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REVIEW ARTICLE

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Co-development of an integrated assessment framework to evaluate the effectiveness and impact of selected nature-based water treatment technologies in Sri Lanka, The Philippines, and Vietnam

Veeriah Jegatheesan[1] | Nevelina Pachova[2] | Perlie Velasco[3] | Mohamed Ismail Mohammed Mowjood[4] | Sujithra Kaushaliya Weragoda[5] | Madhubhashini Makehelwala[5] | Ngo Thuy Diem Trang[6] | Bao-Trong Dang[7,8] | Cong-Sac Tran[8,9] | Thi-Kim-Quyen Vo[10] | Nguyen Thi Thu Trang[11] | Huy Pham[11] | Ma. Catriona Devanadera[12,13] | Antonina Torrens[14] | Xuan-Thanh Bui[8,9] | Phuoc-Dan Nguyen[8,9,15] | Amy Lecciones[14] | Kristhombu Baduge Shameen Nishantha Jinadasa[16]

[1]School of Engineering and Water: Effective Technologies and Tools (WETT) Research Centre, RMIT University, Melbourne, Victoria, Australia

[2]RMIT Europe, Barcelona, Spain

[3]Department of Civil Engineering, College of Engineering and Agro-Industrial Technology, University of the Philippines – Los Baños, Laguna, Philippines

[4]Department of Agricultural Engineering, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka

[5]Joint Research & Demonstration Centre (JRDC), University of Peradeniya, Peradeniya, Sri Lanka

[6]Department of Environmental Sciences, College of Environment and Natural Resources, Can Tho University, Can Tho, Vietnam

[7]Faculty of Chemical Engineering, Ho Chi Minh City University of Technology (HCMUT), Ho Chi Minh City, Vietnam

[8]Vietnam National University Ho Chi Minh City (VNU-HCM), Ho Chi Minh City, Vietnam

[9]Key Laboratory of Advanced Waste Treatment Technology, Ho Chi Minh City University of Technology (HCMUT), Ho Chi Minh City, Vietnam

[10]Faculty of Biology and Environment, Ho Chi Minh City University of Food Industry (HUFI), HCM City, Vietnam

[11]School of Business and Management, RMIT University, Vietnam

[12]Department of Community and Environmental Resource Planning, College of Human Ecology, University of the Philippines – Los Baños, Laguna, Philippines

[13]Society for the Conservation of Philippine Wetlands, Inc., Pasig City, Philippines

[14]Department of Biology, Healthcare and Environment, University of Barcelona, Barcelona, Spain

[15]Asian Center for Water Research (CARE) & Faculty of Civil Engineering, Ho Chi Minh City University of Technology (HCMUT), Ho Chi Minh City, Vietnam

[16]Department of Civil Engineering, Faculty of Engineering, University of Peradeniya, Peradeniya, Sri Lanka

Correspondence
Veeriah Jegatheesan, School of Engineering and Water: Effective Technologies and Tools (WETT) Research Centre, RMIT University, Melbourne, Victoria, Australia.
Email: jega.jegatheesan@rmit.edu.au

Abstract

Water quality is a critical challenge in Asia in the context of growing industrialization, urbanization, and climate change. Nature-based solutions (NbS) could play an important role in reducing urban water pollution, while generating multiple co-benefits that could make cities more liveable and resilient. In this regard, a number of pilot and demonstration projects have been set up to explore their potential across cities in Asia. Their effectiveness and impacts, however, have not been adequately documented, thus how they can be sustained, replicated and up-scaled remain poorly understood. This study aims to contribute to addressing this challenge by co-developing an integrated assessment framework and employing it to understand how existing evaluations of NbS in the region can be improved. It focuses specifically on a set of nature-based solutions that have been employed for water treatment across six cities in Southeast Asia (two in each Sri Lanka, the Philippines, and Vietnam), namely, floating wetlands, constructed wetlands and maturation ponds. The study also suggests specific methodologies for capturing a set of core indicators considered relevant for assessing the effectiveness and capturing the multi-faceted impacts of the examined NbS.

KEYWORDS
constructed wetland, floating wetland, integrated assessment framework, maturation ponds, nature-based solutions (NbS), water treatment

1 | INTRODUCTION

Urban water management is a critical challenge in Asia in the context of growing industrialization, urbanization, and climate change. Over the past decades, access to safe water and sanitation arguably improved for many urban dwellers across the region (United Nations, 2022). Water quality, however, even of tap water, remains a challenge (USAID, 2017) and so does the need for sustaining and expanding existing infrastructure to meet the needs of growing urban populations in the context of a changing climate and the risks to people and infrastructures associated with them (ARCOWA, 2018). For example, in the Philippines, only 11% of the Metro Manila population is connected to sewerage systems before being discharged into water canals that mostly end up in Manila Bay (Claudio, 2015), thus posing significant concerns for the health of people and various ecosystems. The situation is similar in Sri Lanka and Vietnam (World Bank, 2018). In the context of the recent Covid-19 pandemic, addressing public health concerns in cities has also been associated with a growing need for access to green spaces (Lu et al., 2021; SEI, 2020). This has given rise to a need for a reconsideration of how urban water management needs across cities in Asia are met and how new water management infrastructures could be designed in a way that they contribute to making cities greener, more liveable, and resilient (Aerts et al., 2020).

Decentralized, flexible and adaptable, nature-based water treatment solutions have been increasingly employed to test innovative approaches for closing water and material loops, and thus contributing to sustainable urban development transformations and change across Europe, Australia, and the world. Specifically, they have been shown to generate cost savings, reduce carbon footprints, increase resilience to extreme weather events, and support biodiversity and habitat conservation, while improving water quality and availability for water users (Ertel et al., 2019). Thus, they are seen as contributing to meet the targets of the Sustainable Development Goals (SDGs) 6 on clean water and sanitation (SDG 6) but also to a number of the other goals by creating more healthy lives (SDG 3), resilient urban infrastructure (SDG 9), inclusive and sustainable economic growth (SDG 8) and sustainable urban settlement (SDG 11), while helping to reduce the environmental impacts of human activities on water (SDG 14) and land (SDG 15) and the impacts of climate change (SDG13) through enhanced partnerships (SDG 17) and opportunities for environmental education (SDG 4) (Somarakis et al., 2019; WWAP, 2018).

Given their promising potential, international donors and regional financial institutions, such as the World Bank, Asian Development Bank (ADB), Asia-Pacific Network (APN) for Global Change Research and Gesellschaft fur Internationale Zusammenarbeit (GIZ), among others, have begun to promote and finance pilot projects to demonstrate how nature-based water treatment could be integrated in urban development and planning and could contribute to a more water-sensitive urban design in developing countries in Asia. This has added to the efforts of local researchers, who have been testing nature-based water treatment solutions in laboratory facilities for decades. As a result, there is a growing body of knowledge on the potential of nature-based water treatment to contribute to sustainable urban development in Asia. Much of that knowledge, however, has not been compiled, analyzed and translated into replicable methodologies, actionable strategies, and guidelines for supporting the upscaling of good practices and the integration of nature-based water treatment in planning.

Systematic analysis of existing knowledge requires an integrated framework for assessing and comparing experiences across different contexts and sites. This study co-develops and employs such a framework to evaluate the experiences of three types of nature-based treatment technologies, namely, floating wetlands, constructed wetlands and maturation ponds in Sri Lanka, the Philippines, and Vietnam. The focus on those specific nature-based solutions (NbS) was driven by a consideration of what were considered promising technologies in different local contexts but also by the potential for learning through a cross-fertilization of ideas and experiences across them.

The paper starts with an overview of existing NbS assessment frameworks and a description of the process used to co-develop an integrated, yet context and NbS-specific framework for assessing the set of selected NbS case studies from the three countries in the framework of a project funded by the Asia-Pacific Network for Global Change Research that has been acknowledged in the paper. This is followed by an exploration of the urban water management context in each of the examined country, that takes into account historical developments and current approaches to sanitation and water treatment with a particular focus on the role of nature-based water treatment technologies employed for that purpose. Subsequently, an overview of nature-based water treatment case studies selected as a basis for co-developing an integrated assessment framework is presented. The case studies are: (i) floating wetlands installed in two urban lakes in Sri Lanka, (ii) constructed wetlands which are being operated in two cities to treat septic effluents in the Philippines and (iii) a maturation pond and a floating wetland that are being operated in two cities in Vietnam to treat wastewater and surface water. The selection of NbS in each country was made based on a consideration of existing real-life applications of NbS for water treatment, data availability and accessibility, and the expertise and experience of the project partners. It should be also noted that all three types of NbS considered in the paper were selected with a view of their applicability across the three countries as one of the aims is to learn from each other and explore the replicability of the examined NbS in the context of other countries in the future based on the outcomes produced from the project. Following the description of the case studies, the integrated assessment framework is presented and employed to assess the effectiveness and impacts of those NbS. Finally, notable gaps in available data and methodologies for addressing them are suggested for future studies.

2 | INTEGRATED ASSESSMENT FRAMEWORK OF NbS FOR WATER TREATMENT: CURRENT STATUS

2.1 | Existing assessment frameworks measuring the effectiveness of NbS for water treatment

The concept of nature-based solutions draws upon and is related to a range of ecosystem-based approaches, such as ecological restoration, ecological engineering, forest landscape restoration, ecosystem-based adaptation, ecosystem-based mitigation, ecosystem-based disaster risk reduction, ecosystem-based management, green infrastructure, and the various area-based conservation approaches such as protected area management. Based on a comprehensive review of those approaches, Cohem-Shacham et al. (2016) suggested eight general principles for assessing and guiding the design of NbS interventions, including nature conservation, synergies with other solutions, site-specific context, transparency, participation and equitable benefit sharing, maintenance of cultural and biological diversity, landscape scale, trade-offs within social-ecological systems and policy integration (Cohen-Shacham et al., 2016).

The NbS principles given above provide a normative basis for assessing the extent to which a given NbS treats the social and ecological systems involved in an integrated framework. They do not, however, provide a framework for assessing the performance of an NbS with respect to an identified challenge or a specified objective in a specific place (territory), time, and socio-economic context. Such performance can be measured by capturing: (i) change towards targets related to the specified objectives; (ii) change in relation to a baseline/reference; or (iii) a combination of the two. Specifically, performance can be assessed by comparing results before and after the intervention, from different NbS interventions or from alternative non-NbS interventions and may also analyze trends over time. In order for performance assessments to enable adaptive improvements in the course of implementation and capturing of the lessons learnt, however, they need to be linked to a theory of change that reflects the causal linkages between the undertaken actions and the expected or observed impacts.

The NbS principles given above provide a normative basis for assessing the extent to which a given NbS treats the social and ecological systems involved in an integrated framework.

2.2 | Frameworks for measuring the impacts of NbS for water treatment

Capturing impacts, that is, the causal effects of an NbS intervention, is a complex undertaking. Until recently, solutions for treating water were seen as simple technologies, and therefore their performance indicators were basically quality control indicators (concentration indicators of contaminating parameters, contaminant load and % elimination of those indicators). Some assessments of the technologies included economic analysis or indicators, or other aspects such as operation or maintenance expenses but at most, analyses of the life cycle of the technology were carried out. As nature-based technologies for treating water began to gain importance and the concept of NbS became more widespread, the need for a broader and more holistic view became evident, and the need to consider not only economics but also social indicators has been increasingly recognized. As an example, the latest European Union (EU) guide on assessment of NbS includes indicators of climate resilience, water management, natural and climate hazards, green space management, biodiversity enhancement, air quality, place regeneration, knowledge and social capacity building for sustainable urban transformation, participatory planning and governance, social justice and social cohesion, health and wellbeing and new economic opportunities and green jobs (EC, 2021).

2.3 | Challenges with existing assessment frameworks

NbS are extremely diverse and the assessment of their effectiveness and impacts is a challenging and context-dependent task. Evaluation handbooks, such as that developed by experts in Europe (EC, 2021) provide a comprehensive overview of possible indicators and methods for their measurement. Given the small scale and decentralized nature of many NbS, however, carrying out comprehensive assessments in most cases is neither feasible nor necessary. What is needed instead is a process and a set of criteria for selecting NbS and context-specific indicators that enable periodic integrated assessments of the performance and the impacts of the established NbS by addressing challenges, improving performance, enabling learning from the experience and providing an evidence base for sustaining, replicating and scaling them. In the section below we describe the process and criteria employed for co-developing such a framework with respect to the NbS for water treatment selected for assessment in this study.

2.4 | Co-developing a context and NbS-specific framework for integrated assessment

The framework for integrated assessment suggested in this paper was co-developed through an iterative process of consultation and adaptation carried through a series of fortnightly on-line meetings and exchanges in the framework of a collaborative research project focused on NbS for water treatment in Sri Lanka, Vietnam, and the Philippines. Participants in the process included academics with a diverse range of disciplinary backgrounds from the natural and social sciences, including water management, engineering, economics, and planning, from the three target countries, Australia and Europe. Selected practitioners and academics from other fields were invited to share additional experiences and knowledge with the core team in three quarterly meetings and in dedicated presentation and discussion sessions. Furthermore, the national teams engaged with other local stakeholders through individual consultations, targeted stakeholder meetings and surveys.

Content-wise, the co-development process included a consideration of both the core international frameworks for NbS evaluation noted above and the NbS selected for in-depth case studies in the three countries. Drawing upon the existing frameworks, the participants agreed on a set of core indicator categories considered important for an integrated assessment. Those included the following: (1) Effectiveness: technical design and operational aspects considered important for assessing the operational effectiveness of the examined interventions; (2) Impacts: environmental, social, and economic impacts (planned or not) of the examined interventions; and (3) Context: the institutional, policy and governance aspects of the local context considered essential for ensuring the sustainability and potential for up-scaling. For each of those assessment categories, indicators were selected by dedicated task forces of experts involved in the study which reviewed and considered both relevant generic indicators discussed in the literature and context-specific issues and impacts emerging from the review of secondary data and stakeholder consultations related to the specific case studies.

Important aspects considered when selecting indicators for assessing the performance, impacts, and context of the examined NbS included: (a) the intended goals of the NbS; (b) the expected use of the treated water; (c) the socio-economic and ecological co-benefits considered important in the local context; (d) the potential unintended negative impacts of the NbS; (e) existing primary and secondary data from different sources relevant to the monitoring of different impacts; and (f) the capacities of the local agencies responsible for performance and impact monitoring.

Based on the above-mentioned process, a framework for integrated assessment of the selected NbS was co-developed and employed to conduct a preliminary assessment. The integrated assessment framework and the results from its application are described in more detail in section four below. Prior to that, the water management context and the selected NbS case studies in each country are examined in turn.

3 | COUNTRY-WISE NbS CASE STUDIES

The location, land area, population and the climate of Sri Lanka, the Philippines, and Vietnam are summarized in Table S1, given in the Supplementary Material. The six case studies of NbS technologies for water resource management in those countries are summarized in Exhibit 1. This table provides the overview of the types of NbS considered in each country with the information on their location, implementing agency, date established, and status of operation. The subsequent sections discuss the details of each country's wastewater management as well as the details of the case studies given in Exhibit 1.

3.1 | Sri Lanka

In the past, Sri Lanka had an excellent village tank cascade system to use the water sustainably. Over time, urbanization, climate change and population growth increased the water demand and polluted the existing freshwater resources. Various grey, green and blue wastewater treatment systems are being employed to improve the quality of freshwater resources. Over the recent years, one type of nature-based treatment system, floating wetlands, has gained particular attention as a tool for improving the water quality in the lakes. The subsequent sections provide a summary of sewerage treatment and applications of floating wetlands in urban lakes in Sri Lanka as a sustainable solution for environmental challenges.

3.1.1 | Sewage treatment

At present, ancient knowledge and wisdom have been used with advanced modifications for wastewater treatment. Sewage collection, treatment, disposal/reuse strategy has been developed based

EXHIBIT 1 Case studies on NbS used in this study

Country	NbS site	Type	Address	Implementing agency/(Funded or owned)	Date established	Status
Sri Lanka	Kandy Lake	Constructed floating wetland	Kandy, Central Province	Irrigation Department	2014	Operational
Sri Lanka	Kurunegala Lake	Constructed floating wetland	Kurunegala, North Western Province	Kurunegala Municipal Council and Kurunegala Pradeshiya Sabha	2021	Operational
Vietnam	Binh Hung Hoa wastewater treatment plant	Stabilization ponds	Ho Chi Minh City, Vietnam	Ho Chi Minh City Urban Drainage One Member Co., Ltd.	August 2004	Operational
Vietnam	Bung Xang canal	Constructed floating wetland	Can Tho City, Vietnam	College of Environment and natural Resources (CENREs), Can Tho Universit (CTU)	April 2022	Operational
The Philip-pines	Gawad Kalinga-Fishermen's Village Wastewater Treatment Facility	Constructed wetland	Bayawan City, the Philippines	Local government unit (Bayawan City)	September 2006	Operational
Philippines	Life Project for Youth (LP4Y) Eco-Village	Constructed wetland	Calauan, Laguna, the Philippines	Life Project for Youth with partners Global Nature Fund; K'Archer; Sika; Holcim Philippines; K'Archer.	May 2017	Not fully opera-tional

on hybrid solutions. Additionally, the following could be stated as the key regulations and policies and their implementation pathways: Wastewater treatment is a mandate at the source in Sri Lanka. Central Environmental Authority (CEA), Sri Lanka, the government regulating body has the mandate to monitor, approve and take action if the source does not comply with the regulations. Effluent Quality Standard has to be maintained to discharge the wastewater into the environment. Environmental Protection License (EPL) has to be obtained prior to any activity dealing with wastewater generation. The public can make a complaint to CEA with regard to violation of the regulation.

The wastewater treatment for point-source of pollution (industries and domestic sector) in Sri Lanka is regulated by the government. However, there are deficiencies in monitoring and implementing such regulation (effluent quality standard) due to various reasons. Non-point source of pollution is difficult to control in the prevailing context in Sri Lanka. The urban runoff, agricultural runoff and untreated point-source discharge end up in water bodies such as rivers, lakes and reservoirs.

The National Water Supply and Drainage Board (NWSDB) has successfully implemented sustainable nature-based techniques such as waste stabilization ponds systems, floating wetlands, constructed wetlands and, sludge treatment systems to treat wastewater in Sri Lanka. For the sustainability of these systems, the public contribution is essential. Hence, a deep understanding of social aspects would be beneficial to maintain, upscale, and replicate nature-based solutions throughout the country.

Figure S1 (given in Supplementary Material) shows the various types of sanitation systems used in Sri Lanka and the notable use of nature-based treatment systems for wastewater treatment most concretely. Currently, on-site sanitation takes up 87.4% of wastewater treatment. For decentralized wastewater treatment systems, septic tanks along with upflow anaerobic filters, subsurface wetland, and disinfection are being used. In centralized wastewater treatment systems, either waste stabilization ponds or maturation ponds along with other conventional treatment systems are being used. Thus, nature-based treatment systems such as wetlands, waste stabilization ponds and maturation ponds are being integrated with conventional wastewater treatment systems. When it comes to evaluating the performance of NbS, no specific criteria have been used. Performances are evaluated based on the surface water discharge standards set by the Government of Sri Lanka. Social, technical, and governance aspects are considered at the initial stages of the design of the treatment systems but no post-evaluations after the construction of those systems are conducted.

3.1.2 | Floating wetlands in urban lakes

The following are the five major urban lakes in Sri Lanka: (i) Beire Lake in Colombo, (ii) Kandy Lake in Kandy, (iii) Kurunegala Lake in Kurunegala, (iv) Gregory Lake in Nuwara Eliya, and (v) Nuwara wewa in Anuradhapura. Lakes in urban landscapes are unique compared to other water bodies in terms of their services and stresses. They provide drinking water, flood and drought mitigation, groundwater recharge, biodiversity, aquatic resources, aesthetic value, recreation, historical, and cultural significance. However, they are also subject to severe stresses such as water pollution, and sedimentation, leading to a loss of biodiversity and aesthetic value, and affecting the livelihood of urban dwellers. Due to their nature, urban lakes belong to multiple stakeholders such as city residents, institutions (government and private), business ventures, and visitors. In this regard, lakes in Sri Lanka are no exceptions and therefore the ecosystem health of those lakes is challenged. The sustainability of urban lakes and their services needs to be ensured considering their dynamic social complexity.

To improve the performance of lakes, various treatment systems can be used. One of the nature-based treatments employed for such purposes are floating wetlands (FWs) which when installed in a lake appropriately, could improve its water quality and subsequently the social and economic services provided by the lakes. FWs are an innovative type of the more traditionally constructed wetland and pond technologies that offer great potential for the treatment of urban stormwaters. The FWs employ rooted, emergent macrophytes growing on a mat floating on the surface of the water rather than rooted in the sediments. Appropriate governance and policies are required to ensure and maintain the performance of those floating wetlands. This paper considers Kandy lake and Kurunegala lake as case studies in developing an integrated assessment framework to evaluate the effectiveness and impacts of the floating wetlands installed in those lakes.

> *FWs are an innovative type of the more traditionally constructed wetland and pond technologies that offer great potential for the treatment of urban stormwaters.*

Floating wetlands in Kandy Lake

Kandy Lake is located at a World Heritage site in Kandy, Sri Lanka. This is an urban lake located near the Temple of Tooth, a major cultural and spiritual site in the region and the country. Kandy lake was constructed during 1810–1812. The lake has a perimeter of 3.4 km and a maximum depth of approximately 14 m. It has a surface area of 18 ha with a capacity of 8.41 million m^3. The catchment area that is feeding water to the lake is 2.85 km^2. The lake has two spill gates, five major silt traps and twenty-three minor silt traps. It experiences high fish mortality in a cycle of about 5 years due to unknown reasons, arguably linked to accumulated toxic pollutants (Weragoda et al., 2012).

To improve the quality of the water in the lake, in 2014, floating wetlands were installed at six major inlets to the lake (Exhibit 2). The Department of Irrigation is the responsible government agency for the lake which receives assistance in conducting water quality investigation and designing floating wetland systems from th National Water Supply and Drainage Board (NWSDB).

Floating wetlands at Kurunegala Lake

Kurunegala city requires around 5000–7000 m^3 of water to fulfill its daily water demand and water is abstracted mainly from Deduru Oya, a river closer to Kurunegala City. But the water level in Deduru Oya drops significantly down during drought seasons which leads to shortages in meeting the water demand. When this occurs, Kurunegala Lake water is used as a supplementary source. Thus, Kurunegala Lake has become a critical water resource for the city. It occupies 0.46 km^2 and the catchment that drains the surface runoff to the lake has an area of 1.8 km^2. However, the quality of water suffers due to the urban runoff that enters the lake via Moda Ela and other culverts (Hapuarachchi, 2019) and has experienced occasional eutrophication in the recent past (in 2002, 2003, and 2009). The lake was cleaned twice in 2003 and in 2010. Thus, introducing suitable onsite water treatment technologies in the places of the lake where high pollution loads enter has been recommended by researchers (Hapuarachchi, 2019). In response, floating wetlands were installed in 2021 to improve the water quality in the lake (Exhibit 3).

3.2 | The Philippines

The Philippines water resources are as follows: 251,100 million m^3 of groundwater reservoirs storage capacity, 108,923 km^2 of rivers, 1,871.64 km^2 of major lakes used for aquaculture, 8,330 km^2 of swamps, estuaries, brackish ponds, and man-made reservoirs. The Philippines has more than 316 fish species, some of which are endemic, and the coastal waters are considered the center of marine biodiversity in the world. Water resources are largely taken for agriculture, while industry and domestic sectors share the rest (with 96% of water withdrawals are from surface water with 4% from groundwater for drinking purposes). However, water supplies are being threatened greatly by water pollution (from human trash, commercial agricultural chemicals, untreated raw sewage, animal waste, and industrial wastes) in the country. Only 10% of wastewater from households undergoes secondary or tertiary treatment before disposal and only 4% or urban households have access to sewerage systems. Experts have concluded that out of 421 river systems 50 are biologically dead or dying due to pollution. Improper disposal of wastewater contributes to up to 58% of groundwater contamination due to infiltration of industrial, agrochemical and farm wastes, and discharges from septic tanks and subsurface flow of urban runoffs. The annual economic losses due to water pollution are estimated to be around USD 1.3 billion. Aside from water pollution, over-extraction has led to a decline in groundwater levels, over-exploitation of forest resources, and inappropriate land-use practices have disturbed the hydrological condition of watersheds. They

EXHIBIT 2 Current status of the floating wetland in Kandy Lake. [Color figure can be viewed at wileyonlinelibrary.com]

EXHIBIT 3 Implementation of floating wetlands in Kurunegala Lake. [Color figure can be viewed at wileyonlinelibrary.com]

have resulted in accelerated soil erosion, siltation of rivers and valuable reservoirs, increased incidence and severity of flooding, and decreased water supply. Lastly, projected climate change too would have a significant impact on the Philippines where water management will become more challenging over time (ARCOWA, 2018; Claudio, 2015; Sespeñe et al., 2016; USAID, 2017).

The following could be stated as the key regulations and policies and their implementation pathways: the main government body in-charge of the water bodies in the Philippines is the Department of Environment and Natural Resources (DENR). Under the DENR, the Environmental Management Bureau (EMB) is particularly in-charge of the formulation of plans, policies, and appropriate environmental quality standards for the prevention and control of water, air, and noise pollution (emb.gov.ph). The main laws and regulations for wastewater management are the following: (i) Republic Act 9275 (Philippine Clean Water Act of 2004) which provides comprehensive and integrated strategies to prevent and minimize pollution through a multi-sectoral and participatory approach with all the stakeholders, (ii) Presidential Decree 984 (Pollution Control Law of 1976) which provides guidelines for the control of water pollution from industrial sources, and (iii) Presidential Decree No. 856 (Sanitation Code of the Philippines) which provides standards for sewage collection and refuse and excreta disposal (ARCOWA, 2018, emb.gov.ph). Residential and industrial areas are required to have their own wastewater treatment systems, but they need to regulate and report to DENR-EMB on their own. Local Government Units (LGUs) are required to provide sanitation facilities within their jurisdiction. However, although there are laws and regulations in-place, strict implementations are lacking even at LGUs due to limited budget and incentives. In some areas, like Metro Manila, LGUs have contracted private water concessionaires to manage their water and wastewater operations (ARCOWA, 2018).

3.2.1 | Domestic wastewater treatment

The National Capital Region of the Philippines (particularly the east and west zones of Metro Manila) generates around 2.5 million m^3 of wastewater daily based on the 2019 Philippines Statistics Agency (https://psa.gov.ph/environment/peenra/releases/165222). However, only around 15% of this volume is treated before being discharged into water canals and mostly end up in Manila Bay. It is vital that water pollution and public health risk posed by untreated domestic wastewater are addressed through initiatives, such as the expansion of sewerage network and the increase in the availability of improved onsite sanitation (septic tanks) with proper management and disposal (OFID, 2018). However, based on available data from 2010 to 2019, treatment network expansion by only 0.5% per year and only 44% of the fecal sludge and effluent from septic tanks is safely managed (OFID, 2018). The private sector paved the way in offering technical solutions to improve wastewater treatment systems in Metro Manila. Decentralized treatment plants were also built as alternative options for the possibility of reducing the operating costs while ensuring that the discharge is treated to meet the effluent standards. Decentralized treatment systems can be viable options for cities and communities that cannot afford centralized wastewater treatment systems. Rural areas that do not have access to such funds can also opt for decentralized systems based on nature-based water treatment technologies, that can help to achieve the SDG 6 target of ensuring access to clean water and sanitation for all.

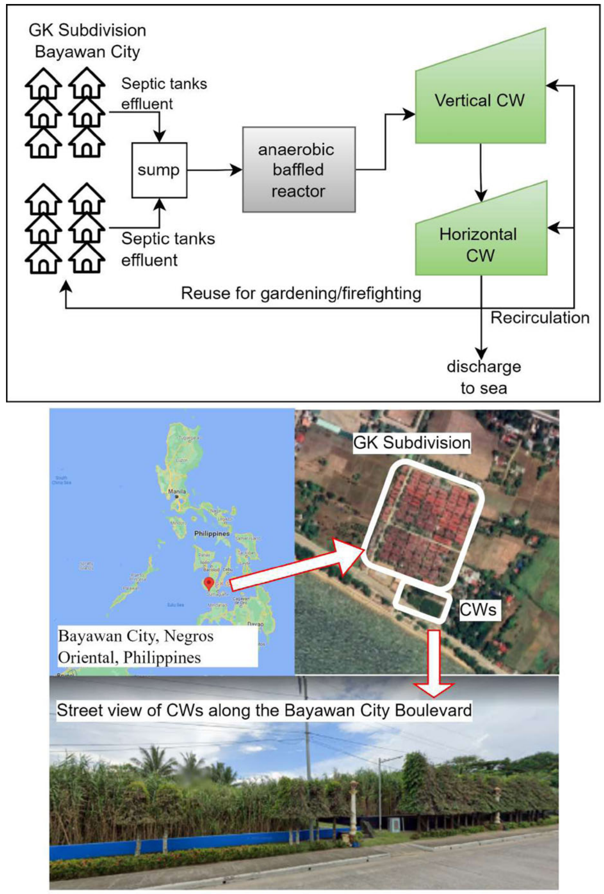

EXHIBIT 4 Schematic of the wastewater treatment facility in Bayawan City, Negros Oriental, the Philippines (Guino-o II et al., 2009) and map view of the reed beds (for horizontal and vertical CW systems) along Bayawan City Boulevard (Google maps, 2022). [Color figure can be viewed at wileyonlinelibrary.com]

3.2.2 | Constructed wetlands for domestic wastewater treatment

Constructed wetlands (CW) as a NbS for water treatment is not very common in the Philippines. Several factors that affect the use of CWs include the lack of (i) available land area (ii) social acceptability, (iii) awareness of the technology, (iv) governmental policy for its use, (iv) understanding of behavioral and cultural issues, and (v) financial capability. Several sanitation technologies, including the reed bed technology (a type of constructed wetlands system) are included in the Philippines sanitation sourcebook and decision aid that provides an overview of sanitation technologies that can be used in the Philippines (Elvas & Sy, 2008). This guidebook for water planners and decision makers was published in 2010, however, CWs have not flourished yet. Most of the constructed wetlands implemented in the Philippines are part of decentralized wastewater treatment systems (DEWATS) where they are used as green filters (or reed bed system).

In the Philippines, two case study sites are identified: (i) the Gawad Kalinga (GK) Wastewater Facility in Bayawan City, Negros Oriental, and (ii) the Green Filters Project in an Eco-Village in Calauan, Laguna. Through those case studies, in-depth understanding of barriers and benefits in using NbS for water treatment will be derived.

Gawad Kalinga (GK) Wastewater Facility in Bayawan City, Negros Oriental

The GK Wastewater Facility (Exhibit 4) is located in Bayawan City, Negros Oriental, Central Visayas, the Philippines. The facility was part of the coastal bay development project of the LGU to relocate the households along the coastal area to the Gawad Kalinga-Fishermen's Village (around 7.4 ha housing project). The low-cost and environmentally friendly facility was established to treat wastewater disposed by around 750 households in the relocation site. The wastewater treatment facility is strategically situated within the GK Village along the shoreline that is now part of its coastal road (popularly called by locals the Boulevard). The total area of the wastewater facility is around 3000 m^2 with a rated capacity of around 540 m^3/day. It is a hybrid type that combines two reed bed systems: vertical flow (1800 m^2 and 1.5 m deep) and horizontal flow (880 m^2 and 0.75 m deep) constructed wetlands systems arranged in two stages. The reed bed is composed

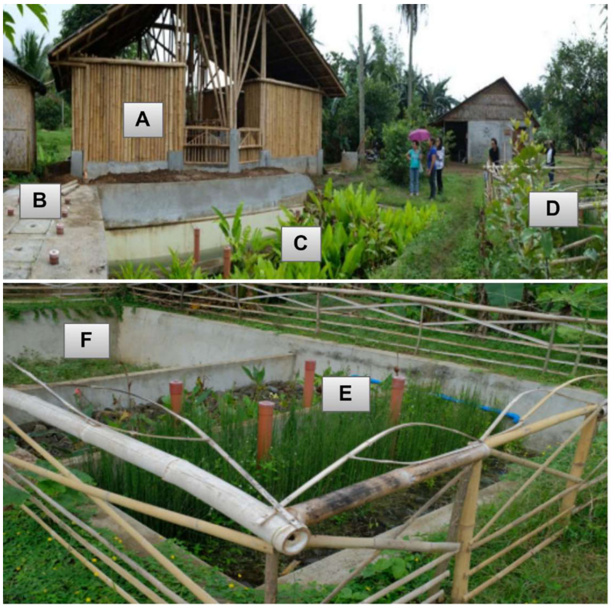

EXHIBIT 5 Wastewater treatment facility at LP4Y, Calauan, Laguna: (a) toilets and showers, (b) ABR, (c) vertical subsurface flow constructed wetland with *Heliconia sp*., (d & e) 2-stage horizontal sub-surface flow constructed wetlands with horsetail and canna lily, and (F) polishing pond. [Color figure can be viewed at wileyonlinelibrary.com]

of sand, pea size gravel, and gravel and planted with tambo (*Phragmites karka*). The *Phragmites karka*, is an indigenous and abundant plant in the locality with a root system that penetrates the whole bed (Exhibit 4). The effluent from the constructed wetlands is being directed as follows: (i) reused for irrigation in the village garden except for leafy vegetables, (ii) recirculated to the vertical and horizontal reed beds, and (iii) discharged to the sea nearby. The effluent of the wastewater treatment facility passed the Philippines' effluent standard Class A water bodies (usage classification for drinking water supply). It has been fully operational since 2010 and successful for almost a decade now. Many local government units visit the GK Wastewater facility as it has become a model for NbS in wastewater treatment technologies through an environmentally friendly and sustainable system (Guino-o II et al., 2009).

Green Filter in Calauan, Laguna

Green Filter was established in May 2017, but it is not fully operational, and is currently managed by the Life Project for Youth (LP4Y). The facility is designed to treat around 70 m^3/d of domestic wastewater generated by a population of around 200–300. The constructed wetlands system in the LP4Y Green Village will minimize household wastewater discharged directly into water bodies which causes water pollution and health related diseases. Treated wastewater can also be reused for the purpose of irrigation and gardening. Learning visits were conducted in the Green Filter Project to showcase the NbS water treatment technologies.

The Green Filters is composed of the following components (Exhibit 5): (i) an anaerobic baffled reactor (ABR) which serves as the septic/holding tank and receives all black wastewater from toilets and showers; (ii) partially treated wastewater from ABR, flows to the vertical subsurface flow CW, then to the (iii) 2-stage horizontal subsurface flow CW; and ends at the (iv) polishing pond. The final effluent is then released to the creek nearby. As mentioned before, the plan is to reuse the treated domestic wastewater for Green Village's organic garden activities.

3.3 | Vietnam

In Vietnam, the total renewable water resources have reached 884 billion m^3/year of which only 42% is sustainably exploited. The renewable internal freshwater resource per capita is 3799.129 m^3 (FAO Aquastat database, 2018). Vietnam's irrigation water storage capacity is about 12.48 billion m^3. Total agricultural water use in 2016 was estimated at 76 billion m^3 and is expected to increase to 91 billion m^3 by 2030. The total amount of water used annually for industrial use is estimated at 6 billion m^3 (in 2016) and is expected to increase to 15.6 billion m^3 by 2030. The total amount of wastewater discharged from the industrial parks is 450,000 m^3/day, excluding factories and craft villages. In 2018, the total water withdrawal per capita for Vietnam was 858.5 m^3 per year (World Data Atlas, 2018).

The following could be stated as the key regulations and policies and their implementation pathways: There are several ministries such as Ministry of (i) Construction, (ii) Health, (iii) Planning and Investment, (iv) Finance, (v) Natural Resources and Environment, (vi) Agriculture and Rural Development, (vii) Science and Technology, and (viii) Training and Education, are involved in the management of urban wastewater. The Ministry of Construction plays a key role in establishing and implementing policies on sanitation and wastewater infrastructure. The Ministry of Natural Resources and Environment is responsible for setting effluent standards and supervising sanitation activities relevant to environmental protection. Other ministries share various responsibilities to fulfill different tasks (ARCOWA, 2018). Similarly, for industrial wastewater management, Environmental Impact Assessment and Wastewater Discharge Permit are handled by the Ministry of Natural Resources and Environment or Provincial Department of Natural Resources and Environment along with other ministries such as the Ministry of Construction and the Ministry of Industry and Trade. Industrial zone developers and tenants lead other activities such as programs, plans, project formulation; budget allocation and management; capital investment; system management, operations and maintenance (ARCOWA, 2018).

Rainwater, river water, and groundwater are commonly used for daily purposes in Vietnam, where rainwater is extensively utilized. In Vietnam and other tropical nations, engineered wetland and green roof systems seem to be efficient and cost-saving wastewater management solutions that help to reduce the effects of air pollution, carbon dioxide emissions, global warming, and climate change. Domestic wastewater can be treated in horizontal subsurface flow-designed wetland systems to meet even the most stringent Vietnamese treatment and discharge criteria for surface water sources (Trang et al., 2010).

In Vietnam, the pollution of urban canal wastewater is a raising concern for human health and environmental protection. Only around 10% of the total sewage in large metropolitan areas, such as Ho Chi Minh City, is currently treated due to severe lack of centralized wastewater treatment systems (Figure S2). In Vietnam, 3,080,000 m^3 of wastewater is discharged every day and 54 municipal wastewater treatment plants (WWTPs) are in operation (treating around 1,000,000 m^3/d of wastewater). Seventy-seven municipal WWTPs are under planning/construction stages, (to treat around 1,500,000 million m^3/d of wastewater). Furthermore, 50% of hospitals do not have wastewater treatment facilities. Industries generate a total of 450,000 m^3/d of wastewater and 60% of it (from 212 out of 283 industrial zones) is treated. NbS for wastewater treatment are becoming increasingly popular since they need less energy and chemicals and leaving behind a smaller amount of solids waste (Crites et al., 2010). Recently, NbS, such as floating wetlands and waste stabilization ponds have been suggested as effective technologies for wastewater treatment and important elements of strategies for sustainable development. Wastewater treatment using NbS not only helps to treat wastewater at a low cost in the long term but can also be integrated into sustainable urban planning to improve the quality of urban environment.

3.3.1 | Floating wetlands in Vietnam

Vietnam is facing the challenge of trying to keep pace with increasing environmental pollution associated with rapid urbanization, especially in the large cities (World Bank, 2013). The wastewater networks in the main urban areas are represented by combined sewer systems which collect both wastewater and stormwater. Collected combined effluents are currently discharged directly into waterways without any treatment (Neumann et al., 2013; World Bank, 2019).

The application of FWs for the treatment of domestic wastewater has the advantage of being low cost in terms of removing nutrients and maintenance and energy consumption when compared to the conventional centralized treatment of effluent (Oliveira et al., 2021). Until now, the FWs have been applied successfully in water quality improvement, habitat enhancement and improved aesthetic appearance in ornamental ponds (Headley & Tanner, 2008). Their effectiveness, however, has not been adequately documented and how they can be sustained, replicated and upscaled remains poorly understood, particularly in Vietnam. There is a large research gap regarding the treatment of domestic wastewater by FWs in decentralized systems in Vietnam, mainly with respect to technical design, treatment efficiency and social aspects. Therefore, an assessment of the effectiveness of existing pilots and demonstration projects of FWs to improve water quality and human well-being, while enhancing the livability and resilience of cities in Vietnam is needed.

The effectiveness and impacts on the removal efficiency and socio-economic aspects of five pilot (experimental) and four existing FWs in Vietnam were reviewed for this study. The review indicates that the common design characteristics required for the pilot and the demonstration scale FWs have not been applied in Vietnam. Water quality assessment and treatment effectiveness have been evaluated well in the experimental FWs. The pilot systems studied provided good treatment efficiency for suspended solids (75.8%–95%), COD (74.7%–83.6%), BOD_5 (63%–94%), TP (50%–98.9%) and TKN (63%–75%) and the effluent quality met the discharge permit levels stipulated by the Vietnamese technical regulation for the domestic wastewater (WW) (Hien & Tinh, 2018; Hoang et al., 2014; Ngan & Tram, 2017). Unfortunately, information on investment costs and the socio-economic benefits for the nine existing FWs projects was not available in the literature. The demonstration FW systems partly contribute to water purification and provide beautiful landscape for urban residents as well as jobs for workers who have been involved in the maintenance activity of floating rafts. They also lead to the engagement of many different stakeholders in the communities. However, there are many challenges which hinder the adoption of FWs for urban WW treatment in Vietnam. The challenges include the inflow of highly polluted urban WW to the canals, poor environmental awareness of local residents, ineffective maintenance of floating rafts, and high sedimentation causing low oxygen concentration in the water. The needs and recommendations to the local and central governments on actions to scale up the existing FWs to improve their performance are proposed in the literature.

Implementation of floating wetlands for urban municipal wastewater treatment: Case study in Can Tho city of Vietnam

Surface water quality assessment was conducted in Bung Xang canal from March to May 2021. Water sampling was conducted at the high and low tides. The COD, NH_4-N and PO_4-P at the high and low tides were in the range of 55.6–76.8, 5.4–14.47 and 0.7–1.2 mg/L, respectively, which are drastically above the Vietnamese standard for surface water quality (QCVN 08-MT:2015/BTNMT) of Class A1 (10, 0.3 and 0.1 mg/L, respectively) for the protection of aquatic lives. This indicates that Bung Xang canal is severely polluted due to several production and business activities which are taking place since the canal has been upgraded with concrete embankment in 2019. The results from interviews showed that solid wastes and untreated domestic wastewater are the cause of water pollution in the canal and the local people did not have knowledge about FWs. However, the local residents showed positive response for the setting up of new FWs in Bung Xang canal and were expecting to see the performance of FWs. Six FWs with an area of 8 m^2 each were established on April 23, 2022 (Exhibit 6). A mixture of ornamental species such as *Canna x generalis*, *Heliconia psittacorum*, *Echinodorus cordifolius*, *Cyperus alternifolius*, *and Ruellia tuberosa* are installed which were planted at a density of 9 plants/m^2. The plants were placed in the hydroponic baskets and their roots were supported by coconut fiber. They were placed on the top of plastic trellis net which was lifted up and floated using PVC pipes with 90 mm diameter. The six FWs were placed in the canal section of about 100 m × 11 m (length × width) and the average depth of the water column at low and high tides was 1.79 m (0.6–3.07 m). The local authorities, youth union, and students at Can Tho University participated in the installation of FWs and the removal of solid wastes from the canal. The community

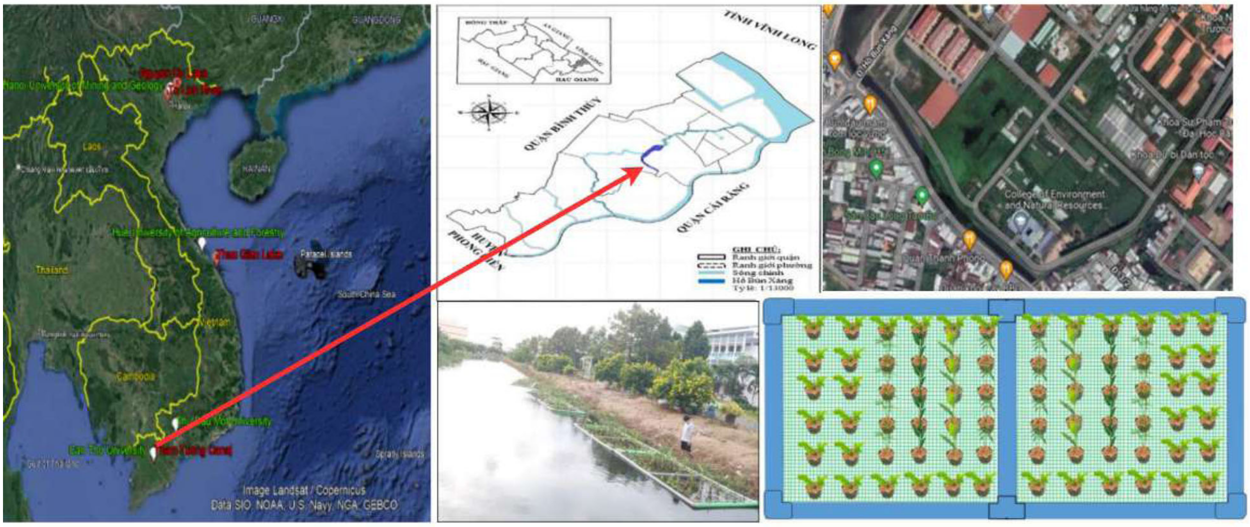

EXHIBIT 6 Installation of six FWs at the Bung Xang canal in Can Tho City. [Color figure can be viewed at wileyonlinelibrary.com]

has started to pay attention to the FWs and has appreciated the initiation. It is expected that the FWs systems will work well and the water pollution in the canal will be reduced to ensure a healthy environment as well as a beautiful and green landscape to provide recreation to the public. Implementation of FWs in Bung Xang canal has provided first-hand information on technical, social, economic and policy/governance aspects of FWs which need to be considered in installing and operating FWs to purify wastewater in canals of Vietnam.

3.3.2 | Stabilization ponds

Wastewater treated by stabilization ponds passes through an anaerobic pond followed by a facultative pond, and a maturation pond in a series. Several such systems can be used in parallel if the quantity of wastewater to be treated is large. While anaerobic and facultative ponds are designed to remove BOD (50%–85% in anaerobic ponds, 80%–95% in facultative ponds and 60%–80% in maturation ponds), a maturation pond is used to remove pathogens (90%) present in the wastewater they receive. No removal of pathogens is expected in the anaerobic and facultative ponds. Thus, the entire waste stabilization ponds system can be considered as a nature-based solution as they do not utilize any grey solutions.

Additionally, maturation ponds can treat the wastewater that is treated by activated sludge processes. For example, wastewater can be treated by an aerated lagoon followed by a sedimentation tank (to settle the microbial biomass produced by the aerated lagoon) first and the effluent from such a system can be treated by a maturation pond. Generally, the effluent reaching a maturation pond from both systems will have similar qualities with respect to the concentrations of BOD and pathogens.

Maturation ponds

Canals in Ho Chi Minh City (HCMC) have long been recognized as important for providing water, mitigating floods, and enhancing transportation connectivity (Givental, 2014). Due to untreated waste and garbage that are being dumped into the canals, their functions have been severely degraded and therefore require a proper solution for wastewater treatment and solid waste management. Among NbS processes, waste stabilization ponds (WSP) such as maturation ponds (MPs) could be technically feasible for treating canal wastewater. Waste stabilization ponds can be operated efficiently over a wide range of flow and pollutant loads at low costs. They are simple in construction, operation, and maintenance. However, to date, there has been little review and discussion of the applicability of WSPs in the treatment of inner-city canals, as well as in the positive aspects that WSP bring to local ecosystems and the society. Therefore, this study looked at how well WSP in Binh Hung Hoa WWTP might work in reducing pollution while also adapting to climate change and creating a more beautiful cityscape.

Maturation ponds at Binh Hung Hoa WWTP

Binh Hung Hoa WWTP was built and operated since 2006 (Exhibit 7), with a design capacity of 30,000 m^3/day (phase 1) and will be expanded to 46,000 m^3/day in phase 2. The wastewater was collected from the Black Canal, located northeast of Ho Chi Minh City. The drainage basin of the Black Canal is about 785 hectares. The Binh Hung Hoa WWTP is composed of: (i) Inlet pumping station, (ii) Aerated lagoon, (iii) Sedimentation ponds, (iv) Maturation ponds (MPs), and (v) Sludge drying bed. The total area of the WWTP is 36.4 ha, of which about 22 ha is occupied by ponds and 5.3 ha is provided for green space. The MPs have a water depth of 1.5 or 2.0 meters. The first, middle and final ponds have an area of 2400 ha, 2700 ha and 3.300 ha, respectively (Trang et al., 2006).

(a)

(b)

Pond	Depth (m)	Area (ha)	Volume (m^3)
A11/A12	4.0	1.486	59,440
A21/A22	4.0	1.485	59,440
S1	4.0	0.963	38,520
S2	4.0	0.871	34,840
M11	2.0	2.446	48,920
M21	2.0	2.455	49,100
M12	1.5	2.655	39,830
M22	1.5	2.800	42,000
M13	1.5	3.376	50,640
M23	1.5	3.226	48,390

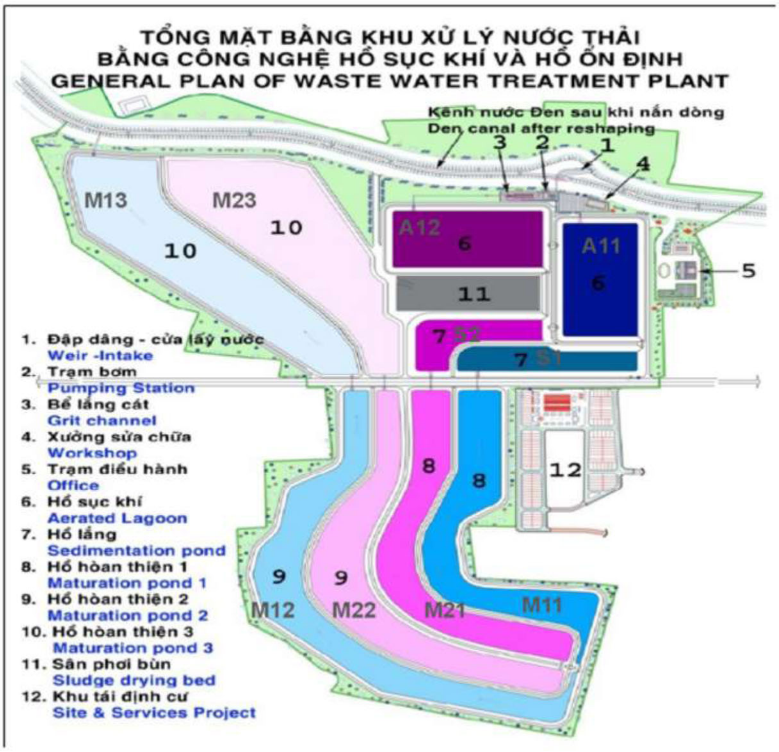

EXHIBIT 7 Binh Hung Hoa wastewater treatment plant, (a) Aerial photo, (b) Detailed distribution and size of pond units. [Color figure can be viewed at wileyonlinelibrary.com]

The influent entering the WWTP has 117–303 mg/L of COD, 25–119 mg/L of BOD_5, 22–129 mg/L of TSS, 9.2–38.1 mg/L of $NH_4{}^+$-N and 1.7–7.0 mg/L of $PO_4{}^{3-}$P. The treated effluent has 25–78 mg/L of COD, 2–17 mg/L of BOD_5, 2–42 mg/L of TSS, 4.1–12.6 mg/L of $NH_4{}^+$-N and 0.1–1.0 mg/L of $PO_4{}^{3-}$-P. The effluent meets the Class-B standards which should have 60 mg/L of BOD, 100 mg/L of TSS, 10 mg/L of $NH_4{}^+$-N and 10 mg/L of $PO_4{}^{3-}$-P. The total number of coliforms was reduced to less than 3000 MPN/100 ml. However, many other water quality parameters such as $NO_3{}^-$-N. heavy metals and other persistent pollutants should be analyzed to evaluate and improve the performance of the entire treatment system.

Urban heat islands can be potentially reduced using a combination of large-aerated lagoons and MPs; however, more quantitative research is needed. MPs can also be used for a variety of purposes, including flood control, urban green space enhancement, and aquaculture etc. (Trang et al., 2006). MPs employed in wastewater treatment must be maintained to avoid unwanted effects, such as odors, breeding of mosquitoes, and algal bloom.

4 | INTEGRATED ASSESSMENT FRAMEWORK

In this study, the effectiveness of NbS is considered as the degree to which objectives are achieved and the extent to which targeted problems are solved. Effectiveness is seen as dependent on a sound technical design and adequate operation and maintenance of the facilities. Therefore, a consideration of those technical aspects of the system is essential for understanding and assessing thperformance. In contrast to efficiency, effectiveness is determined without reference to costs. Furthermore, it may focus on a set of narrowly defined targets, for example, linked to water quality, which may be set by the implementing

EXHIBIT 9 Matrix for the development of an assessment framework

Category / Aspect for evaluation	Objective	Targeted outcomes	Potential impacts
Technical	• Meeting good design standards • Good operation and maintenance practices	• Complete design details • Adequate staffing • Regular maintenance	• Ease of replications • Reduction in maintenance cost
Environmental	• Improved water quality • Climate resilience and contribution to combat climate change • Improved ecosystem health	• Increased dissolved oxygen • Reduced concentrations of nutrient other organic and inorganic pollutants • Reduced concentration of biological contaminants • Sustainable operations under extreme weather conditions • Reduction in heat islands • Sufficient footprint of the treatment system • Increased species and increase number of each species (both flora and fauna)	• Reduction in downstream treatment cost due to the removal of physical, chemical and biological pollutants • Attenuation of peak flow • Increase in lag period • Level of decrease in temperature around the NbS • Increase in flora and fauna
Social	• Increased visibility and acceptance • Willingness to participate and pay • Improved health and sanitation	• Adequate promotional tools • Equitable sharing of costs and benefits • Use of the surroundings of the NBS for health benefits	• Increase in in-kind contribution • Reduction in medical costs
Economics	• Harvesting of resources • Increased tourism	• Increased income due to resources and tourism	• Increase in income due to the production of resources • Increase in income due to tourism
Policies and governance	• Existence of well organized governance structure • Appropriate policies and procedures in place	• Enabling environment for the implementation of NbS	• Increased life span, uptake and replication of NbS

agency, but may not capture the broader environmental, social and economic impacts of the given intervention. Examining those is considered important for capturing the diverse co-benefits of NbS, identifying and addressing undesirable impacts and providing an evidence base for sustaining, scaling and replicating them. Finally, the institutional set up and governance and policy context are also considered important to capture since they may determine the effectiveness, impacts and potential for up-scaling and replication. Some suggested indicators and methods for capturing those aspects are given in the text below. The simplified schematic of the relationship and factors considered for the effectiveness and impacts of NbS case studies (including their contributions to SDGs) are shown in Exhibit 8. The above definition of effectiveness and impacts of a NbS was used to formulate a matrix (Exhibit 9) that will identify objectives to be achieved and targeted problems to be solved. This matrix is applied to the three different nature-based systems that are considered in this study.

4.1 | Assessment framework to evaluate the technical aspects

4.1.1 | Development of a framework to evaluate the effectiveness of the technical aspects of a nature-based water treatment

The assessment framework to evaluate the effectiveness was based on the three types of NbS considered in this study. In the framework, data on the following factors should be collected to compute a score of those factors to evaluate the effectiveness: (i) meeting good design standards; (ii) improving water quality; and (iii) providing good operation and maintenance practices.

Meeting good design standards

a. Floating wetlands (FWs): Data on the following design and configuration of FWs should be collected to evaluate their effectiveness: (i) Ratio of catchment area to FW area; (ii) Water depth of the FW; (iii) hydraulic residence time (HRT, per day); (iv) hydraulic loading rate (HLR, $m^3/m^2{\cdot}d$); (v) solids loading rate ($kg/m^2{\cdot}h$); and (vi) vegetation. The above data will be compared against the benchmark values obtained from the literature for the above parameters. The benchmark values for the above factors are:
b. Ratio of contributing catchment area to FW area is proposed to be 0.37% for the effective removal of TSS, TN, and TP.
c. Water depth of the FW could have a range of values (see Table S2 in the Supplementary Materials), depending on the type of water to be treated by a FW as well the scale of a FW.
d. HRT should be maintained for at least 3 min. at high flows (2.335 m^3/s) and 5 h at low flows (0.024 m^3/s) (Nichols et al., 2016).
e. HLR could be as high as 731 $m^3/m^2{\cdot}d$ at high flows and 7.5 $m^3/m^2{\cdot}d$ at low flows (Nichols et al., 2016).
f. Solids loading rates could be as high as 2.1 kg/m^2.h at high flows and 0.03 $kg/m^2{\cdot}h$ at low flows (Nichols et al., 2016).

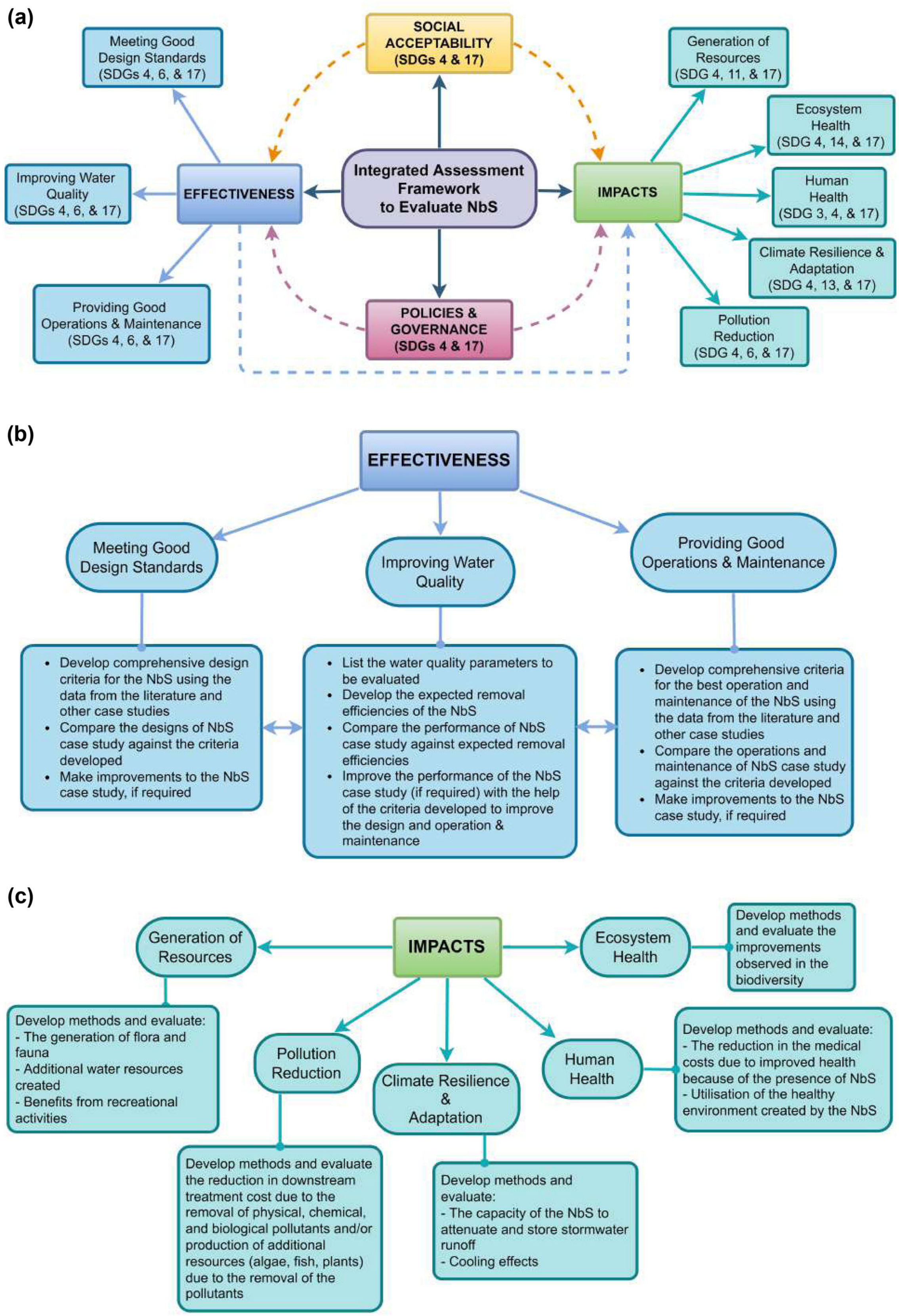

EXHIBIT 8 Schematic of (a) Components of the proposed integrated assessment framework to evaluate NbS and the contributions of those components to SDGs, (b) Procedures to assess the effectiveness of NbS, and (c) Procedures to assess the impacts of NbS. [Color figure can be viewed at wileyonlinelibrary.com]

g. Vegetation: plants suiting to the climate and pollutants in the water should be selected. Their availability and cost are also factors which are to be considered. For example, the following plants will be suitable for tropical regions: aquatic emergent, such as the umbrella plant *Cyperus alternifolius*, narrow-leaved cattail *Typha angustifolia*, fragrant pandan *Pandan amaryllifolius*, dwarf papyrus *Cyperus haspan* var. *vivipurus*, aquatic canna *Canna glauca*, and blue rush *Lepironia articulata*.

The FWs constructed for the case study in Vietnam considered the availability and cost of the plant species. The project team found plants such as *Canna spp. Heliconia*, *Typha spp.*, *Scirpus spp.*, which were easy to find in the field at no cost. Canna is also planted in the FWs systems in Sri Lanka. The Vietnam project team also selected plants which will be flowering based on the feedback obtained from their interviews with the stakeholders.

a. Constructed wetlands (CWs): Similar parameters can also be used to evaluate the technical effectiveness of CWs. Studying the CWs in Bayawan City, the Philippines (which is considered as one of the successful implementations of hybrid CWs for domestic wastewater treatment), the values of key parameters are summarized as follows:
b. Location: as close as possible to the wastewater source and downgradient (i.e., 2% slope for horizontal CW) so that water can flow through the system by gravity; above the water table; not located in a floodplain, does not contain threatened or endangered species, and archaeological or historic resources
c. HLR: minimum value of 0.2 $m^3/m^2 \cdot d$ to provide enough retention time (at least 10 h) for the constructed wetlands to treat the wastewater
d. Local standard classification for water bodies (i.e., https://emb.gov.ph/wp-content/uploads/2019/04/DAO-2016-08_WATER-QUALITY-GUIDELINES-AND-GENERAL-EFFLUENT-STANDARDS.pdf): passing at least the Class C for fishery, agriculture, and recreational uses
e. Plants/vegetation used: use of local and abundant vegetation that is typically used in constructed wetlands (e.g., *Phragmites karka*)
f. Substrate: average of 0.75 m in depth with hydraulic capacity (k_f value) of about 10^{-4} to 10^{-3} m/s (Hoffman et al., 2010), (e.g., combination of sand, pea size gravel, and gravel)
g. Use of high-density polyethylene liner to provide additional protection from wastewater leak from the constructed wetlands and prevent major cracking of the reed bed slab (e.g., one earthquake event near the area resulted in a large cracking of the concrete slab which serves as the foundation for the reed bed)
h. Use of hybrid system: vertical followed by horizontal CW, with pretreatment such anaerobic baffled reactor (improved septic tank)
i. Maturation ponds: Design criteria to be used for maturation ponds such as the depth and hydraulic retention time of the pond, configuration of the pond (inlet, outlet, embankment, bottom and the shape) and safety concerns should be established (see Supplementary Materials Table S3) to meet the good design standards.

Improving water quality

Physical, chemical, and biological water quality parameters (WQP) should be measured and used in water quality indexing. While measuring a wide range of physical, chemical and biological WQP will ensure the quality of treated water, the analytical cost could be unaffordable if funds are limited to have analytical facilities. Then specific water quality parameters need to be considered when assessing the effectiveness of floating wetlands, constructed wetlands and maturation ponds. The purpose of those NbS will determine the WQP to be analyzed. Comprehensive WQP to be collected for all the NbS considered in this study for evaluating effectiveness are listed below:

a. Physical WQP: temperature (°C), oxidation-reduction potential (ORP) (mv), conductivity (μs/cm), turbidity (NTU)
b. Chemical WQP: dissolved oxygen (DO) (mg/L), pH, Alkalinity (mg/L as $CaCO_3$), total dissolved solids (TDS) (mg/L), heavy metals (ppm), biological oxygen demand (BOD) (mg/L), chemical oxygen demand (COD) (mg/L), anions, total suspended solids (TSS) (mg/L), total phosphorus (TP) (mg/L), phosphate phosphorus (PO_4^{3-}-P), total nitrogen (TN) (mg/L), total ammoniacal nitrogen (TAN) (mg/L), nitrate nitrogen (NO_3^--N) (mg/L), nitrite nitrogen ((NO_2^--N) (mg/L), total Kjeldahl nitrogen (TKN) (mg/L), total organic carbon (TOC), Polycyclic aromatic hydrocarbons (PAHs), pharmaceuticals and personal care products (PPCPs), herbicides and pesticides, Per- and poly-fluoroalkyl substances (PFASs), Oil and Grease, Ch-a and
c. Biological WQP: total coliform (TC) (MPN), faecal coliform (FC) (MPN), *E.Coli* (MPN), algal density (cells/100 ml) and algal diversity.

To evaluate the effectiveness of a NbS in improving the above WQPs, one of the following methods can be used:

a. Stipulating the required water quality after NbS treatment and comparing the performance of the NbS against it. For example, the effectiveness of a floating wetland can be evaluated against the required water quality standards of a canal or a lake in which the floating wetland is installed.
b. Comparing the performance of NbS against the established baseline performance of such NbS. A list of all the water quality parameters to be considered for a specific NbS should be prepared and used for this purpose (Exhibit 10). Thus, the purpose of Exhibit 10 is to establish the expected removal capabilities of each NbS which can be used to evaluate the actual removal capabilities of a similar NbS. While the influent quality might vary depending on the type of pre-treatment applied, the percentage removal of pollutants by the NbS can still be compared against the values presented in Exhibit 10.
c. Defining classes of a given water quality parameter and evaluating the performance of the NbS with respect to that water quality parameter; the following procedure can be carried out to evaluate the effectiveness:

Step 1: Define the accepted value of a given water quality parameter.

EXHIBIT 10 Important water quality parameters to be monitored in the selected NbS and the expected removal efficiencies of some parameters as well as effluent quality of some other parameters

Parameter	Floating wetlands[a]	Constructed wetlands[b]	Maturation Pond[d]
Removal efficiency			
BOD	63%–94%	80%–95% (99%)	60%–80%
COD	74.7%–83.6%	80%–98%	
Suspended solids	75.8%–95%	96%–99%	
Total dissolved solids		(54%)	
Turbidity		90%–98%[c]	
Total nitrogen	63%–75%	15%–80%[c]	
TKN		40%–83%	
NH_4^+-N		85%–99%	
NO_3^-N	50%–98.9%	46%–85%[c]	
Total phosphorus		85%–96% (62%)	
PO_4^{3-}P			60%–80%
Total coliform		99% (71%)	99.9%–99.99%
Fecal coliform			95.6%–99.96%
Helminth eggs			74.7%–99.93%
Effluent quality			
pH		6–7 (7.06)	
Temperature		29–30°C	
Color		(clear)	
Odor		(odorless)	

[a]Values obtained from existing studies on pilot-scale domestic/municipal wastewater treatment in Vietnam
[b]Performance of reed bed or CWs used in wastewater treatment in the Philippines, values in parenthesis are from the hybrid CWs in Bayawan City, the Philippines (Center for Advanced Philippine Studies, 2011, Guino-o II et al., 2009)
[c]Parde et al. (2021).
[d]Kayombo et al. (2004), Water Corporation (2019).

Step 2: Compute the percentage variation between the measured and accepted value.

Step 3: Define a class table based on the range of percentage difference.

Step 4: Find the corresponding class of the water quality parameter in consideration.

Step 5: If the water quality parameter is measured at the inlet and outlet of the floating wetland, comparing the class of the WQP at those locations will help to quantify the effectiveness of the floating wetland in treating that particular water quality parameter.

Step 6: Summation of classes of all water quality parameters will help to obtain an overall effectiveness of the floating wetland with respect to the total water quality.

Typical examples of the above procedure considering two water quality parameters, namely, oil and grease and dissolved oxygen are shown in Supplementary Materials (Tables S4 and S5). For example, the floating wetland is expected to reduce the concentration of oil and grease and increase the DO of the water that enters the FW.

The first method forces an NbS to perform to a given set of expected standards. In this case, selecting an appropriate NbS is essential otherwise the NbS of interest can easily be considered as ineffective. The second method utilizes the benchmark values of water quality parameters that can be achieved by a given type of NbS and evaluates the performance of a similar NbS that is under study. The third method can be used to evaluate the performance of a given type of NbS against other types of NbS or grey systems.

Good operation and maintenance practices

a. Floating wetlands: Data on the following should be collected and compared against the benchmark values: (i) frequency and protocols for cleaning, including the inlet and the outlet; (ii) frequency of replacing components; (iii) frequency of calibration of flow measurement devices; (iv) frequency of harvesting of biomass; (v) frequency of silt removal; and (vi) odor control measures. Benchmark values should be established using the existing literature on floating wetlands.
b. Constructed wetlands: Regular checking of the following: (i) visual appearance and odor of the effluent (if turbid or odorous effluent: ensure that the feeding of the wastewater is constant and reduce the load to the CWs), (ii) pumps and inlet and outlet structures for obstructions and water level), (iii) harvesting frequency of the plants used (at least once a year depending on the growth rate), (iv) presence of plants' disease, insects, weeds, and other predatory plants, and (v) filter media replacement (at least 5 years depending on the conditions). (Hoffman et al., 2010; Huhn et al., 2015)
c. Maturation Ponds: Regular maintenance required are: (i) cleaning the inlets and the outlets of the ponds, (ii) replacing components, (iii) calibrating flow measurement devices (iv) removing scum from the surfaces of the ponds, (v) removing weed on the embankments of the ponds, and (vi) preventing mosquito breeding. Very little accumulation of sludge would occur in the maturation pond over a long period of time.

4.1.2 | Development of a framework to evaluate the impacts of the technical aspects on a nature-based water treatment

The assessment framework proposed here to evaluate the impacts can be applicable to all the three types of nature-based water treatments considered in this study.

EXHIBIT 11 Direct costs and benefits of a NbS (adapted from Lienhoop et al., 2014)

Costs		Source
Direct costs	Construction costs	Secondary data
	Operation and maintenance (O&M)	Secondary data
	Capital investment	Secondary data
Benefits		
Direct benefits	Reducing pollutant parameters	Primary data
Indirect benefits		
Non-monetary	Environmental and Social benefits	Primary data
	• Reducing noise, air pollution etc.	
	• Building resilience against extreme weather events	
Monetary	Health benefits	
	• Avoided treatment expenditure	Primary data
	• Avoided income loss	Primary data
Monetary	• Create jobs and income	Primary data

Improving water quality

Reduction in downstream treatment cost due to the removal of physical, chemical and biological pollutants is a possible secondary impact from improved water quality by an NbS.

In case of maturation ponds, when they are used to produce algae and/or fish, they can also reduce the nitrogen and phosphorus contents from the effluent. Therefore, the benefits due to the production of algae and fish can be added to the benefit of removing nutrients from the effluent.

Increasing climate resilience and combating climate change

Attenuation of peak flow and increase in the lag period to peak flow downstream of a nature-based system will depend on its storage capacity. Even a floating wetland could add additional storage and therefore contribute to the above which will help in preventing floods.

All three types of NbS discussed in this study can decrease the surrounding ambient temperature to varying degrees due to evaporation as well as absorption and transportation of heat. In a study conducted at a reach of Sabarmati River, an average dip of about 1.57 and 1.71°C was observed during summer and winter, respectively, on the right bank of the river (with an influence distance of 200–300 m). On the other hand, the average fall of temperature near the left bank was about 0.69 and 0.65°C during summer and winter, respectively (Gupta et al., 2019).

In as far as the examined systems serve as alternatives to more energy-intensive conventional water treatment technologies, avoided carbon emissions could also be considered as potential impacts and calculated based on a comparison of the carbon footprints of the alternative technologies.

Good operation and maintenance practices

Practicing good operation and maintenance will have the following benefits which can be estimated based on the available data for the following: (i) reduction in maintenance cost; (ii) ease of replications; (iii) increase in safety around the NbS treatment systems; (iv) increase in the use of the surrounding environment which can bring customers to the businesses situated closer to the NbS systems; and (v) increase in the health of ecosystem due to the presence of diverse flora and fauna.

Increasing ecosystem health

Ecosystem health indicators at the habitat, species and resources level could be used to assess impacts on the condition of the given water ecosystems. Changes in the number and diversity of local flora and fauna species but also indicators of impacts on the functions and resilience of local ecosystems are possible additional aspects to consider.

4.2 | Social acceptability and policy aspects

Social acceptability through stakeholder participation is equally important to address the issues associated with the adoption of NbS for water and wastewater treatment. Involvement of diverse groups (such as academics, managers, practitioners, businesses and policy makers) should be the priority in all stages such as design, implementation, management, and monitoring. On the other hand, policy or governance would be crucial for the NbS to be replicated and maintained. Moreover, management capability would prove a practical approach to the implementation of NbS. Existing policies on environmental protection measures, cultural heritage, spatial planning, economic opportunities, and incentives can be used or a new institutional framework can be created for the implementation of NbS (Sowińska-Świerkosz & García, 2021).

For the social acceptability, the two main questions to be considered are: (i) Does a given NbS obtain the acceptance of the diverse group of stakeholders? and (ii) Can changes be introduced to improve the acceptance? Similarly, for the policy, the main questions to be asked are: (i) Is the existing policy framework adequate to implement and manage the NbS? (ii) Can changes be easily introduced in policy, legislation, and spatial planning? The following procedure were carried out in the respective countries with respect to social acceptability and policy aspects.

4.2.1 | Sri Lanka

Social acceptability can be assessed by the active and passive engagement of the individual and institutions on the floating wetlands. At the outset, several consultative stakeholder meetings were held to

EXHIBIT 12 Cost-benefit analysis on all the case studies

NbS Type	Year #	Cost, US$	Cost description and assumptions[a]	Benefit, US$	Benefit description and assumptions[b]	Total Cost, US$	Total Benefit, US$	BCR
(a) Floating wetlands (case of Kandy Lakes, Sri Lanka)[c]	0–1	4200.00	Assumed construction time of 1 year (includes capital cost)	0.00	No benefits during the construction phase	262,800.00	2,850,000.00	10.84
	2—9	108,000.00	Annual O&M cost of 13,500	2,850,000.00	Annual benefit from reduced pollutants and indirect benefits: US$150,000			
	10	15,600.00	Annual O&M cost + rehabilitation cost (assuming 50% of capital cost)					
	11–20	135,000.00	Annual O&M cost and ssumes lifespan of CW of 20 years					
(b) Floating wetlands (case of Kurunegala Lakes, Sri Lanka)[c]	0–1	3400.00	Assumed construction time of 1 year (includes capital cost)	0.00	No benefits during the construction phase	233,100.00	741,000.00	3.18
	2—9	96,000.00	Annual O&M cost of 12,000	741,000.00	Annual benefit from reduced pollutants and indirect benefits: US$39,000			
	10	13,700.00	Annual O&M cost + rehabilitation cost (assuming 50% of capital cost)					
	11–20	120,000.00	Annual O&M cost and assumed lifespan of CW of 20 years					
(c) Constructed Wetlands (case of Bayawan City, Phililppines)	0–3	340,000.00	Assumed construction time of 3 years (includes capital cost and land cost)	0.00	No benefits during the construction phase	799,000.00	3,003,536.23	3.76

(Continues)

EXHIBIT 12 (Continued)

NbS Type	Year #	Cost, US$	Cost description and assumptions[a]	Benefit, US$	Benefit description and assumptions[b]	Total Cost, US$	Total Benefit, US$	BCR
	4–9	102,000.00	Annual O&M cost of 17,000	3,003,536.23	Annual benefit from reduced pollutants: US$176,678.60			
	10	187,000.00	Annual O&M cost + rehabilitation cost (assuming 50% of capital cost)					
	11–20	170,000.00	Annual O&M cost and assumed lifespan of CW of 20 years					
(d) Maturation Pond (case of Binh Hung Hoa WWTP, Vietnam)	0–3	13,244,218.12	Assumed construction time of 3 years (includes capital cost)	0.00	No benefits during the construction phase	33,065,220.01	47,226,613.70	1.43
	4–9	4,658,432.76	Annual O&M cost of 776,405.46	47,226,613.70	Annual benefit from reduced pollutants: US$2,778,036.1			
	10	7,398,514.52	Annual O&M cost + rehabilitation cost (assuming 50% of capital cost)					
	11–20	7,764,054.60	Annual O&M cost and assumed lifespan of CW of 20 years					

[a]Sartori et al. 2014, costs are estimated for the current year.
[b]Benefit from reducing pollutants (per kg removed): COD = US$0.139072; SS = US$0.005406; N = US$8.544024; and P = US$32.800852 (Singh and Kazmi, 2017).
[c]Indirect benefits from tourism and educational training (annual cost of US$30,000 and US$11,000 for Kandy Lakes and Kurunegala Lakes, respectively).

EXHIBIT 13 Preliminary assessment on the effectiveness and impact of the NbS considered in this study

	Floating Wetlands(case studies from Sri Lanka (SL)/Vietnam (Vn))			**Constructed wetlands(case of Bayawan City, Philippines)**	**Maturation Ponds(case study from Vietnam)**
	Kandy Lake, SL	Kurunegala Lake, SL	Bung Xang Canal, Vn		Binh Hung Hoa wastewater treatment plant
Flow rate			Open canal (water flow follows the tides).	540 m^3/d	30,000 m^3/d (in 2006) 46,000 m^3/d (in 2010)
a.1 Technical effectiveness					
Meeting good design standards	The design criterion of the floating wetland was based on total weight of the model and Maximum weight that can be carried by the model without sinking. Area covered by the floating wetland should be less than 30% of the free surface area direction The constructed floating wetlands were installed at six major inlets to the lake with the plant *Canna iridiflora*.	Same as Kandy Lake. Positioning the wetlands is a challenge due to wind and tidal effects.	Average depth of water column is 1.79 m (0.6–3.07 m). The length x width of the canal section where six FWs have been placed is about 100 m × 11 m. Designed six floating wetlands (8 m^2 each (4 m x 2 m) with a total area of 48 m^2) planted with *Canna x generalis*, *Heliconia psittacorum*, *Echinodorus cordifolius*, *Cyperus alternifolius*, and *Ruellia tuberosa* at a density of 9 plants/m^2	• HLR = 0.2 m^3/m^2/d • Location: close to the source and with gradient of at least 2% • Plant: *Phragmites karka* (abundant and locally available) • Substrate: sand and gravel • Other: use of liner, hybrid system with pre-treatment (ABR)	Area = 10 ha HRT = 4.1–6.15 days (mean 4.92 days)
Improving Water Quality[a]	Lake water quality is better than the inflow water quality.	Water quality has been improved as follows comparing before and after installation (2021 test results; $n = 40$); pH : 0.5%, EC: (-.0.2%) COD: 8.9% BOD_5: 6.4% DOC: 6.8% PO_4^{3-}: 16% NO_3^-: 21% Total Coliform: 19.8 % *E. coli*: 21.1 %	Water quality improvement is not recognized clearly because canal water is changed 4 times/day due to tidal effect; however, the plants grow very well, and the biomass increases with tine. This indicates nutrient removal (nitrogen, phosphorus) via plant uptake and the biomass production enhances water quality.	(2021 test results) • pH (6–9.5) **7.06** • DO (NA) **4.7** • BOD_5 ($\leq$ 50 mg/L) **6** • Oil and grease ($\leq$ 5 mg/L) **1.3** • Nitrate ($\leq$ 14 mg/L) **3.8** • Ammonia ($\leq$ 0.5 mg/L) **0.3** • Phosphate ($\leq$ 1 mg/L) **3.0 (failed)** • Surfactants ($\leq$ 14 mg/L) **0.69** • Total Coliform ($\leq$ 10,000 MPN/100 ml) **6.8**	• BOD ($\leq$ 50 mg/L) **2–17 (mean 10)** • COD ($\leq$ 100 mg/L) **25–78 (61)** • TKN ($\leq$ 60 mg/L) **no data** • NH_4^+-N (free) ($\leq$ 1 mg/L) **4.1–12.6 (8.6) (failed)** • Total Coliform < **3,000/100 ml** • Fecal Coliforms (10^3/100 ml) **40–100** • PO_4^{3-}-P (< 4 mg/L) **0.1–1.0 (0.3)** • pH (5.5–9.0) **no data** • Temperature ($\leq$ 40°C) **no data** • SS ($\leq$ 100 mg/L) **2.0–42.0 (22)** • heavy metals and other persistent pollutants should be analyzed

(Continues)

EXHIBIT 13 (Continued)

	Floating Wetlands(case studies from Sri Lanka (SL)/Vietnam (Vn))			Constructed wetlands(case of Bayawan City, Philippines)	Maturation Ponds(case study from Vietnam)
Good operation and maintenance practices	Floating wetlands are maintained by the Irrigation Department. Cleaning, and placing have been done daily while replanting is done periodically	Floating wetlands are maintained by Kurunegala Municipal Council. Maintenance is being done when required.	• Solid wastes in the canal are a considerable problem for maintenance work • It is hard to identify and measure the inlet and outlet in the open canal • Require much work for maintenance practices	• LGU is in charge of the operation and maintenance of the CW, while the local water utility finance the water quality testing • Feeding during early morning (7:00 a.m.) and late night (11:00 p.m.) to lessen impact of the fouled odor • Visual checking of the effluent (turbidity and odor) • Checking of the inlet and outlet structures for clogging or other issues • Harvesting and replacing the plants at least once a year	• Evaporation could carry volatile odor causing compounds to the surrounding air • Evaporation could lower the water depth which in turn will allow rooted plants to invade the pond; also allow the floating duckweeds to grow • Algae should be removed regularly unless albal-fish culture is combined
a.2 Technical Impact					
Improving water quality	Ambient water quality standard is maintained in the lake. Lake water is not used for drinking purposes.	Ambient water quality standard is maintained in the lake The water is used for drinking water after the treatment during the drought.	Increase in the health of ecosystem due to the presence of diverse flora and fauna	• Reuse: (a) concrete production, thereby reducing construction costs; (b) organic cut flower and vegetable farming; and (c) fighting fires. • Provide additional livelihood opportunities • Venue for a demonstration site for local engineers and decision-makers from other local government units. • An increase in visitors at the housing project to view the facility was observed	Effluent water quality met the discharge standards

(Continues)

EXHIBIT 13 (Continued)

	Floating Wetlands(case studies from Sri Lanka (SL)/Vietnam (Vn))			Constructed wetlands(case of Bayawan City, Philippines)	Maturation Ponds(case study from Vietnam)
Increasing climate resilience and combating climate change	Data is not available particular to floating wetlands. However, the lake mitigates the extreme flood and drought.	Data is not available particular to floating wetlands. However, the lake mitigates the extreme flood and drought.	The plants are the sink of CO_2 via photosynthesis	The plants are the sink of CO_2 via photosynthesis	Reduction in heat islands need to be quantified
b. Social and governance aspects					
b.1 Social acceptability	As another outcome of the establishment of floating wetlands, a Wetland Education Club at the Mahamaya Girls School. Photo shooting is one of the features that can be used as an evidence of public acceptability for the aesthetics status of the floating wetlands.	Photo shooting is one of the features that can be used as evidence of public acceptability for the aesthetics status of the floating wetlands.	Besides project implementation support, local authorities and people express their special interest in our activities and are excited to see how the floating wetlands work	• Most of the residents were not consulted during the planning stage since they were not official residents then • Majority of the residents are satisfied with the CW in terms of its location and benefits they were getting from it • One major issue is the fouled odor (which was eventually diminished over time) • Most of them are not willing to pay for their wastewater treatment	Data to be collected
b.2 Policy/Governance Aspect	Inland water bodies are under custody of Irrigation department with the ordinance. Finance allocation and decision making are done at the Irrigation department, Kandy Regional office	Kurunegala Municipal Council has the responsibility to maintain the lake and its surroundings. National Water Supply Board has the intake point.		• LGU took ownership of the operation and maintenance of the CW • LGU appropriates from their annual budget • Collaborations with the water utilities to shoulder the water quality tests	Data to be collected

(Continues)

EXHIBIT 13 (Continued)

	Floating Wetlands(case studies from Sri Lanka (SL)/Vietnam (Vn))			Constructed wetlands(case of Bayawan City, Philippines)	Maturation Ponds(case study from Vietnam)
c. Economic aspect					
Costland/water area usedCost of land usedCost of construction -Labor -Materials -Others Cost of operation -Maintenance -Harvesting of biomass -Water quality analysis	Data is not available at present	Data is not available at present.	- Six FWs (8 m^2 each; 4 x 2 m) were placed - No cost for area as they are in the canal **The total cost of construction** - Labor: 10 pax x 5 days x 15 US$/pax/day = US$750 - Materials: 111.5 US$ for each floating wetland (8 m^2) x 6 FWs = US$669 **Estimated monthly operating costs** - for conducting maintenance, water quality analysis and harvesting biomass activities (basic salary for one assistant) = US$250	• Land cost (3000 m^2): US$40k (2022 rate for land cost and conversion factor) Construction cost: US$300k (2022 CPI and conversion rate)O&M: US$17k per year (2022 conversion rate) and cost US$0.086/$m^3$ of wastewater treated	O&M: US$745,971 includes the O&M of the entire treatment system and costs US$0.071/$m^3$ of wastewater treated
BenefitsMonetary -Aquaculture -Agriculture -Improved water quality -Utilization of biomass -Increase in visitors -Reduction in flooding -Use the site for better health activities -Cooling effects	Increased aesthetic values, number of visitors are yet to be documented (US$/year 150,000)	Increased aesthetic values, number of visitors are yet to be documented (US$/year 39,000)	- Cannot evaluate fish biomass/productivity because the canal is connected to the river. - There are some people use the canal water to irrigate their crops (okra, *Colocasia gigantea*, *Luffa cylindrica*, are planted along the canal banks) - Water quality improvement is not recognized clearly because canal water quality changes four times/day due to tidal effect; however, the plants grow well, and the biomass increases over time. This indicates nutrients removal (nitrogen, phosphorus) via plant uptake which enhances water quality. - Ornamentals plants have been planted (provide aesthetic value) - Landscape provision	• Money is saved from reuse of the treated wastewater • Reduced load to the nearby sea where the residents derived most of their income from fishing (US$/year 176,678.60) • Health, tourism in the coastal area (turned into boulevard and recreational area), positive perception from the LGU and communities	• Improved water quality (US$/year 2,778,036.1) • Aquaculture is possible • Algal production is possible

(Continues)

EXHIBIT 13 (Continued)

	Floating Wetlands(case studies from Sri Lanka (SL)/Vietnam (Vn))			Constructed wetlands(case of Bayawan City, Philippines)	Maturation Ponds(case study from Vietnam)
Non-monetary					
Increase in biodiversity	Yet to be quantified, Ducks and other fauna have been observed	Yet to be quantified, Turtles and other fauna have been observed.	Bird/amphibians/insects have been attracted to the floating wetland - Local awareness is expected to increase	Migratory birds, snakes	Yet to be quantified
Contributions to SDGs	SDGs 4, 6, 11, 13, 17	3, 6, 11, 13, 17	3, 4, 6, 11, 13, 14, 17	3, 4, 6, 11, 13, 17	3, 6, 11, 13, 17

[a]Water quality test results: values in parenthesis are based on the local standards (allowable values), while the values in bold are the actual results from the case study considered.

appraise the solutions to fulfill the aspiration of the institutions concerned with lakes such as Sri Dalada Maligawa, Governor's office, Urban Development Authority, Kandy Municipal Council, National Water Supply and Drainage Board, Irrigation Department, Central Environmental Authority and Mahamaya Girls College in addition to the researchers from University of Peradeniya, Sri Lanka and Nanyang Technological University, Singapore. The owners of restaurants around the lakes also involved. Design & development and establishment of wetlands were a collective work of individuals and institutions. After the establishment, the operation & maintenance of floating wetland in Kandy and Kurunegala lakes are carried out by the Irrigation department and Kurunegala Municipal Council, respectively. A preliminary google questionnaire survey conducted among the dwellers who were not involved actively found that:

- the floating wetlands in lakes add aesthetic value to the lake
- the prime goal of water purification in lakes by the floating wetlands is not "visible" to the public
- no organized mechanisms for public to express their feelings and contribute physically or financially
- lack of awareness on ownership and functions
- lack of education and training on the NbS

Public has no specified role in day-to-day operation and decision making for the extension or development of the floating wetlands. The public participation in floating wetlands of the lake yet to be institutionalized. This could be brought to practice by using a better management tool such as sanitation safety plan in Kandy Lake and water safety plan in Kurunegala Lake. Moreover, the application of integrated water resource management would strongly link all the different stakeholders in action.

On the government policy perspective, Sustainable Sri Lanka 2030 vision and strategic plan set the goal for 2030 to ensure the quality of water in rivers and water bodies at WHO standards for drinking water sources or ambient water quality standards. It is difficult to find a policy guideline dedicated for NbS in Sri Lanka. However, there are many policies that include the basis of NbS. There are over 50 acts, and 40 government line agencies deal with water. The adequacy of policy towards NbS on the existing policies need to be assessed. By the ordinance, the urban lakes are under the custody of Irrigation Department, the government agency responsible for operation and maintenance of the lakes and reservoirs in Sri Lanka. There is a social awareness, acceptability, consensus, and blessing from all sides concerned to the floating wetland solutions in both lakes to be effective. The social acceptance and enabling environment through policies are important for the sustainability of NbS in Sri Lanka.

4.2.2 | The Philippines

Some of the sample questions which were used to evaluate the social acceptability of CW considered in the Philippines are:

Public participation (consultation before construction, agreement about the construction)

- Are you involved in the creation/implementation of the CW?
- Do you want to be informed and involved in the implementation of the CW for the community?
- Do you trust the local government unit when it comes to the operation and maintenance of the CW?

Public perception/perceived quality of CW (accessibility, amenities, natural features, recreational facilities)

- What are the benefits of the CW?
- What are the challenges/risks/impacts of CW?
- Do you think that the CW has been beneficial/not beneficial to community? Why or why not?

Sense of place (When you hear about the wastewater facility, what comes to your mind?)

- Do you want to live in an area where there is a CW? Why or why not?
- What will you advise people/friends/other communities, if another CW is built?
- Will you promote the creation of CW in other communities?
- What do you think should be done to replicate CW in communities?

Social acceptability study for the GK Village Wastewater Facility in Bayawan was done in 2010 (Guino-o II et al., 2009) with number of respondents of 90 households. Overall, the establishment of the CWs in the village was positively accepted by the majority of the households and they are aware of the functions and benefits brought about by the CWs, such as wastewater treatment, reuse of treated wastewater for washing, watering plants, help in water scarcity, and add attraction to the community. However, community consultation was perceived to be lacking since some of the respondents were relocated in the village during or after the construction of the CW. However, the majority of them do not want to pay a user's fee for the operation and maintenance costs of the CW and their major issue is with the odor. To limit the issues with odor, the wastewater to the CWs is fed or sprayed only during very early or late at night. Also, the odor was only severe during the early stages of the operation (due to insufficient buffer brought by the vegetation).

Some of the sample questions to be asked for the policymakers and implementing agencies are:

- What are the good points in the establishment of the CW in the area during:
  (i) Planning Stage
  (ii) Pre-construction
  (iii) Construction phase
  (iv) Operation and Maintenance
- What were the challenges experienced with the CW project during:
  (v) Planning Stage
  (vi) Pre-Construction
  (vii) Construction Phase
  (viii) Operation and Maintenance
- How were these challenges handled? Were they resolved?
- Based on your personal experience, can CW be adopted and replicated in other communities in the Philippines for domestic wastewater treatment and reuse?
- Any recommendations on the project phases to improve its replicability in other areas?
- How were Institutional Arrangements helpful in the project?
- Provide some details on common reactions regarding the acceptance of the community and people who have seen the CW and have used the facilities attached to the CW.

Similarly, looking at the construction of CW in the Bayawan City, the planning started with the Memorandum of Agreement (MOA, for technical assistance, signed in April 2005) between the government of Bayawan and the German Technical Cooperation Agency (GTZ) and with the loan from the World Bank. The sustainability of the CWs could be attributed to the operation and maintenance ownership by the local government, which allocated annual budget for the wastewater treatment services. Also, they were able to collaborate with the local water service provider to shoulder the cost for water quality tests. With this scheme, the households do not need to pay additional fees for their wastewater treatment (Asian Development Bank, 2014). However, this puts the replicability of the scheme under question.

4.2.3 | Vietnam

Social acceptability and policy aspects of the FWs have been investigated for this study (but not for the maturation pond). As we discussed in previous sections, the FWs in Can Tho city is a new initiative and set up in April 2022. To evaluate the social acceptance, a survey was conducted by interviewing the community having 60 household. The questionnaire is included in the Supplementary Material (Figure S3). At the early stages of the establishment of the FWs, there were stakeholders such as Youth Union and students/lecturers of Can Tho University participated in the installation of FWs and the cleaning up of solid wastes in the Bung Xang canal. The community (people passing by the canal and people living in front of the canal) started to pay attention to the FWs and appreciated the initiative. However, from the survey, it was found that the community has no knowledge on the roles/functions of the FWs. But they expected that the FWs to work well and the water in the canal will be purified to ensure the health of the environment. The community agreed that the ornamental plants on the CFWs will create aesthetic appearance and create greening of the urban landscape.

Implementation of the FWs in Bung Xang canal has generated first-hand information on technical, social, economic and policy/governance aspects; however, there are still several social challenges and technical issues to be considered for the operational application of such systems at full-scale in Vietnam. Furthermore, existing policies on environmental protection measures/legal documents, spatial planning, economic opportunities, and incentives can be used or a new institutional framework can be created for the implementation of NbS in Vietnam. However, strict implementation of legal requirements should be carried out for enhancing the application of FW.

4.3 | Economic aspect

Cost–benefit analysis (CBA) is an effective tool, which estimates the advantages and disadvantages of alternatives used to determine choices, which generate the best approach to acquire benefits while preserving savings, systematically (Sassone & Schaffer, 1978). This tool is used widely in water management (WM) to assess the economic, health and environmental benefits of a WM system (Lienhoop et al., 2014; Molinos-Senante et al., 2011; Prihandrijanti et al., 2008).

> *Cost–benefit analysis (CBA) is an effective tool, which estimates the advantages and disadvantages of alternatives used to determine choices, which generate the best approach to acquire benefits while preserving savings, systematically*

The CBA method is used to compare the economic feasibility associated with the implementation of WM before and after applying the proposed NbS. The benefits of those two options are compared with the costs of theirs. The net profit of each option is the difference between benefits and costs as shown in the equation below:

$$NP = \sum B_i - \sum C_i \quad (1)$$

where, NP is the net profit, B_i is the benefit of item i, C_i is the cost of item i of a given option. The costs and the benefits of a NbS application with respect to social, environmental, and economic aspects can be computed.

The list of parameters that needs to be considered in evaluating the CBA of a NbS are:

a. The costs (Dixon, 2013; Lienhoop et al., 2014; Singh & Kazmi, 2017): (i) Construction costs (CoC), (ii) Operation and maintenance (O&M) costs, (iii) Capital investment (CI), and (iv) Environmental costs.
b. The benefits: (i) Quantitative factors such as water quality parameters (pH, TSS, TN, TP, BOD_5, COD etc.). These parameters bring benefit to environment, which can be calculated using shadow prices for the removed pollutants (Singh & Kazmi, 2017) or mass removed per year (kg/year) (Suriyachan et al., 2012; Lavee, 2011) and (ii) Qualitative factors such as public health risk. Health benefit is equivalent to the costs of health problems recently occurred among residents (COI). The COI approach is a survey-based approach to assess the costs of health impacts (Hutton & Haller, 2004; Pearce et al., 2006). For the non-monetary benefit, there are no market that signals the price, so that the Contingent Valuation Method (CVM) can be applied. CVM is a survey-based approach. The application elicits people's preferences for environmental changes in terms of their willingness to pay (Mitchell & Carson, 1989; OECD, 1995; Pearce et al., 2006). Exhibit 11 shows some direct costs and benefits and how they can be sourced.

Cost-benefit analyses were carried out for all case studies and the details of their direct costs and direct and indirect benefits are given in Tables S6 through S9 in the Supplementary Material. The direct costs are computed through secondary data such as construction cost, land acquisition cost, and annual O&M cost. The direct benefits due to the removal of pollutants such as COD, TSS, NH_4^+-N and PO_4^{3-}-P are computed using primary data along with shadow prices associated with the removal of those pollutants. Average removals of those pollutants were used to compute the total mass removed annually. The benefits to the environment due to the removal of those pollutants were calculated using shadow prices as follows: US$0.139072 per kg COD removed; US$0.005406 per kg of SS removed; US$8.544024 per kg of N removed, and US$32.800852 per kg of P removed (Singh & Kazmi, 2017). Data was not available to compute some other monetary and non-monetary benefits indicated in Exhibit 11.

Exhibit 12 shows the overall cost-benefit analysis carried out for the NbS case studies: (a) FW in Kandy Lake, (b) FW in Kurunegala Lake, (c) CWs in Bayawan City, and (d) Binh Hung Hoa WWTP. The cost analysis for Binh Hoa WWTP does not differentiate the costs incurred and benefits generated by aerated lagoons, facultative ponds and maturation ponds individually. However, this data is valuable to understand the benefits of the integration of grey solutions with NbS. On the other hand, for the floating wetlands in Bung Xang canal, Vietnam (since they are just established) there are no data available for the analysis of economic benefits. The total cost was computed from the annual cost as follows:

(i) Capital and land acquisition costs were considered during the years of NbS construction (e.g., assumed 1 year for FWs and 3 years for CWs and WWTP)
(ii) Annual O&M costs were considered for the remaining years of operation of the NbS (assumed a life span of 20 years for all NbS types)
(iii) It is assumed that there will be a rehabilitation period at the middle of the NbS life span (after 10 years of operation), and the

EXHIBIT 14 Contributions of the case studies to SDGs

	Floating wetlands (case studies from Sri Lanka (SL)/Vietnam (Vn))			Constructed wetlands (case study from the Philippines)	Maturation ponds (case study from Vietnam)
	Kandy Lake, SL SDGs 4, 6, 11, 13, 17	Kurunegala Lake, SL SDGs 3, 6, 11, 13, 17	Bung Xang Canal, Vn SDGs 3, 4, 6, 11, 13, 14, 17	Bayawan City SDGs 3, 4, 6, 11, 13, 17	Binh Hung Hoa wastewater treatment plant SDGs 3, 6, 11, 13, 17
SDG 3 – Good Health and Wellbeing		The city depends on the lake for potable water.	Purified canal will provide good health and wellbeing of the neighbors of the canal.	Provides good health and wellbeing by treating the septic effluent before discharge.	Purified canal will provide good health and wellbeing of the neighbors of the canal.
SDG 4 – Quality Education	Establishment of floating wetlands, a Wetland Education Club at the Mahamaya Girls School which close to the lake. University of Peradeniya conduct research and training to its undergraduate and postgraduate students.		Students from Can Tho university are directly involved in constructing, commissioning, maintaining and monitoring the floating wetland and gain significantly knowledge about the floating wetland. They will be great resource in replicating floating wetlands in various parts of Vietnam.	The partner organizations in the case study are the Society for the Conservation of the Philippines Wetlands (SCPW) and the University of the Philippines – Los Baños (UPLB). SCPW provides forum and technical assistance on wetland-related issues and engages on research, training, and CEPA (communication, education, participation and awareness) programs. The UPLB, on the other hand, produces research related to constructed wetlands, where undergraduate and graduate students are involved.	
SDG 6 – Clean Water and Sanitation	Removal of COD, TSS, NH_4^+-N and PO_4^{3-}-P is estimated to provide an annual benefit of US$120,000; Part of the water released to the river is taken for water supply after treatment.	Removal of COD, TSS, NH_4^+-N and PO_4^{3-}-P is estimated to provide an annual benefit of US$28,000; lake water is treated and supplied to the city for various uses.	Removal of COD, TSS, NH_4^+-N and PO_4^{3-}-P.	Removal of COD, TSS, and PO_4^{3-}-P is estimated to provide an annual benefit of US$176,678.60.	Removal of COD, TSS, NH_4^+-N and PO_4^{3-}-P is estimated to provide an annual benefit of US$2,778, 036.10.
SDG 11 – Sustainable Cities and Communities	Kandy city benefits greatly due to the presence of lake through attracting visitors, creating recreational and cultural values.	The city depends on the water supplied from the lake during drought seasons and its sustainability is greatly dependent of the availability of clean water in the lake.		The treated effluent is reused for various purposes, such as irrigation and firefighting, providing resilience to the community.	Cleaner canal is very important to the sustainability of the Ho Chi Minh City and the communities along the canal as the canal carries large amount of water which is current being considered as wastewater.

(Continues)

EXHIBIT 14 (Continued)

	Floating wetlands (case studies from Sri Lanka (SL)/Vietnam (Vn))			Constructed wetlands (case study from the Philippines)	Maturation ponds (case study from Vietnam)
SDG 13 – Climate Action	The lake provides flood control and reduces heat island around the lake.	The lake provides flood control and reduces heat island around the lake.	Different species of fish found to live in the canal along with turtles.	The constructed wetland keeps the surrounding greener and cooler.	The pond system can reduce the surrounding temperature.
SDG 14 – Life below Water	The lake harbors fish habitat which are a great attraction.				
SDG 17 – Partnerships for the Goals	The lake brings multiple stakeholders for the operations and maintenance and the stakeholders collaborate with international partners to conduct further research for the improvement of the lake.	The lake brings multiple stakeholders for the operations and maintenance and the stakeholders collaborate with international partners to conduct further research for the improvement of the lake.	Can Tho university is leading this program and communicating with local government authorities and the community. It also works with international collaborators.	The SCPW was registered as a non-stock, non-profit corporation under the Philippine national law, with the main aim to promote the sensible use of wetlands in the Philippines through the promotion of linkages and networking among wetland advocates, such as engaging in wetland conservation activities locally and abroad.	Ho Chi Minh City University is active in collaborating with various national and international partners in order to develop NbS which in turn will contribute to the SDGs.

associated costs will be the annual O&M along with 50% of the capital costs (Sartori et al., 2015)

The benefit-cost ratio (BCR) was computed from the ratio of the total costs and benefits (considering the life span of the NbS type). For the considered case studies, the BCR ranges from 1.43 to 10.84. The minimum BCR is from Binh Hoa WWTP, where the contribution of NbS (combined grey and green technologies) is not clear from the available data. The maximum BCR from the case studies is from the FWs of Kandy Lake. The BCR is very high due to the relatively high benefit from pollutants removal. The average BCR for the wetlands considered, FWs (Kurunegala Lake) and CWs, is around 3.47. This is similar with the study of Irwin et al. (2018), where the CWs they studied had an average BCR value of 3.0.

4.4 | Preliminary assessment on the effectiveness and impact of the NbS considered in this study

Identification of technical, social, governance, and economical factors that influence the performances of the NbS case studies and criteria are highly relevant to assess the performance of impact and effectiveness. This section identifies the gaps in the overall assessment in the case studies and the specific factors for the effectiveness and impacts assessment are discussed in Exhibit 13. The first column gives the indicators to evaluate the effectiveness and impact of the three aspects considered: a. technical; b. social and governance; and c. economic. Technical aspect is divided into effectiveness (i.e., operations and water quality tests) and impact (i.e., water quality and climate change impacts). Similarly, social and governance aspect is also divided into social acceptability and policy. For the economic aspect, direct costs (CoC and O&M) and benefits (monetary and non-monetary indicators) are included to evaluate the benefit-cost ratio of the selected NbS.

The data shown in Exhibit 13 indicate that all the NbS considered perform well in general with respect to improving the water quality. However, more data need to be collected for some NbS such as the floating wetland in Kandy Lake. Information on meeting good design standards can be improved for many NbS considered in the study. Operation and maintenance seem to be good in all NbS but again detailed information is lacking in some cases. No qualitative analysis is available in any of the case study to evaluate their contributions towards climate resilience. Scattered data are available on all other factors such as social aspects, policy and governance and economy. The methods for capturing those aspects suggested in the paper provide a basis for further research aimed at assessing the effectiveness of NbS for water treatment in Asia in an integrated framework. While conducting individual case study assessments is important, given the current state of implementation of NbS in the examined countries, however, possibilities for the systemic integration of water quality, biodiversity, health and well-being monitoring conducted by public agencies in the examined countries should be considered with view of promoting synergies and reducing monitoring costs.

4.5 | Contributions of NbS to SDGs

Further, all the NbS considered in this study are expected to contribute to SDGs 3, 4, 6, 9, 11, 13, 14, and 17. However, for example, the floating wetlands in Sri Lanka are used to treat lake waters which are less polluted compared to the canal water that is being treated by floating wetlands in Vietnam. Thus, their contributions to SDGs are not identical. But the final goal is to make them contribute to similar SDGs. The contributions to SDGs and specific scenarios of the NbS case studies are shown in Exhibit 14.

5 | CONCLUSIONS

Appropriate guidelines should be available in order to replicate and upscale nature-based solutions for water treatment. The guidelines should contain general instructions that are applicable to all types of nature-based solutions for water treatment as well as instructions for specific treatment systems. This study considered three types of nature-based treatment systems, namely, floating wetlands, constructed wetlands and maturation ponds and provides a preliminary assessment framework co-developed based on a review of relevant literature and insights and the examined case studies considered in this paper. When the NbS considered in this study were assessed against the proposed assessment framework it was found the data available for those NbS give a general evaluation about their effectiveness and impacts but require systematic data collection for accurate assessment in order to enable learning from the case studies, improvement and replication.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article cd_value_code=text.

ORCID

Veeriah Jegatheesan https://orcid.org/0000-0002-8038-4854

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