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Designing Ecological Floating Wetlands to Optimize Ecosystem Services for Urban Resilience in Tropical Climates: A Review

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ABSTRACT

Floating wetland systems potentially can provide a diverse set of ecosystem services that collectively improve urban resilience. Despite the growing studies and use of floating wetlands in temperate and subtropical climates, the design of floating wetlands in tropical climates is still understudied. This paper therefore aims to identify the research gaps in landscape planning and synthesize the design typology that can be applied to tropical urban conditions. The purpose of this research is i) Identify opportunities and challenges in applying floating wetland systems for landscape planning and design, ii) synthesize the design typology that can be applied to urban tropical climate conditions and iii) demonstrate the application of ecological wetland principles for the built environment. This research uses a mixed methods approach by including both a narrative review based on 67 peer-reviewed articles as well as case studies from tropical climates. The review captures the challenges and opportunities of designing ecological floating wetlands in terms of multifunctional usage, site limitation, cost effectiveness, social benefit, and ecological habitat creation. For design typology of floating wetlands in a tropical climate, we discuss design components based on size, floating mat types, structures and materials, planting design, and additional technology. While the first case study showcased a design for an ecological floating wetland, the second case study illustrates how mathematical modeling can guide sizing and performance assessment in planning floating wetland implementation. Ecological floating wetlands can provide a positive impact to the urban environment under tropical conditions, but the main research gaps include an incomplete understanding of contaminant uptake rates associated with different plants, required maintenance of the systems, plant robustness, and community appreciation.

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INTRODUCTION

Landscape structures and patterns are considerably impacted by urbanization and, in particular, lead to the loss of natural wetlands and biodiversity (Loc et al. 2020; Ballut-Dajud et al. 2022). This discouraging trend occurs despite the estimated global ecosystem service value of wetlands (Costanza et al. 2014). Natural wetlands near or in an urban area face the dual challenges of ecological degradation and mainstreaming ecosystem service concepts as an integral part of landscape planning, management, and decision making (Loc et al. 2020). This type of wicked problem may lead us to consider how we might effectively approach the sustainability of urban wetlands. Certainly, such wicked problems require a multidisciplinary approach to be addressed effectively (e.g. Allan 2008; Irvine et al. 2022). In the case of reimaging urban wetlands as a reflection of Nature-based Solutions (NbS), landscape architects could use native plants to create habitat structure for native species (Chang et al. 2021), while mimicking the ecological functions of wetlands including water treatment and habitat creation sites, as well as providing recreational or educational facilities and ecological art areas (Stefanakis 2019). The design concurrently needs to link with engineering performance (Irvine et al. 2022). Furthermore, the multidisciplinary approach to NbS wetlands reimaging will help to enhance urban resilience through flood management, reduced environmental degradation, greater urban liveability, urban heat island mitigation, carbon sequestration, and food security (Bozza et al. 2017). Reimaging urban wetlands, in part, is an issue of contested space, with competing pressures of urban development and conservation (Mialhe et al. 2019). In this context, floating wetland systems can be used in urban conditions since they do not require additional water surface area (Keizer-Vlek et al. 2014; Zhang D Q et al. 2014), yet have the potential to enhance aquatic ecosystem services (Dai & Chiang 2008). Most floating wetland systems designed by engineers focus on the treatment function (Smith 2009; Pavlineri et al. 2017), but there is a need to expand the multidisciplinary design thinking approach to NbS in general, and floating wetland systems in particular, to optimize ecosystem services delivery, including elements of community wellbeing and aesthetics. This paper will explore and review the fundamental design of ecological floating wetlands, especially in tropical climates.

Floating wetlands can be implemented in both lotic (De Stefani et al. 2011; Kamble & Pathid 2012) and lentic systems (Borne et al. 2013; White & Cousins 2013). Research has shown that this novel sustainable cleansing approach can perform well even under challenging environmental conditions (Headley & Tanner 2012; Zhang D. Q. et al. 2014), but the performance can vary, depending on hydraulic loading rate, size, depth, and hydraulic residence time (Winston et al. 2013; Pavlineri et al. 2017), plant types, physiology, and density (Chang et al. 2013; Keizer-Vlek 2014; Chua et al. 2012), floating mat types (Kamble & Pathid 2012; Lynch et al. 2015), plant harvesting methods (Wang et al. 2014; Zhang C B et al. 2014), and additional technology (Lu et al. 2014). Common plants normally used for floating wetland structures include Typha, Vetiver Polygonum, and Iris. Despite research done using conventional plants for floating wetlands, few studies have examined the performance of edible plant species for floating wetlands. Thick mats of floating morning glory (*Ipomoea spp.*) cultivated as a crop in the natural wetland of Boeng Cheung Ek, Phnom Penh, Cambodia (Loc et al. 2020) reduced E. coli and detergents levels by 99.9% and 87% respectively, within 200 m from sanitary sewage point of entry to the wetland (Irvine et al. 2008). Zhang Q. et al. (2014) also showed that morning glory could improve water quality in carp aquaponic pond systems, although, safety issues for human consumption were flagged. Zheng et al. (2009) in a laboratory study found the treatment efficiency of edible spicy water celery was limited but water celery can be edible since the plant slowly uptakes the nutrients. Floating wetland studies have been conducted in temperate and subtropical climates (De Stefani et al. 2011; Winston et al. 2013; Chang et al. 2013; Li et al. 2018; Spangler et al. 2019), but examination of floating wetlands in tropical climates is still limited (Chua et al. 2012). Lim & Lu (2016), suggested that Singapore's "Active, Beautiful, Clean (ABC) Water Policy" included innovative visioning but required stronger scientific evidence with respect to performance of the green infrastructure. Ecologic and hydrologic modeling often are employed by the engineering community to assess design performance and these techniques should be adopted to the landscape architecture toolkit (Irvine et al. 2021; Salata & Arslan 2022).

This brief introduction suggests more research is needed to explore the value of floating wetlands as a support mechanism for ecological functions within tropical cities, i.e. performance-based aesthetics and ecological design. The purpose of this paper therefore is i) identify opportunities and challenges for applying floating wetland systems in landscape planning and design ii) synthesize the design typology that can be applied to urban tropical climate conditions and iii) demonstrate the application of ecological wetland principles for the built environment.

METHODS

This research uses a narrative review approach based on 67 articles from the Scopus and Google Scholar search engines. Keywords, including 'Floating wetland'; 'Artificial floating islands'; 'Ecological floating bed'; 'Constructed wetlands'; 'Ecological stormwater treatment'; 'Urban water management'; 'Nature-based solutions'; 'Landscape design'; Landscape planning'; 'Tropics'; and 'Tropical climate' were used to search for the pertinent articles.

In addition, we provide two case studies to illustrate the application of ecological wetland principles for NbS and the built environment following the embedded case study approach that focuses on multiple-case design as outlined by Yin (2014). The two selected case studies of ecological floating wetlands share a similar context, being situated in a tropical climate. The first case study has embedded units of analysis associated with the design typology that reflects planting design variation. The second case study has embedded units of analysis related to nutrient uptake for water quality improvement.

The first case study explores the design and implementation of a floating wetland that was constructed at the Faculty of Architecture and Planning, Thammasat University, between 2019–2021. This demonstration wetland shows the possibility in design with complexity concepts and plant diversity as an educational tool.

The second case study presents a modeling application to assess performance of free floating (but spatially contained) emergent macrophytes in managing nutrient levels for a reservoir in Singapore. Constructed between 1972 and 1974, the reservoir has a surface area of about 450 ha, a mean depth of around 3.5 m and a maximum depth of 17 m. Dissolved phosphate levels were highest in the years immediately following the reservoir construction, up to a range of 1.22 mg/L, but decreased after implementation of stricter discharge controls (Appan and Wang, 2000). Nonetheless, TN, TP, and chlorophyll *a* levels in the eutrophic range still are observed for parts of the reservoir (Te & Gin 2011; Xing et al. 2014) and management of nutrient sources would be beneficial in reducing potential issues with algae blooms. The reservoir catchment is 5,700 ha in area and has four main tributaries. Land use is a mix of high and low density residential and commercial areas, but there also is a large proportion of forested area (33.5%) and agriculture (5%, mostly chicken farms, with smaller areas of horticulture, nurseries, and aquaculture activities). The area is serviced by a concrete-lined separate stormwater drainage system. PCSWMM (Personal Computer Version of the Stormwater Management Model) was used to model total phosphorous (TP) and total nitrogen (TN) loading rates (kg/day) entering the reservoir from the catchment. To evaluate the ability of emergent macrophytes in reducing reservoir loadings, the period 17 November 2014–18 December 2014 was assessed, since the total rainfall depth during this time (271 mm) was typical of November-December rainfall (250–300 mm/month, http://www.weather.gov.sg/climate-climate-of-singapore/).

RESULTS AND DISCUSSION

OPPORTUNITY AND CHALLENGE FOR LANDSCAPE PLANNING AND DESIGN

The opportunity for applying floating wetlands in urban areas is impacted by several issues, including water quality, site limitation, aesthetics, community needs, cost effectiveness, wildlife and aquatic habitat (Hwang & LePage 2011). Maintenance also is a crucial issue when implementing floating wetlands for water treatment. The opportunities and challenges related to these issues as identified in the literature review are summarized in Table 1.

Material from Table 1 suggests that floating wetlands can be applied successfully within urban environments for multifunctional usage. The review showed that the ecological system can improve water quality with minimum cost and land requirements. It is clear that the ecological design of floating wetland systems bridges between engineering and landscape architecture.

From the aspect of social needs and benefits, this green technology is socially accepted for small to medium sized wastewater treatment (Zhang D Q et al. 2014; Sharley et al. 2017), but the aesthetic of it might be less understood by the general public and requires improved community outreach (Ngiam et al. 2017). Ultimately, the future challenges of ecological floating wetland design can be addressed through design typology, as discussed in the next section.

DESIGN TYPOLOGY OF FLOATING WETLANDS IN A TROPICAL CLIMATE

Constructed wetlands have long been used in urban water management practices (Kadlec, 1995), and can be classified as Free Water Surface (FWS) systems, Subsurface Flow (SSF) systems (SFS), Vertical Flow (VF) systems, or a hybrid system from an engineering perspective (Koottatep & Panuvatvanich 2010). While the engineering focus is on the hydraulic and water quality performance of the wetland, Kadlec (1995) noted that ancillary wildlife and human uses were an important component of constructed wetlands and should be acknowledged in the design. In a different approach to classifying constructed wetlands, Sundaravadivel & Vigneswaran (2001) suggested three typologies: constructed habitat wetlands, constructed flood control wetlands, and constructed aquaculture wetlands. An important advantage for wetlands in tropical climates is that plants grow year-round with a positive water treatment impact (Koottatep & Panuvatvanich 2010). With respect to design typologies for floating wetlands, there appear to be three principal typologies and tropical climates may produce signature characteristics i) treatment floating wetland ii) habitat floating wetland and iii) productive floating wetland. The design typology can be characterized based on ecosystem services (Reid et al. 2005) as show in Table 2.

ISSUES		OPPORTUNITY (O) & CHALLENGE (C)	REFERENCE
Multifunctional usage Water quality improvement	O	Artificial wetland can be used in gold mine rehabilitation for leachate treatment in the subtropical climate of Australia	Greenway & Simpson (1996)
	O	Floating wetlands can be a useful component for stormwater treatment trains providing an optional design to existing pond-based treatment system	Headley & Tanner (2012)
	O, C	Controlled and field experiment using floating wetland system to treat water for a reservoir in Singapore. Typha nutrient uptake rate was superior to Vetiver and Polygonum	Chua, et al. (2012)
	O	Artificial floating islands were used in the River Mula and Mutha, in Pune City, India to improve water quality	Kamble & Patil (2012)
	O	Comparison study between retention pond with floating wetlands vs. regular pond shows that retrofitting the floating wetlands can effectively improve water quality	Borne et al. (2013)
	O, C	In temperate climate, Iris can be used in floating treatment wetlands in urban and agricultural conditions which overcome with the excessive algae growth	Keizer-Vlek et al. (2014)
	O	In sub-tropical climates, floating wetlands can be used for agricultural wastewater runoff treatment	Spangler et al. (2019)
Edible green infrastructure	O, C	Water spinach as part of a floating wetland significantly improved water quality in crab ponds, Wushe, Shanghai City, China, however heavy metals should be tested for safe consumption	Zhang, Q. et al. (2014)
Site limitation Locations	O	An experiment using a commercial floating system filled with macrophyte species in a lotic system shows efficiency to improve water quality in COD, BOD, N and P	De Stefani et al. (2011)
	O, C	Full scale experiment using floating marsh for uptaking Ni and Zn from highway runoff in Northern France.Biomass needs to be harvested yearly	Ladislas et al. (2015)
	C	It is important for planners to understand urban land uses and evaluate landscape activities in catchment areas before choosing the right stormwater treatment option and application	Sharley et al. (2017)
Cost effectiveness Minimum cost and land requirement	O, C	The research confirmed that Typha angustifolia can be used in floating wetlands when space and cost are limited compared to Canna iridiflora	Weragoda et al. (2012)
	O	From the review, constructed wetlands were recommended for wastewater treatment in small and medium sized towns where land is available and affordable	Zhang, D.Q. et al. (2014)
Social benefit Community needs	O	Constructed wetlands are socially accepted to be a green technology for stormwater treatment in an urban landscape	Sharley et al. (2012)
Perception and aesthetic	C	City dwellers surveyed in London did not appreciate the natural function or wild look of wetland plants	Ngiam et al. (2017)
Ecological habitat creation Increasing urban biodiversity and landscape diversity	C	Review showed a limited number of macrophyte species are used in wastewater treatment wetlands compare to possibilities over 150 species that can be found in the systems globally	Dai & Chiang (2008)
	O	A good design and suitable plant selection for artificial wetland design can also create the ecological benefit for example, urban wildlife habitat	Shaharuddin et al. (2011)
	O	The artificial floating island can form a unique ecological habitat for aquatic species, insects, dragonflies and birds in the Li-Yu Lake, Taiwan	Wu et al. (2014)
	O, C	Since urban ponds are neglected and tend to have a very poor ecological quality, there should be strategies to increase biodiversity	Noble & Hassall (2015)
	O, C	Landscape architect could use native plants to create habitat structure in the urban environment for improved connection with the natural ecosystems	Samal et al. (2019)
Climate change	C	Climate change needs to be considered for designing the future of ecological floating wetlands	Chang et al. (2021)

Table 1 Opportunities and challenges in designing an ecological floating wetland.

FLOATING WETLAND DESIGN TYPOLOGY	ECOSYSTEM SERVICES (Reid et al. 2005)
Treatment floating wetland	Provisioning (Water, Biochemical products) Regulating (Water quality, Local climate)
Habitat floating wetland	Regulating (Climate regulation, Biological regulation) Habitat or supporting (Nursery habitat, Genetic pool protection) Education and science opportunities for formal and informal education and training
Productive floating wetland	Provisioning (Food, Ornamental species and/or resources) Cultural and amenity (Aesthetic, Recreational, Inspiration for culture, art, and design, Cultural heritage and identity)

Table 2 Floating wetland design ecosystem services.

The review by Samal et al. (2019) focusing on ecological floating beds suggested that additional research was needed on design varieties and conditions affecting floating wetland systems. The design of floating wetlands can be understood through the concepts of structure, function, and operation (Headley & Tanner 2012). Lim & Lu (2016) examined the design of ABC feature performance in Singapore and concluded that uncertainty remains with respect to vegetation selection, performance over time, location/size/coverage and maintenance issues.

Recommendations and experiences related to raft size, raft material, planting variety, and additional technology, as a step towards formalizing technical aspects of design typology, are summarized in Table 3. The sizes of the artificial floating bed usually are in the 1 m × 2 m range which allows the mat to be easily transported and maintained. In modular systems, floating mats can be combined and joined to create a larger platform (Wong et al. 2013). The size of the floating mat also depends on the structure and material. The mat can be designed either with or without a frame structure, depending on the buoyant material. The commonly used synthetic materials are Styrofoam sheet (Yang et al. 2008), special foam polyurethane (Kamble & Patil 2012), high-density polyethylene (HDPE) (Wong et al. 2013), PVC pipe and plastic mesh (Wang & Sample 2013), and recycled plastic bottle raft (Siaga et al. 2018). Natural materials also are commonly used in raft construction, including bamboo (Bernas et al. 2017) and coconut palm fiber (Kamble & Patil 2012). Normally, the synthetic material lasts longer than the natural material but there is concern over the use of synthetic material which might release micro plastics to the aquatic ecosystem. Patented, commercial mats generally advertise that the material consists of high-grade plastic or high-density polyethylene meant to reduce harmful byproduct release.

White & Cousins (2013) reported that floating wetland systems consisting of Typha angustifolia, Canna iridiflora, Chrysopogon zizanioides (L.), Cyperus papyrus and Heliconia sp. can lower the N and P from stormwater runoff. Dai & Chiang (2008) noted that generally there are only a few different macrophyte species selected for wastewater treatment, while there is potential for over 150 species globally that could be implemented. Furthermore, Dai & Chiang (2008) expressed concern that monoculture planting may result in invasive species replacing the local habitat if not maintained well. Studies also highlight that biomass harvesting must be undertaken to optimize the remediation rate. Above ground harvesting can improve phosphorus uptake (Wang & Sample 2013), while Zhang C B et al. (2014) found that the removal performance of floating wetland systems depended on plant type and method of biomass removal. Interestingly, Zhang C B et al. (2014) also reported that the bacteria and biofilm on the root systems had a relatively small influence on the level of pollutant uptake.

For habitat creation Nyakang'o & Bruggen (1999) used several plant varieties including, *Typha, Cyperus latifolius,*

	TYPOLOGIES	RECOMMENDATION
Sizes	Small to Medium	1 m.– 5 m. (Kamble & Patil 2012) 2 m. × 1 m. (Siaga et al. 2018) 2.5 m. × 2 m. × 1 m. (Chua et al. 2012)
	Large	7.8 m.–15 m. × 25 m. using HDPE modular systems (Wong et al. 2013)
Floating mat types, structure, and materials	Synthetic material	Sheets made of foam (Yang et al. 2008) Special foam polyurethane (Kamble & Patil 2012) High-density polyethylene (HDPE) modules (Wong et al. 2013) PVC pipe and plastic mesh (Wang & Sample 2013)
	Reused material	Plastic bottle raft (Siaga et al. 2018)
	Natural based	Bamboo rafting with dirt and compost (Bernas et al. 2017) Coconut palm fiber (Kamble & Patil 2012)
	Patent materials	BioHaven (Headley & Tanner, 2012 Lynch et al. 2015) Beemats (Lynch et al. 2015; White 2021) Tech IA (De Stefani et al. 2011)
Planting design	Water treatment	Typha augustifolia (Koottatep & Polprasert 1997) Typha angustifolia and Canna iridiflora (Weragoda et al. 2012) Chrysopogon zizanioides (L.) (Daeajeh, et al. 2016) Cyperus papyrus and Heliconia sp. (Pérez-Salazar et al. (2019)
	Habitat creation	Typha, Cyperus latifolius, Cyperus papyrus, Hydrocotyle, Hydrocleis and Pontederia (Nyakang'o & Bruggen 1999)
	Edible species	Ipomoea spp. (Loc et al. 2020) Rice (Bernas et al. 2017) Chili pepper (Siaga et al. 2018)
Additional technology	Solar panel	Green energy floating island is tested to quickly enhance water quality (Lu 2014)
	Camera Video recording	Wildlife observation activity, including; habitation, forage, breeding, nursing, and rest, associated with the floating wetland can be observed (Wang et al. 2014)

Table 3 Recommendations and experiences from the literature on floating wetland design in tropical climate.

Cyperus papyrus, Hydrocotyle, Hydrocleis and Pontederia. A number of studies found a positive linkage between suitable native plant species and enhancement of the urban wildlife habitat (Shaharuddin et al. 2011; Wu et al. 2014; Samal et al. 2019). In a tropical climate with fluctuating flood conditions, native rice (Bernas et al. 2017) and chili pepper (Siaga et al. 2018) can be grown on the floating wetland raft. As noted in section 3.4, plant selection is an important component for water treatment in addition to the habitat creation function. If the condition of the water is suitable for planting edible species, such plants may be included on the floating wetland.

Additional technology and equipment can be added to increase the efficiency and function of the ecological wetland. Solar panels can be used on floating islands as a green energy source to enhance the process of water treatment (Lu 2014). Wildlife activities associated with the floating wetland can be observed using camera and video recording equipment (Wang et al. 2014).

DEMONSTRATION OF ECOLOGICAL FLOATING WETLAND AT THAMMASAT UNIVERSITY

The first case study describes an ecological floating wetland design and experimental project at the Faculty of Architecture and Planning, Thammasat University in Thailand. As discussed in the review on floating wetland typology, the design focused on the habitat of the floating wetland and aimed for creating education and science opportunities. The project was included in a year-3 Landscape Architecture class design competition for PTT Plant Together. The floating wetlands were installed in the front pond of the school between 2019–2021. This front pond has a surface area of 0.12 ha and a mean depth of around 1 m with concrete edges and earth bottom. The pond is nutrient-rich due to fish waste from a high density of ornamental fish but no filter system, although mechanical mixers and fountains are employed to increase dissolved oxygen levels and water movement. The plan to install ecological floating wetlands not only aimed to improve water quality but also emphasize ecosystem service design and an aesthetic approach to the building entrance.

As illustrated in Figure 1 (below), the ecological floating wetlands design was purposed along with the other landscape design elements associated with the pond, green façade design, and vertical structures. In this section, the discussion will only focus on the design process and the implementation through maintenance perspective over the three years of study.

As illustrated in Figure 2 (below), the students chose to apply local material such as discarded PET plastic bottles framed with 15 – 20 cm diameter underground drainage pipes filled with organic matter. A geotextile layer also

Figure 1 Floating wetland design and demonstration in front pond of Faculty of Architectureand Planning, Thammasat University, Pathum Thani, Thailand.

Figure 2 A design on the floating wetland beds with discarded PET plastic bottles framed with drainage pipes and geotextile.

was used to support the floating beds. The shape of the floating structure could be either rounded or freeform. Recommended size of these floating wetland structures is about 1 m in diameter or smaller per the technical typology of the small to medium raft size in Table 3. Some of the larger beds were anchored with a bamboo structure. A diversity of tropical plant species was used, with a focus on varying the size, form, color, and root depth. The selected species included: *Canna indica L.* (Indian shot), *Homalomena 'Emerald Gem'* (Emerald Gem), *Crinum amabile Donn* (Red Crinum), *Hydrocotyle umbellata L* (Water Pennywort), *Equisetum debile* (Horsetail), *Cyperus imbricatus* (Umbrella plant), *Heliconia spp.* (Heliconia), *Cyperus papyrus L.* (Egyptian papyrus), *Thalia geniculate L.* (Bent Alligator-flag), and *Pandanus amaryllifolius Roxb.* (Fragrant Pandan). While most of the plants are native to the region, some imported plant species that commonly are used in landscape design also were included. The planting design of each floating bed combined at least three types of plant species to mimic the diversity of a natural wetland (Figure 1, bottom left and right). The plant selection of this ecological floating wetland design illustrates plant diversity following the technical typology for habitat creation (Nyakang'o & Bruggen, 1999, Table 3). From a construction and maintenance perspective, the demonstration wetlands were relatively low in cost, relying on common and local material as well as a low maintenance involvement. If the design can mimic the ecological plant community well, this floating structure can be used as a bio-filter and at the same time create a naturalist landscape. This floating wetland habitat can also provide ecosystem services for climate regulation, biological regulation, habitat, and education opportunities (Table 2).

MODELING NUTRIENT MANAGEMENT OF FLOATING EMERGENT MACROPHYTES IN A SINGAPORE RESERVOIR

The second case study was conducted under the auspices of the PUB, Singapore's National Water Agency, and illustrates a technical approach to evaluating total phosphorus (TP) and total nitrogen (TN) uptake, an issue identified within the literature review as being an important co-benefit of floating wetlands. This case study focused on assessing potential treatment efficacy of floating wetlands, thereby addressing regulating ecosystem services for water quality improvement. Previous research on floating wetlands in this reservoir (Chua et al. 2012) reported nutrient removal for *Chrysopogon zizanioides* (Vetiver grass), *Typha angustifolia* and *Polygonum barbatum*. These species were included in the evaluations, as were water hyacinth and lotus, which commonly grow wild in the reservoir. A summary of the daily nutrient uptake rates by the different plant species is provided in Table 4.

The uptake results presented in Table 4 were used to develop different nutrient load reduction scenarios. Based on uptake rates and possible installation areas, six scenarios (outlined in Table 5) were assessed for macrophyte load uptake near the head of embayment, in the vicinity of catchment discharge points to the reservoir. The PCSWMM model configuration is shown in Figure 3 (left), while the rainfall and modelled flow at outfall OF4, as an example outfall, are shown in Figure 3 (right) for the period 17 November 2014 – 18 December 2014. The total uptake masses of TN and TP under the different uptake/installation area scenarios were calculated for this model period (see Table 5). In comparison, the TN and TP inflows to the reservoir collectively from OF1, OF2, OF3, OF4, and OF5 would be 4,007 kg and 6,513 kg, respectively, based on PCSWMM model results for this November-December time period. The low uptake scenarios would reduce the total inflow loads by 1% or less and therefore would not be an effective management strategy. However, if the moderate uptake rates could be achieved, TN and TP reduction for the low cover area would be 58% and 7%, respectively, and for the high cover area, TP reduction would increase to 27%. The high uptake rate scenarios potentially would remove more TN and TP mass than was input from the 5 outfalls and this is an unlikely scenario. Based on the planning level calculations, it is possible that water hyacinth, in particular, could positively impact nutrient levels in the reservoir, but this should be explored in more detail using a field demonstration approach (see Chua et al. 2012) before full implementation. In addition, water hyacinth in the headwater areas of the embayment may produce adverse hydraulic conditions due to clogging and could result in localized flooding. This issue should

PLANT SPECIES	TN UPTAKE, MG/M²/DAY	TP UPTAKE, MG/M²/DAY	REFERENCE
***Chrysopogon zizanioides* (Vetiver grass)**	1.74	0.16	Chua et al. 2012
Typha angustifolia	16.2	1.57	Chua et al. 2012
Polygonum barbatum	2.82	0.4	Chua et al. 2012
Typha orientalis	180	20	Wu et al. 2011*
Water hyacinth	1,310	270	Sato and Kondo 1981
Water hyacinth	1,278–3,276	243–371	Reddy and De Busk 1985
Water hyacinth	10–200	1–40	Mahujchariyawong and Ikeda 2001**
Water hyacinth	260–340	33–64	Boyd 1976
Lotus	10–31	38	Seo et al. 2010

Table 4 Nutrient Uptake Rates by Macrophytes.

* Wetland microcosm experiments with rooted plant; ** River environment.

SCENARIOS	TN MASS UPTAKE, KG	TP MASS UPTAKE, KG
Low Uptake (TN – 1.74 mg/m²/day; TP – 0.16 mg/m²/day), Low Cover Area (22.1 ha), uptake rates based on Chua et al. (2012)	11.9	1.10
Low Uptake (TN – 1.74 mg/m²/day; TP – 0.16 mg/m²/day), High Cover Area (90 ha), uptake rates based on Chua et al. (2012)	48.5	4.46
Medium Uptake (TN – 340 mg/m²/day; TP – 64 mg/m²/day), Low Cover Area (22.1 ha), uptake rates based on Boyd (1976)	2,329	438
Medium Uptake (TN – 340 mg/m²/day; TP – 64 mg/m²/day), High Cover Area (90 ha), uptake rates based on Boyd (1976)	9,486	1,786
High Uptake (TN – 2,277 mg/m²/day; TP – 307 mg/m²/day), Low Cover Area (22.1 ha), uptake rates are from the mid-point of the ranges reported by Reddy and De Busk (1985)	15,600	2,103
High Uptake (TN – 2,277 mg/m²/day; TP – 307 mg/m²/day), High Cover Area (90 ha), uptake rates are from the mid-point of the ranges reported by Reddy and De Busk (1985)	63,528	8,565

Table 5 Estimated Mass Uptake of TN and TP by Macrophytes in the Reservoir, 17 November 2014 – 18 December 2014.

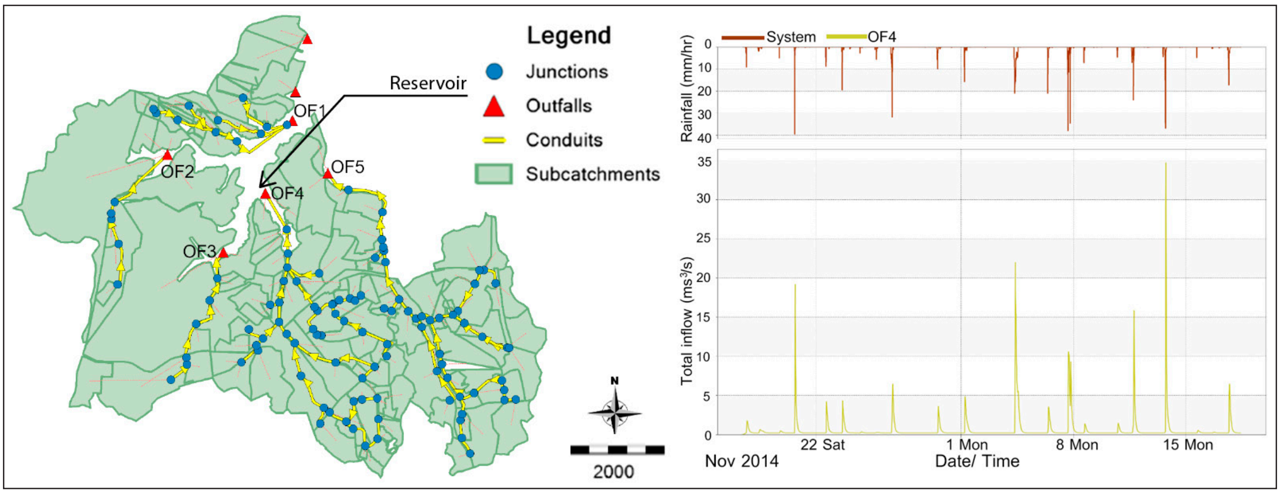

Figure 3 The study catchment as represented in PCSWMM (left). The yellow lines are the modelled surface drains (conduits) while the red triangles represent outfalls to the reservoir. Modelled inflow to the reservoir from OF4 for the study period 17 November 2014 – 18 December 2014 (right).

be further assessed. We note that there is up to 3 orders of magnitude variability in the reported macrophyte uptake rate data, which produces uncertainty in this analysis. While the general modelling approach is valid, the uptake rate characteristics require considerably more research and refinement.

CONCLUSION

The combined literature review and case studies presented herein illustrate opportunities for investing in urban floating wetlands including, water quality improvement and increasing urban biodiversity. The ecological floating wetland can be applied in various urban conditions with minimum cost and land requirement. However, there are challenges related to maintenance issues, harvesting strategies, consumer safety if used for edible purposes and social perception. The relationship between plant community and uptake ability in the face of climate change should also be explored further with respect to designing and managing floating wetlands in a tropical climate. The design typologies should be considered by understanding suitable floating structures, plant diversity and selection, and additional technology which can be local and eco-friendly.

The two case studies highlight the positive benefits of ecological floating wetlands in tropical cities. Ranging from a small-scale fish pond in Thailand to the larger-scale reservoir considerations in Singapore, ecological floating wetlands can provide ecosystem services including, provisioning, regulating, habitat, aesthetics (cultural), and education, to the existing water bodies in a tropical environment. Future research must include better data collection and development of design guidelines associated with nutrient and contaminant uptake rates, maintenance strategies of the systems, plant diversity and adaptation to climate change, and community perception and appreciation.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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