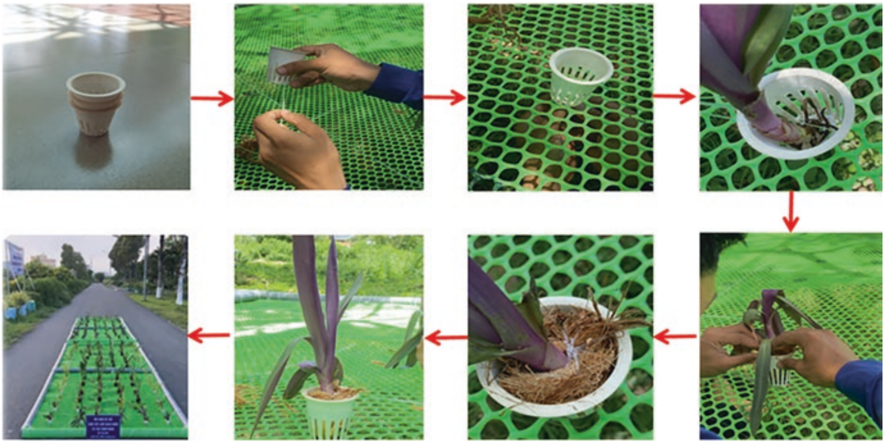


Fig. 10.11 The process of fixing the baskets and the plants within the baskets

20 cm, then, using these 4 ropes to fix plant into the basket. The distance between the baskets is 30 cm or the plants are 30 cm apart (Fig. 10.11). This results in a plant density of about 9 plants/m^2 (Huth et al. 2021; Schwammberger et al. 2019).

Plant species used to grow on the CFWs, should be selected from the species that are available and easy to collect from the surrounding fields. In addition, plants with fast growth rates and high biomass should be selected for high water treatment efficiency (mentioned in Sect. 10.2.2.1).

After tying the baskets to the plastic net, check the plastic baskets again and make sure that the plastic baskets are firmly tied to the net because when they are tied insecurely, the plants will fall and may die.

Next, take the coconut coir and wrap it around the roots of the seedling. The use of the coconut coir has the effect of keeping the seedlings firmly fixed within the basket. In addition, it also has the effect of keeping the plant roots moist. The coconut coir should not be tied too tightly that the roots cannot develop fully.

The last step is to use the remainder of the nylon string to fix the plants to the plastic baskets, be careful not to tie the plants too tightly to affect their growth. The raft is complete, as shown in Fig. 10.11.

10.2.4 Launching and Fixing the Rafts

After completing the fixation of the plastic baskets to the net and the raft is fully designed (Fig. 10.11), the raft is launched into the water body (Fig. 10.12), where the wastewater needs to be treated (noted that the rafts should be placed near the point at the inlet wastewater of the water body to increase pollutant uptake). Select a location in the water body where there is an open space, avoiding shaded trees and underwater stakes to launch the raft. It is advisable to wait for the highest tide of the day to facilitate the release of the raft, easy to manipulate and avoid affecting the seedlings (Fig. 10.12). If the place where the raft is launched has floating garbage on the water body, it is necessary to remove the garbage before launching to avoid the garbage getting caught in the raft, causing difficulties in future maintenance.

The way of placing and fixing the floating rafts on the water body to be treated also determines their efficiency. It is recommended that the rafts are placed so that the water flow is perpendicular to the rafts and there is no gap for the water to flow parallel to the raft (Lucke et al. 2019). In addition, as mentioned above, depending on the function and role of the water body, if the movement of waterways is not restricted, the rafts should be placed perpendicular to the width of the canal (Fig. 10.5), which increases the exposure of the water direction, lengthening the path and the passage of the water will increase the water treatment efficiency of the rafts.

The next step is to tie the drawstring to both ends of the raft and fix the raft on the shore with melaleuca poles to prevent the raft from drifting away with the tide. It is also possible to tie the end of the string to fix the raft on trees planted along the shore. For water bodies affected by tides, it should be noted that when fixing the

Fig. 10.12 Launching and fixing the rafts

Fig. 10.13 Maintaining the plants on the rafts

raft, it is necessary to leave a length of string with a length according to the water level of low tide and low water level, to avoid the case of low water level causing the raft hanging and the plants lacking water. In addition, for the inspection, maintenance of the raft, and plant biomass collection or cleaning on the raft, if you want to do it on the shore, just wait for the high tide and pull the raft ashore easily (Fig. 10.13). In the case that the pond or canal is quite large; it is possible to invest in a small boat or raft to harvest plant biomass.

10.3 Operation and Maintenance Manual

10.3.1 Operation

For the CFWs, the operation is very simple, just launch the raft into the water bodies to be treated. The raft works by itself according to the water filtration mechanism as described in Sect. 10.1. Seedlings use nutrients in the wastewater to grow and develop until the plants flower or show signs of ageing (depending on the species, the harvest time will be different). However, in order to increase the efficiency of nutrient uptake of the plants, after about 2 months, pull the raft to prune/trim and reduce the plant biomass (only collect old branches and flowering stems). Leave about 2–3 seedlings/cluster (Fig. 10.14) for the plants to regenerate without needing to replace plants (due to the nature of aquatic plants they have a very good self-regeneration ability), only replace new plants in the case of plant death or poor growth performance.

10.3.2 Maintenance and Management

10.3.2.1 Plant Well-Being and Pruning

In order for aquatic plants on the raft to grow well and create a beautiful landscape, the plants need to be cared for regularly and periodically pruned. Every month, cut weeds on the baskets for the optimal growth of plants. Additionally, replace dead plants with new ones. To prune/trim plants and clear grass on the raft, the raft can be pulled close to shore for trimming (Fig. 10.13). When pulling the raft ashore, be very careful not to damage the root system.

Depending upon each species, the plant growth time will be different, so it is advisable to select a combination of planting species on the same raft with the same growth period. The plants need to be pruned of old branches, flowering plants/stems in order to create space and stimulate the growth of young shoots. For *Cyperus alternifolius*, *Canna* sp., *Heliconia psittacorum* etc., it is advisable to prune the plant biomass once every 2 months (Fig. 10.14).

10.3.2.2 Using Plant Biomass

Some of the ultimate uses of plant biomass are as follows:

- The harvested plants' biomass can be used for biogas composting or composting.
- Ornamental flowers such as *Canna* sp., and *Heliconia psittacorum*, can be cut and sold.
- Branches of *Echinodorus cordifolius* can be separated into seedlings to sell as ornamental plants, with the remaining biomass composted for biogas.
- *Cyperus alternifolius* can be cut and dried for use as a lanyard or fresh branches can be sold at the florist.

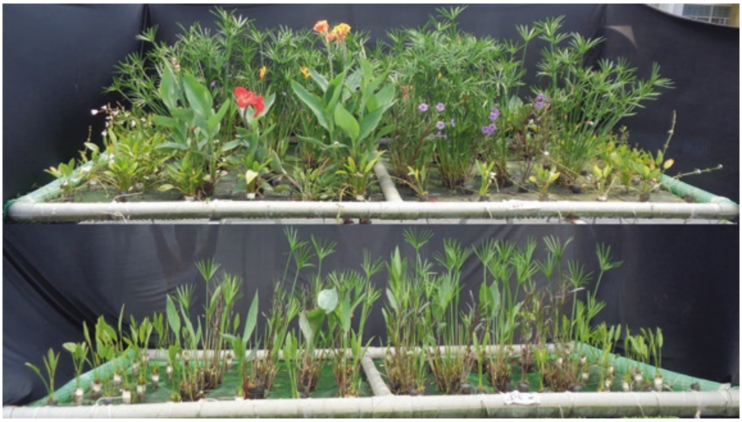


Fig. 10.14 Prune the plants on the raft once every 2 months

10.3.2.3 Common Problems

Some of the common problems or challenges in the management of CFWs are as follows:

- For water bodies with a lot of garbage, it is common for garbage to drift and entangle with the rafts, so it is necessary to monitor the raft regularly and clean up the trash on the rafts, otherwise, they will affect the plants and cause damage to the raft. More seriously, the plants may die, and the rafts may tilt or sink.
- The raft is placed in the water body, so depending on the tidal regime, it is necessary to check the fixed line regularly because the raft can become stuck on the shore at low tide, and the plants will die when there is no connection to water (Table 10.4; Fig. 10.15).

Table 10.4 Some frequent incidents, causes, and solutions

Problems	Causes	Solutions
Water leaking into the connecting pipes (raft tilting or sinking)	Insufficient gluing, or the operation of pulling the raft to the bank to collect the plant/grass because the plant's weight is too heavy, causing the joints to crack	Pull up the rafts, remove the pipes and joints and re-install/re-fix it, or add a float to raise the raft
The raft is hung on the shore when the water dries up	The string is too short in relation to the water level at low tide	Monitor the raft regularly and check the string

Fig. 10.15 Some common problems

10.4 Conclusions

The guidelines presented in this chapter for the installation, operation, and maintenance of constructed floating wetlands are intended to encourage investment in these urban ecological solutions. These guidelines offer a cost-effective approach to replicating constructed wetlands in various urban settings whilst minimising land requirements. Constructed floating wetlands can deliver significant ecosystem services, including provisioning, regulation, support, and cultural benefits. Their primary contribution lies in improving surface water bodies and subsequently enhancing biodiversity. However, challenges related to maintenance, plant harvesting strategies, and community involvement exist. Future endeavours could focus on improving data collection, enhancing design guidelines for nutrient and contaminant uptake rates, refining maintenance strategies, promoting plant diversity and adaptation to climate change, and understanding community perceptions and appreciation to ensure the sustainable replication of constructed floating wetlands.

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Chapter 11
Replicability and Pathways for the Scaling of Nature-Based Solutions for Water Treatment: Examples from the Philippines, Sri Lanka, and Vietnam

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Abstract The importance of nature-based solutions (NbS) for urban water treatment is growing due to their cost-effectiveness and the multitude of ecosystem services they offer, contingent on appropriate design and meticulous implementation. Drawing upon the experiences of a project that assessed the effectiveness of a set of NbS solutions in South and Southeast Asia, namely, constructed wetlands in the Philippines, constructed floating wetlands in Sri Lanka and Vietnam, and green roofs for water treatment in Vietnam, this chapter explores possible approaches to and pathways for the scaling of those solutions. Specifically, it discusses the results of targeted efforts aimed at supporting the replication of those technologies in different locations and contexts and other possible pathways for scaling that have emerged in the course of the implementation of the project.

Keywords Constructed wetlands · Constructed floating wetlands · Green roofs · Nature-based solutions · Scaling

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11.1 Introduction

Growing populations in cities across Southeast Asia are turning water quality into a pressing challenge for human well-being and ecosystem health in the context of climate change. Increased demand for clean water for both people and nature, coupled with limited resources for the implementation of large-scale grey infrastructural interventions and increasing awareness of the multiple services offered by nature itself, has opened up spaces for experimentation with nature-based water treatment across the region over the past decade (Pachova et al. 2022). Assessments of the effectiveness and impacts of such interventions have begun to provide evidence for policymakers and practitioners interested in taking existing experiments further (Jegatheesan et al. 2023). Understanding whether and if so, how existing interventions can be replicated across different contexts and by different actors, however, remains limited. This chapter contributes to addressing this gap by sharing the experiences with the replication of a set of NbS for water treatment tested in the framework of a project on Integrated assessment of existing practices and development of pathways for the effective integration of nature-based water treatment in urban areas in Sri Lanka, the Philippines, and Vietnam, funded by the Asia-Pacific Network for Climate Change Research.

11.2 Innovative Approach to Exploring Existing Practices and Scaling Opportunities

Designed as a 2-year initiative that aims to explore and learn from existing small-scale nature-based water treatment practices employed across cities in Sri Lanka, the Philippines, and Vietnam, the project employed an integrated and participatory approach consisting of three core elements: (a) an integrated assessment of existing practices, (b) stakeholder consultations and knowledge exchange, and (c) exploration of alternative pathways for scaling (see Fig. 11.1). The project was led by RMIT University in Australia and included seven partners from different research, non-government organisations (NGO) and public sector institutions in Sri Lanka, the Philippines, and Vietnam, alongside two academic partners based in Europe. The discussion in subsequent sections provides an overview of its major findings and achievements.

11.2.1 Integrated Assessment of Existing Nature-Based Water Treatment Solutions in Sri Lanka, the Philippines, and Vietnam

Nature-based solutions (NbS) are solutions that are inspired and supported by nature and are seen as cost-effective and able to simultaneously provide environmental, social, and economic benefits and help build resilience (European Commission

Fig. 11.1 Integrated and participatory approach for exploring and learning from existing nature-based water treatment practices

(n.d)). As such, they are expected to generate a range of diverse benefits and a number of methodologies for capturing those have been developed and advanced over recent years (Kooijman et al. 2021). Most methodologies, however, are generic and need to be adapted to the specific nature-based water treatment solutions and contexts in which they are to be employed. In the framework of the specific project, an integrated approach for assessing and learning from a set of selected nature-based water treatment practices employed across the countries participating in the project was developed and tested during the first year of the initiative (Jegatheesan et al. 2023).

The nature-based water treatment technologies selected for the study included constructed floating wetlands (CFWs), constructed wetlands (CWs), and green roofs (GRs). The technologies were selected by project partners familiar with existing practices and opportunities in the local contexts, with a view of their potential to contribute to addressing important water quality challenges in different countries. Biweekly consultations amongst the project partners at the initial stages of the project helped to agree on a set of indicators and develop methodological approaches for assessing the multi-faceted impacts of the selected technologies. Those included a range of targeted water quality but also broader environmental, social, and economic indicators that were captured through a combination of methodological approaches, including review and analysis of secondary data capturing the institutional context, history, and process for setting up and managing the selected technologies, alongside with a review of existing quantitative data, targeted surveys and consultations with relevant local stakeholders.

The findings from the study suggest that whilst relevant water quality indicators were adequately captured by existing monitoring sources in most cases, evidence of the broader environmental and social impacts was only anecdotal. Targeted surveys and stakeholder consultations employed to capture those provided an indication of their range, but further research is needed to develop and validate comparable and easily replicable tools for capturing and validating the environmental and social impacts of the examined NbS. In terms of capturing the costs and benefits of the examined projects, a simplified cost-benefit ratio assessment methodology found a positive return to investment for all of the examined nature-based water treatment solutions, even without accounting for a range of intangible benefits that were left out of the calculations (Jegatheesan et al. 2023).

With the intent of addressing prevailing limitations, the project sought to establish comprehensive guidelines for the assessed NbS, and these guidelines constitute a significant portion of this book's content. These guidelines encompass various aspects, including the mapping of current NbS in partner countries, suitability assessment, economic analysis, considerations of social acceptability, as well as detailed guides for CWs, GRs, and CFWs (both in Sri Lanka and in Vietnam), along with a guide for selecting plants suitable for CFWs.

In tandem with these chapters, this chapter is dedicated to shedding light on the pathways for upscaling and replication, drawing on the project's experiential insights. By sharing the lessons and outcomes derived from the project, this chapter seeks to enrich the understanding of how these NbS can be extended to broader contexts and effectively replicated.

11.2.2 Replicability of Examined Nature-Based Solutions (NbS)

The project then delved into the viability of replicating the aforementioned NbS, resulting in diverse approaches by project partners to identify external entities willing to undertake these replications. The guidelines developed in the project were applied and tested during the replication. The ensuing sub-sections provide detailed insights into the approaches and outcomes of these trial initiatives.

11.2.2.1 Replicability of Constructed Wetlands (CWs) in the Philippines

As part of the project, trialling the developed framework and the tools incorporated in the guide (please see Chap. 6) were considered to provide the validation and test of the replicability of CWs for wastewater treatment in the Philippines. The trial was the application of CWs in the septage treatment of a Panguil River Eco-Park in Laguna, Philippines. The eco-park highlights the Panguil River, which has an estimated length of 12.5 km and is one of the tributaries of Laguna de Bay. The Laguna Lake Development Authority (LLDA) regularly monitors the river through one of its 15 river monitoring stations. The river is used for domestic, agricultural, ecotourism, and economic purposes by the Municipality of Pangil.

The Society for the Conservation of Philippine Wetlands, Inc. (SCPW), which is one of the APN project partners, has an existing collaboration with the municipality of Pangil and the managers of the eco-park to provide a series of training on NbS and their ecological benefits, particularly CWs, to the communities (barangays) surrounding the Panguil River. The SCPW plans to build the CWs at the site to treat the septage from their septic tanks. Thus, the developed guide framework will be tested at the Panguil River Eco-Park.

The SCPW conducted a capacity-building activity focused on NbS and CWs and their role in wetland management in June 2023. It comprised lectures and learning sessions about wetlands conservation and management, NbS, and CWs framework. In addition, there was a section in the training about how to culture Effective microorganisms (Bokashi) to ensure adequate supply for the CWs and for use by local communities in their homes. Further, a survey and focus group discussions (FGD) with the local community were conducted to determine the social acceptability of CWs for septage treatment.

11.2.2.1.1 Training on NbS and CWs

This learning event was primarily conducted as a way of community preparation and promoting the social acceptability of CWs (or Green Filters) amongst the local communities to secure its successful operation at the Pangil River Eco-Park. Over a 100 participants from the eight Barangays of Pangil participated in the event, consisting of barangay officials, youth, women groups, and other local community groups. The objectives of the training are as follows: (i) to increase awareness of wetlands and the ecosystem services they provide, (ii) to understand and appreciate the importance of NbS in the treatment of wastewater, (iii) to take actions towards wetland restoration by helping to reduce water pollution in Panguil River and Laguna de Bay through local community initiatives.

During the open forum for the framework (detailed in Chap. 6), the participants were keener to learn when the CWs will be constructed and how they can be involved. They had no pressing feedback on the framework but would like to see a working system first. They emphasised that visiting an actual CWs set-up will help to appreciate more the role of CWs for their septage treatment. They also worried that CWs might not apply to them since their septic tanks already exist, and it would be hard to connect them if new CWs were built. This was then clarified to them that CWs are not necessarily connected to the septic tanks, but the septage will be desludged and directed to the CWs (location still requires further study). Overall, the participants generally accepted the framework as useful in the implementation of CWs. Finally, It was also evident that the participants showed more interest during the workshops on making Effective Microorganism (EM) solutions and bokashi balls, which means they are willing to engage with these kinds of NbS, provided with training and technical support.

11.2.2.1.2 Focus Group Discussion

Three sets of Focus Group Discussions (FGDs) were conducted with officials from different barangays in Pangil, Laguna, Philippines, including (1) Barangay San Jose and Dambo, (2) Barangay Balian, and (3) Barangay Natividad. A total of 126 participants were surveyed and interviewed. During these sessions, it became evident that the barangay officials were largely unaware of the concept and functions of CWs. They expressed that the FGDs and learning events on NbS and CWs conducted by SCPW were their initial exposure to CWs and the first time they learned about the establishment project of CWs in their municipality.

The FGD participants acknowledged that whilst they grasped the theoretical explanation of CWs, they believed that witnessing operational CWs would provide a clearer understanding. They expressed confidence in the potential benefits this approach could bring to their community, particularly if implemented across the barangays. Anticipated advantages included access to clean water, an enhanced and biodiverse wetland environment, nature conservation, improved public health, increased tourism appeal, and a potentially positive impact on long-term food security by substantially reducing water pollution. Moreover, the Barangay officials noted that implementing CWs would be especially advantageous in newly established communities, where the location and integration of CWs system within the sewerage infrastructure could be strategically planned. Some officials also suggested that CWs system could offer valuable assistance in livestock farming, notably in managing organic waste, particularly pig and poultry farming.

Whilst their response was largely positive, the officials acknowledged several potential risks. They were concerned about issues such as leaks and overflows, particularly during adverse events like storms and floods, the possibility of biological hazards from CWs, which may adversely affect community health and cause diseases, and the potential attraction of mosquitoes and flies, which CWs may bring. Furthermore, some FGD participants highlighted the importance of sustainable maintenance and operations of CWs system, expressing reservations about the government's capacity to ensure ongoing viability. They were worried that inadequate maintenance could lead to project failure.

Despite these reservations, the officials expressed overall support and acceptance for the project's pursuit and establishment within their Local Government Units (LGUs) as a pilot demonstration of the CWs technology. They believed a functional CWs example within their community would foster greater appreciation and understanding of the technology, encouraging replication in their respective barangays if resources, funding, and space permitted. They were also considering and asking for the possibility of integrating a constructed wetland with their existing waterways and rivers to reduce water pollution in the river.

To ensure successful implementation, the FGD participants emphasised key factors: raising public awareness through effective information dissemination campaigns, community involvement, unwavering commitment and support from barangay officials and the Municipal LGU, effective waste management, secure funding, robust CWs design and construction, and proper operation and maintenance protocols. Officials recommended seeking the support of the Sangguniang Bayan or Municipal Legislative Body of Pangil, Laguna, to enact an ordinance outlining the support, operation, and maintenance of CWs system, which can contribute to its sustainability. Public hearings and community participation were seen as crucial components of this process. Additionally, they mentioned that establishing a comprehensive waste management system within the municipality, including improvements to the sewerage infrastructure, should be prioritised.

When asked about their willingness to pay for ecosystem services provided by CW, all officials expressed readiness to contribute. They said the amount varied based on the extent of services and the community's financial capability. In general, officials indicated a willingness to pay an average of 20–50 Philippine pesos per month (around 1 USD per month), with a maximum limit of 300 Philippine pesos (6 USD) per month, given if CWs services could rival those of private companies in domestic wastewater management.

11.2.2.2 Replicability of Constructed Floating Wetlands (CFWs) in Vietnam

Application of CFWs for urban canal water management was conducted successfully in pilot studies at Can Tho University (CTU) and implemented in Bung Xang Canal, Can Tho City of Vietnam (10°01′37.7 "N 105°45′51.9" E) as a pioneering field-scale application in the country. The learning from the CFWs in Bung Xang

Canal was extended to the Agricultural Seed Centre in Vinh Long province (10°09′43.2 “N 106°01′10.4” E) located approximately 50 km from Can Tho City. A staff member of this centre residing alongside Bung Xang Canal has displayed a keen interest in CFWs installed at Bung Xang Canal. During a meeting at CTU, the staff inquired about the installation process for CFWs. Further, they expressed the desire to implement them for the centre’s water management and landscaping. This contributed to revising the Vietnamese version of a guide on CFWs (see Chap. 10). The confidence in comprehending the installation instructions led the staff to undertake the process independently. Upon obtaining approval from the APN project leader, the financial support was extended for the materials necessary for CFWs installation.

Additionally, the project team in Vietnam assisted the staff by preparing plants during the installation phase. Several staff members have actively engaged in all project activities within the centre. Moreover, a group of final-year agriculture students from Cuu Long University, Vinh Long province, have also played a role in installing the new CFWs.

To validate the methodology and guide produced on CFWs (Chap. 10), new trials were devised, meticulously following the guide construction steps. Notably, the dimensions of the CFWs were adjusted to accommodate the canal’s narrower width, shorter length, and shallower depth (averaging approximately 3.5 × 40 × 1.5 m). Within the 140 m^2 canal, where water drained from paddy fields flows, a total of 12 m^2 of CFWs were installed, with each CFW covering an area of 2 m^2. This installation accounted for 8.5% coverage of the canal’s top surface area. A selection of four ornamental species, including *Canna × generalis, Heliconia psittacorum, Echinodorus cordifolius*, and *Cyperus alternifolius*, were planted at a density of 9 plants/m^2 (Fig. 11.2).

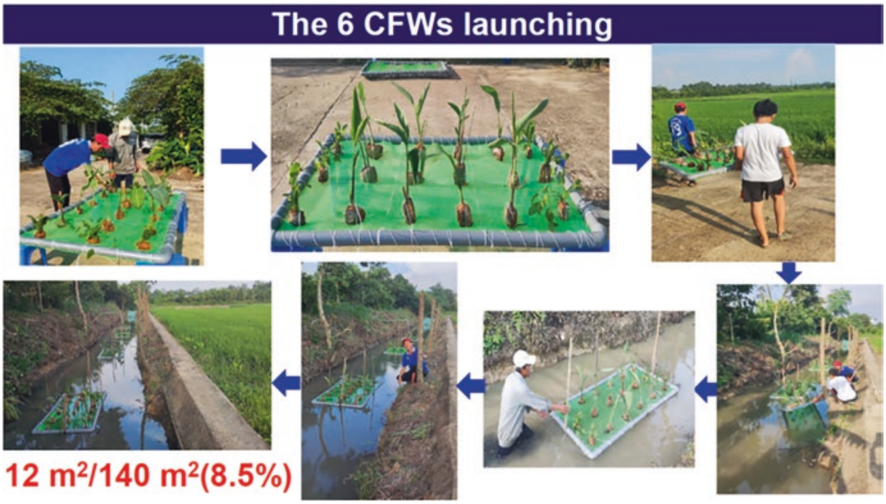

Fig. 11.2 The installation and launch of six CFWs

The installation of the six CFWs was successfully completed in June 2023. Following the construction guidelines, ongoing maintenance tasks were diligently carried out, including assessing raft materials and trimming plant biomass every 2 months. Moreover, two bachelor's students were scheduled to undertake their final BSc theses, focusing on plant growth and water quality monitoring as part of the ongoing project activities. Water quality monitoring was scheduled to be conducted monthly, whilst plant growth and biomass measurements were to be made once every 2 months. The materials used to install each CFW cost about 30 USD/2 m^2.

The Agricultural Seed Center serves as a pivotal venue for showcasing new rice varieties and restoring rice varieties, attracting numerous visitors, including farmers, local authorities from various districts and provinces, and even international visitors. This is the primary motivation behind the decision to install the CFWs, as it was recognised that the CFWs contribute to an aesthetically pleasing landscape adorned with vibrant flowers. Furthermore, the staff member anticipates that the CFWs will effectively mitigate nutrients and pollutants in the drainage water from paddy rice fields before reaching the river. Remarkably, a week after installation, the staff member personally observed and captured images of fish gathering near the CFWs during noon hours. Further, as the six newly installed CFWs have been in place for 2 weeks, the plants have exhibited robust growth. In addition to adhering to the guidance for testing the methodology and guide, alternative methods of securing plants onto the raft netting in these trials were explored. Given that hydroponic plastic cups used in the previous CFW system in the Bung Xang canal limited root growth, three different approaches were employed: (i) utilising coconut coir to secure roots and fastening them to the net with nylon string, (ii) employing coconut shells to anchor roots and attaching them to the net with nylon string, and (iii) incorporating coconut coir to stabilise roots before placing them in a rolled net structure to ensure plant stability (Fig. 11.3).

The trial in Vinh Long province remains a personalised initiative. Consequently, the replication of CFWs is considered to only occur in regions with genuine interest. The success of the practical application model of CFWs in urban water management and landscape enhancement serves as a testament to the efficacy of the guide produced (as discussed in Chap. 10). Developed through the practical implementation of CFWs in the urban Bung Xang Canal, Can Tho City, the guide has facilitated the design and installation of replicated CFWs at the Agricultural Seed Center in Vinh Long province. The design and installation of the six new CFWs closely followed the guide's materials and step-by-step instructions.

11.2.2.3 Replicability of Green Roofs (GRs) in Vietnam

Urban households are increasingly prioritising enhanced quality of life, driving them to seek green space expansion, improved air quality, and enhanced landscapes. Green roof systems emerge as potent solutions, particularly in space-constrained urban areas like Ho Chi Minh City (Vietnam). Beyond aesthetics, these systems bolster stormwater drainage infrastructure and foster healthier urban environments.

Fig. 11.3 Installation of plants into the rafts with three modified methods to hold the roots of plants

Adaptability to rapid urbanisation and the mitigation of environmental strains, especially as traditional green spaces dwindle, make green roof installations effective and pertinent (see Chap. 7 for the detailed guide to constructing and installing green roof systems).

A survey of canal-dwelling residents in Ho Chi Minh City yielded valuable life perspectives. This insight led to collaborations with specific households willing to pilot green roof installations. One such household agreed to trial a green roof system on their rooftop. Challenges arise with older buildings sporting undivided grey and black wastewater drainage systems, hampering operational efficiency. Temporary grey wastewater collection was implemented, though aesthetics suffered. New buildings require separate drainage systems during construction. Interestingly, government and public permission for green roof installations on Vietnamese building rooftops is unnecessary. As interest in green roof installations gains traction, it is foreseeable that regulations and permissions will be formulated to govern the process.

11.2.2.3.1 Description of the New Trial GRs System

The new trial system was successfully set up and operated on a household rooftop in Ho Chi Minh City, Vietnam (Fig. 11.4), in strict accordance with the comprehensive guide provided by the research team. This compact system measures 2000 × 200 × 170 mm (length × width × height) (Fig. 11.5). The media arrangement includes a coconut shell layer (1880 × 200 × 30 mm) on top, followed by a charcoal layer (1880 × 200 × 70 mm) at the bottom. Alongside, rock layers (60 × 200 × 100 mm)

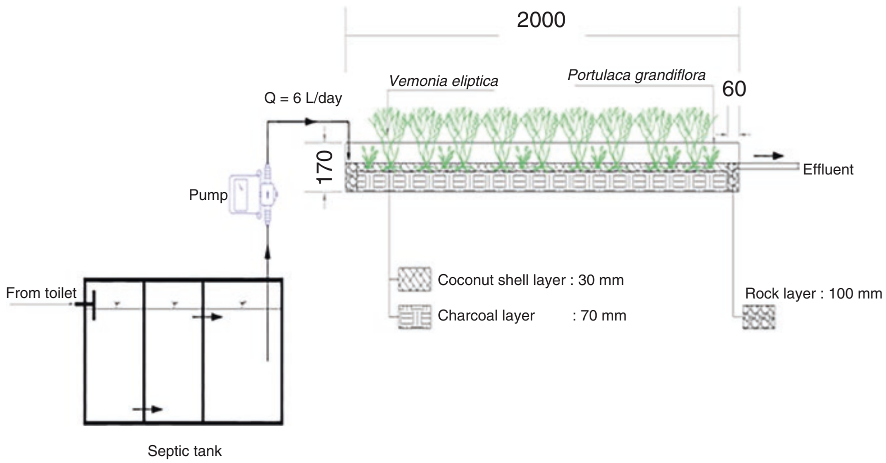

Fig. 11.4 Schematic diagram of the trial green roof

are placed on both vertical sides. Within this set-up, Vernonia elliptica and Portulaca grandiflora were planted, with densities of 40 and 20 plants/m^2 and initial heights of 30 and 5 cm, respectively. The installation involves five straightforward steps: (i) setting up the tray, pipes, and influent tank; (ii) adding charcoal to the tray; (iii) adding coconut shell to the tray; (iv) introducing rocks to the tray; and (v) planting the green roof system. The information on water quality improvement due to the implementation of GRs is summarised in Table 11.1.

Operating parameters for the green roof system were set at a flow rate of 6.0 L/d, organic loading rate of 9.0 ± 1.0 kg COD/ha/d, and nitrogen loading rate of 0.6 kg N/ha/d. The average removal efficiency of Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), ammonium (NH_4^+-N), and Total Phosphorus (TP) were 66 ± 8%, 46 ± 2%, 80 ± 5%, and 50 ± 6%, respectively. The treated water from the green roof meets the discharge standard limits stipulated by the Ministry of Natural Resources and Environment (QCVN 14:2008/BTNMT, level B). The treated water was thus discharged into the urban sewerage system. On the other hand, the plant development of the GRs is summarised in Table 11.2 and Fig. 11.6. Table 11.2 shows plants are well adapted to grey wastewater in the green roof system installed at a specific household. Remarkably, the system has remained consistently functional without encountering significant issues for over 2 months.

The green roof system's construction cost comprised the material and labour expenses. The material costs comprised 30 USD for a 2000 × 200 × 170 mm chamber, 2 USD for a 0.06 m^3 plastic influent tank, 2 USD for PVC/uPVC pipes, 4 USD for 0.026 m^3 charcoal layer, 2 USD for 0.011 m^3 coconut shell layer, and 22 USD for 16 *Vernonia elliptica* and 8 *Portulaca grandiflora* plants. The total expense for a green roof module is approximately 60 USD. When the green roof systems have been well-designed and well-maintained, many benefits have been achieved, such as (i) stormwater management due to the reduction of the flow of stormwater from

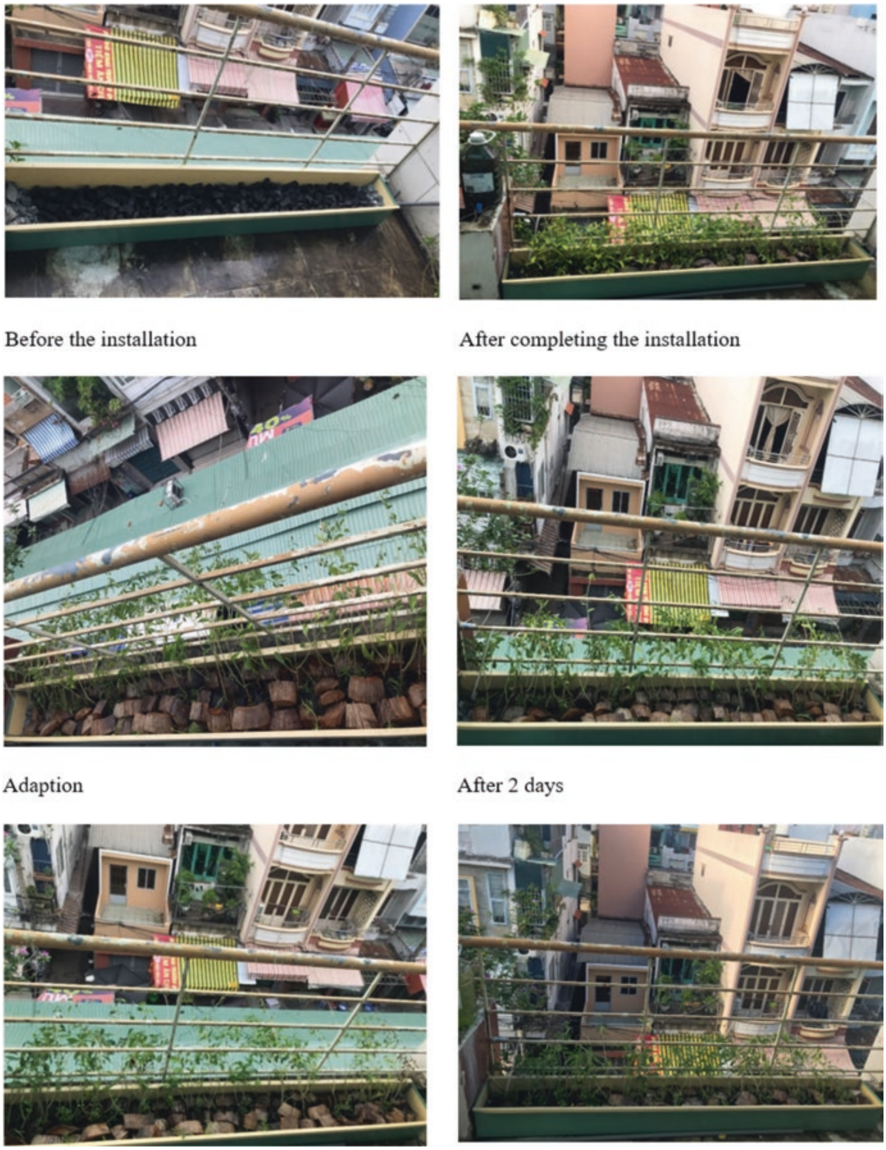

Fig. 11.5 Successful replication of a green roof in a household and the progression of plant growth for 2 months after the installation

Fig. 11.5 (continued)

Table 11.1 Characteristics of influent and effluent grey wastewater

Parameter	Unit	Influent	Effluent	Discharge standard*
pH	–	8.1 ± 0.6	7.9 ± 0.5	6.5–7.5
TSS	mg/L	38 ± 25	13 ± 7	100
COD	mg/L	59 ± 5	32 ± 6	–
NH_4^+-N	mg/L	40.0 ± 2.4	8.1 ± 1.2	10
TP	mg/L	0.6 ± 0.5	0.3 ± 0.2	10

a The national standard for domestic wastewater (QCVN 14:2008/BTNMT—Level B)

Table 11.2 Plant development of the GRs system

Plant	***Vernonia elliptica***	***Portulaca grandiflora***
Initial average height (cm)	30 ± 2	5 ± 1
Average height after 3 months (cm)	90 ± 10	15 ± 5
Average plant growth (cm/day)	0.8 ± 0.2	0.1 ± 0.1
Average fresh weight (g/plant)	10.3 ± 0.5	1.3 ± 0.2
Density (plant/m^2)	40	20

Fig. 11.6 *Vernonia elliptica* (**a**) and *Portulaca grandiflora* (**b**)

a roof; (ii) providing new urban habitat for plants and animals, like birds and insects, thereby increasing biodiversity; (iii) reducing the effect of heat-related illness and death, and air pollution; and (iv) adding beauty and value to buildings.

11.2.2.3.2 Upscaling of GRs System

The ongoing operation of the new trial system over an extended period will determine its stability and performance, providing valuable insights for potential replication. This autonomous trial module offers a versatile approach to scalability, allowing the seamless integration of multiple units to construct larger systems. The arrangement of green roof modules can be tailored to suit the characteristics of the wastewater, available installation space, budget considerations, and other factors. This adaptable configuration can involve direct or parallel connections, offering flexibility in system design.

The trial green roof system, currently established within a specific Ho Chi Minh City household, boasts numerous benefits. These encompass efficient grey wastewater treatment, augmentation of green spaces, moderate cost (approximately 60 USD per module), ease of installation, and the added advantage of not requiring formal clearance from local authorities. Given these merits, the green roof system emerges as a highly promising solution for broader implementation across metropolitan areas.

In terms of public acceptance, many people are willing to install GRs in their houses because they recognise that these systems can improve the environmental quality and enhance the landscape. However, upscaling green roof systems depends on the installation space, cost etc. Thus, it needs more time to convince people to employ the GRs systems.

11.2.2.4 Trial of Improved Floating Wetlands in Kurunegala Lake, Sri Lanka

The CFWs implemented at Kandy and Kurunegala lakes, pivotal to the framework's development, yielded significant insights into their operational performance. The evaluation process informed an important enhancement to the design, introducing a coir pith mat with a geomembrane outer layer. This revision aimed to curb erosion of the original growth media (coir pith mat), optimising system durability. Despite the plants being in their vegetative stage, their average height ranged from 30 to 50 cm, demonstrating robust growth even in the absence of regular maintenance. These advancements were guided by design criteria drawn from the project's comprehensive guidebook (Chap. 8), and the following are some essential parameters along with their corresponding values: Seven units of CFWs, each having approximately 14 plants, were installed at a site in Kurunegala Lake in June 2023. The dimensions of a floating wetland unit were 1.98 × 0.58 (= 1.14 m^2) (Fig. 11.7), and the views of those CFWs in the lake are illustrated in Fig. 11.8.

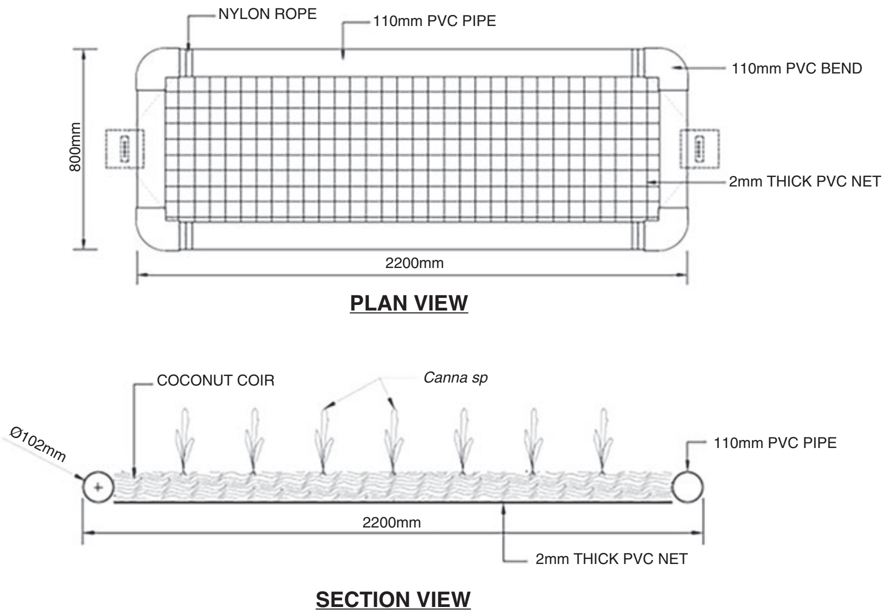

Fig. 11.7 Plan and sectional view of a constructed floating wetland

Fig. 11.8 Views of CFWs

Materials and labour costs per unit of constructed floating wetland with 220 cm × 80 cm (outer area) were LKR 8613.00 and LKR 7000.00, respectively. Fabrication and installation costs per unit were LKR 15,613.00 and LKR 10,000.00, respectively. Thus, the total cost per unit was LKR 25,613.00 or USD 79.42 (1 USD = LKR 322.55 on August 29th, 2023).

These improved CFWs are in the process of being installed at Kandy Lake. Additionally, biofilm carrier incorporation is being tested in the laboratory to evaluate their impacts on plant growth and nutrient uptake in CFWs. It will be applied in a lake situated in the eastern province of Sri Lanka through a research study to further development of pathways. Thus, the trials highlight that the design, fabrication, installation, maintenance, and performance assessment of CFWs in urban lakes for water pollution control are continuous and evolving processes that demand meticulous attention and well-informed decision-making.

11.2.2.5 Lessons Learnt from the Replicability Studies

From the replicability of the examined solutions, it can be said that they are potentially justifiable from a long-term investment perspective, but set-up costs and availability of resources (human, financial, institutional etc.) arguably play a stronger role in determining decisions on establishing small-scale trials. The following findings were made from the study: (i) The set-up of such small-scale initiatives and trials is usually not based on formal cost-benefit analysis but is driven by intrinsic interests, professional motivations, relevant supporting networks, an enabling context and appropriate windows of opportunities; (ii) formal analysis of the costs and benefits, however, could be important to convince potential donors for investing in the scaling of good practices; and (iii) there are different types of scaling, and again, arguably, many of those could be seen as somewhat bigger trials themselves and thus are driven by and require a wide range of different resources and creative approaches for exploring and mobilising them.

11.2.3 Approaches to Scaling

Scaling is often oversimplified, with a common belief that producing evidence for policymakers constitutes the extent of researchers' contributions. However, scaling is a complex endeavour. Even with adequate funding, the intricate interplay of contextual variations can determine the triumph or failure of endeavours. In light of these challenges, a more nuanced approach emerges, which can be termed as action research. This approach seeks to engage stakeholders in the research process and implementation of the interventions. By adopting a bottom-up perspective, action research delves into the intricacies of scaling pathways, acknowledging the vital role of grassroots efforts in driving meaningful expansion. Further, such research should emphasise scaling pathways for impact to provide larger-scale changes (Moore and Riddell 2015). Some known scaling pathways are scaling up, scaling deep, scaling across, and scaling out or wide (Westley et al. 2014; Moore and Riddell 2015; Nardini et al. 2022). In the case of the APN project presented here in the book, several types of scaling pathways of NbS can be identified, which are described below:

- Scaling deep: Scaling deep can be defined as enhancing the performance and impacts of existing measures by deepening the understanding and relations with the broader socio-ecological ecosystem. Improvements of existing demonstration projects through closer engagement of local stakeholders and searching for additional partners and resources, as were the case in the trials of CFWs and GRs and large-scale application of CWs, are types of scaling deep. Further, community engagement activities, such as NbS-CW training, done at the Pangil, Laguna, establish and will eventually deepen the relationships with the stakeholders (Nardini et al. 2022).

- Scaling up: Scaling up can be considered as integrating relevant concepts, guidelines, and tools in governance and planning to improve the enabling environment for both sustaining existing interventions and supporting the establishment of new ones. Examples of scaling up of this project are (i) the commitment to establishing a regular stakeholder consultation group by the Sri Lankan project partners and forming lake management committees, fostering stakeholder exchanges in Sri Lanka and (ii) the co-development of guidelines for the establishment of nature-based water treatment solutions by the Philippines project partners with local policymakers, for use by local authorities, as transpired during the national consultative meeting in 2022.
- Scaling out or wide: Scaling wide is the replication of existing good practices and examples in different geographic locations and socio-economic contexts. Examples are the integration of guidelines in planning and potential up-taking by other cities in the Philippines and the development of the local network of NbS in Sri Lanka. In Vietnam, one of the staff at the Agricultural Seed Centre in Vinh Long province adopted the CFWs to manage the canal adjacent to the centre, whilst the GR is being implemented at one household in Ho Chi Minh City.
- Scaling across: Scaling across entails the expansion of prevailing methods and strategies into different realms. This involves adapting and redefining existing interventions or incorporating components of those interventions into various sectors, as in the case of transitioning from maturation ponds as NbS due to their large size and limited control to more manageable and replicable GR trials in urban settings. Meanwhile, in Sri Lanka, the impact of constructed floating wetland trials extended to educational settings, as seen in integrating these trials into a school environment alongside the formation of a youth researchers exchange group—both instances exemplifying scaling across. Notably, an unconventional form of scaling across emerged from addressing water pollution caused by bird droppings in Sri Lanka's lakes, a pertinent concern under the project's objectives. On the other hand, including biofilm carrier trials and plant tests in CFWs in Sri Lanka, as well as green roof substrate improvements and Bokashi cultivation in the Philippines, can be considered as scaling across.

11.3 Conclusions

The efficacy of the framework devised to assess the effectiveness and impacts of nature-based solutions (NbS) for urban water treatment was validated through trials involving constructed floating wetlands and green roofs. This validation aimed to ensure the framework's robustness. Furthermore, the socio-economic facet of the framework was put to the test during a planned CWs trial. These experimental endeavours provided valuable insights into the applicability of different facets of the framework when considering the scaling of NbS. The project partners' guidelines played a pivotal role in enabling the replication of NbS, such as constructed floating wetlands and green roofs at various stakeholder locations in Vietnam, illustrating wide-scale implementation or scaling out. Scaling deep manifested in the enhancement of existing NbS through trials and community engagements. Scaling up was evidenced by the adoption of wetland construction guidelines by the local government in the Philippines and the formation of lake management committees in Sri Lanka. Scaling across is exemplified by studying water pollution caused by bird droppings, biofilm carrier trials, and plant experimentation in Sri Lanka, as well as improvements to green roof substrates and the cultivation of Bokashi in the Philippines.

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