# A REVIEW OF CURRENT KNOWLEDGE AND RESEARCH PRIORITIES FOR CONSERVATION OF LENTIC BIODIVERSITY IN TROPICAL WET AND MONSOONAL URBAN LANDSCAPES

Selam S. Gebreselassie[1], Alex M. Lechner[2], Matthew J. Hill[3], Fang Yenn Teo[4], Christopher N. Gibbins[1]

[1] School of Environmental and Geographical Sciences, University of Nottingham Malaysia, Jalan Broga, 43500, Semenyih, Selangor, Malaysia. Email: hgxsg1@nottingham.edu.my; Christopher.Gibbins@nottingham.edu.my

[2]Urban Transformations Hub, Monash University Indonesia, Green Office Park 9, The Breeze BSD City, Tangerang Selatan Banten 15345, Indonesia Email: alex.lechner@monash.edu

[3]School of Applied Sciences, University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, UK. Email: m.hill@hud.ac.uk

[4] Department of Civil Engineering, University of Nottingham Malaysia, Jalan Broga, 43500, Semenyih, Selangor, Malaysia. Email: fangyenn.teo@nottingham.edu.my

Corresponding Author: Selam S. Gebreselassie, School of Environmental and Geographical Sciences, University of Nottingham Malaysia, Jalan Broga, 43500, Semenyih, Selangor, Malaysia.

Email: hgxsg1@nottingham.edu.my

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## Abstract

1. Urban expansion is a major threat to diversity, especially in rapidly developing tropical countries where urban areas are growing at great pace and protection is limited.
2. We conducted a systematic review of published research on the ecology of lentic habitats in tropical urban areas. The review focused on understanding (i) how much is currently known about the biodiversity of these habitats, (ii) whether this knowledge is biased towards certain taxonomic groups and/or geographic areas, (iii) what is known about the factors influencing their diversity, and (iv) which ecosystem services urban lentic habitats provide. The review aimed to establish whether existing knowledge is sufficient to help guide conservation and provide evidence to policy-makers of the importance of conserving tropical urban wetlands.
3. We found 64 papers that addressed questions about the diversity and/or distribution of lentic ecosystems within tropical urban areas. Papers came from 15 countries, although almost half (45%) were from India; relatively few countries from Southeast Asia, tropical Africa or South America were represented in the literature.
4. Publication patterns revealed a growing interest in urban wetlands, but several biases and gaps were evident from the review. Firstly, papers generally focused on larger natural or semi-natural wetlands, with other types and sizes of lentic habitat under-represented in published work. Secondly, most papers focused on a single site, with a limited number of multi-site, city-wide or landscape-scale diversity assessments. Thirdly, studies tended to focus on understanding the influence of water quality on diversity, with work assessing the influence of physical habitat or factors related to dispersal and connectivity very limited. Finally, work assessing the ecosystem services provided by wetlands in tropical urban areas remains narrow in focus, with few quantitative assessments of the relationship between ecological characteristics and ecosystem functions and services.
5. We suggest a number of research focal points and approaches to help address these biases. Research is needed to improve understanding of the distribution patterns tropical freshwater species in urban areas and of the relationships between species diversity and a wider set of environmental and spatial conditions. Overall, there is a need for diversity assessments of

tropical urban wetlands of all types and sizes, especially new and novel habitats, and scope for much greater adoption of ecosystem service concepts and evaluation tools to help emphasise the importance of these habitats.

## Introduction

Freshwater species and populations are declining globally at rates higher than their terrestrial counterparts, with a decline in the annual population index (WWF Living Planet Index) of 3.9% compared to 1.1% for terrestrial species (Reid et al., 2019; WWF, 2018). Urbanisation is one of the major threats to freshwater biodiversity, especially in tropical regions where urban expansion is rapid and there is limited consideration of the ecological implications of urban growth (Cantonati et al., 2020; Sundar et al., 2020).

Urbanisation may impact biodiversity through the loss and modification of natural habitats (Grimm et al., 2008; McDonald et al., 2020). Increasingly, research is highlighting the potential of urban areas to support terrestrial and freshwater biodiversity (Beninde et al., 2015; Ives et al., 2016; Oertli & Parris, 2019; Seto et al., 2012). New habitats (e.g., stormwater ponds) are often created as cities expand, forming new ecosystems that may contribute to freshwater diversity (Briers, 2014; Hassall, 2014; Holzer, 2014). The sustainable management and conservation of freshwater diversity requires an approach that considers the processes governing species distribution patterns at multiple spatial and temporal scales, as well as their responses, in terms of diversity and function, to environmental factors (Geist, 2011). This may be particularly important in urban environments where freshwater habitats are often managed to cater for societal needs (Noble & Hassall, 2014).

Tropical freshwater ecosystems are characterized by high endemism and species richness (Barlow et al., 2018; Cantonati et al., 2020; Dudgeon et al., 2006) attributed to geographical isolation and specialization (Boyero et al., 2021; Cantonati et al., 2020). The high degree of specialisation in the tropics is facilitated by environmental conditions (notably high solar energy), including their temporal stability (Brown, 2014; Fine, 2015). Changes to these conditions, especially temporal patterns and the magnitude of variability, therefore has great potential to impact tropical freshwater ecosystems (Cantonati et al., 2020; Jardine et al., 2015; Liew et al., 2020; Wohl et al., 2012). In urban areas, changes to temporal patterns arise as a result of management regimes and infrastructure that can alter the dynamics of runoff (e.g. concrete surfaces) and channel flow (e.g. weirs, canalisation of water courses), and may be accompanied by deterioration in physical and chemical quality (Grimm et al., 2008; McGrane, 2016).

The ecological communities of ponds and wetlands (lentic systems) differ in their responses to urban conditions to those of streams and rivers (lotic systems) (Hill et al., 2017; Prescott & Eason, 2018). Lotic systems are generally characterized by impoverished communities, and this is attributed to poor water quality, alteration to flow regime and loss of habitat heterogeneity and variability in urban areas (Allan, 2004; Beavan et al., 2001; Jesús-Crespo & Ramírez, 2011; Reid & Tippler, 2019). While, lentic systems exhibit inconsistent patterns, with some research highlighting urban ponds and wetlands as important refuges for aquatic and semi-aquatic species in urban areas, including invertebrates, amphibians, birds and bats (Ancillotto et al., 2019; Hamer & Parris, 2011; Hill et al., 2019; Holtmann et al., 2017; Johansson et al., 2019; O'Brien, 2014; Prescott & Eason, 2018) but other studies finding urban lentic habitats to be ecologically impaired or dominated by invasive species (Noble & Hassall, 2014; J. S. Sinclair et al., 2020)

Current research suggests that with management strategies that promote biodiversity, including maintaining multiple wetlands that vary in characteristics that are favourable to different species, small wetlands and ponds may be of particular ecological value (Blicharska et al., 2016; Hassall, 2014). Urban wetlands may also be an important component of Water Sensitive Urban Design approaches, providing Nature-based Solutions such as flood alleviation, local climate regulation, and retention of both sediment and nutrients (Hamel & Tan, 2021; Wong & Brown, 2009). In addition, they provide provisioning services such as freshwater, food and fuel and cultural services linked to urban ponds and wetlands include well-being and aesthetic benefits, as well as opportunities for education and recreation (Manuel, 2003; Ngiam et al., 2017; Thornhill et al., 2019).

Although the physical structure of urban landscapes tends to be broadly similar globally (Wu, 2014), biogeographic contexts, socioeconomic circumstances and socioecological settings differ markedly from country to country. Also, in the tropics the demands placed on urban infrastructure by the climate differ from those in temperate regions (Lechner et al., 2020; Lourdes et al., 2021; Muñoz-Erickson et al., 2014; Ramírez et al., 2009). These factors may influence the nature, diversity and perceived value of urban wetlands. Intense rainfall events in tropical cities lead to frequent flooding, with floodwaters that are high in nutrients and suspended sediment, and may be highly polluted (Parkinson et al., 2010; Rivard et al., 2006). These issues require different approaches to management to those needed in cities where such floods are less frequent or intense. In tropical Kuala Lumpur (KL), for example, all new housing developments require sediment retention ponds designed to receive overland flow, resulting in a proliferation of new wetland habitats across the city. However, while these and other novel habitats (as well as remnant natural ones) may contribute positively to pond diversity in tropical urban areas, negative social or environmental impacts including health risks associated with standing water, notably mosquitos (Rivard et al., 2006), may create social pressures that run counter to the desire to conserve or create new urban wetlands.

The potential significance of urban wetlands in tropical regions, in terms of their diversity and the services they provide, raises questions about how much we currently know about these habitats. As an evidence base is needed to support the conservation and management of urban wetlands (Ehrenfeld, 2000; McInnes, 2014), and the threats posed by the ongoing and rapid expansion of tropical cities are increasing, a review of current knowledge is necessary and timely. In this paper, we present a systematic review of literature on the ecology and diversity of lentic freshwater in tropical urban landscapes. We focus on urban areas in tropical wet and monsoonal climate regions, as defined by the Koppen climate classification scheme (Peel et al., 2007); hereafter these regions are simply referred to as ‘tropical.’ The review addresses the following questions: 1) How much research has been conducted on ponds and wetlands in tropical urban areas? 2) What are the ecological focal points of published literature, and which countries does it come from? 3) What patterns of diversity (species richness, community composition) do tropical urban ponds and wetlands exhibit? 4) What are the factors influencing this diversity? and 5) What ecosystem services are provided by urban ponds and wetlands in tropical regions? Identifying limitations in our understanding of the ecology and diversity of tropical urban wetlands is a key focus of the review, and so we provide recommendations for future research needed to improve this understanding and to guide their conservation.

## Methods

### *Data collection*

A literature search was conducted to find original research articles that focused on inland, lentic freshwater bodies (ponds and wetlands) within tropical urban landscapes. The scope was limited to studies of their distribution, ecology and ecosystem service provision, so excluded purely hydrological or water quality studies. The search was conducted through the online publication databases Web of Science and Scopus. The following search terms were used, adapted from Oertli & Parris (2019):

*Web of Science:* TOPIC: ((urban* OR cit*) AND (pond OR wetland*)) AND TOPIC: (flora OR plant* OR macrophyte* OR vertebrate* OR invertebrate* OR mammal* OR fish* OR bird OR insect OR amphibi* OR frog* OR macroinvertebrate* OR crustac* OR dragonfl* OR damselfly* OR odonat* OR reptilian OR mollusc* OR beetle* OR coleopter* OR butterfly* OR turtle* OR fung* OR biodiversity* OR diversity) NOT TOPIC: (marine OR coast*)

*Scopus:* ( TITLE-ABS-KEY ( urban* ) OR TITLE-ABS-KEY ( city ) OR TITLE-ABS-KEY ( cities ) AND TITLE-ABS-KEY ( pond* ) OR TITLE-ABS-KEY ( wetland* ) OR TITLE-ABS-

KEY ( lentic ) AND TITLE-ABS-KEY ( biodiversity ) OR TITLE-ABS-KEY ( diversity ) OR TITLE-ABS-KEY ( richness ) OR TITLE-ABS-KEY ( ecosystem* ) ) AND PUBYEAR > 1989 AND ( LIMIT-TO ( DOCTYPE , "ar" ) ) AND ( LIMIT-TO ( LANGUAGE, "English" ) )

Web of Science returned 3,131 and Scopus 2,531 publications (Figure 1). We screened these based on several criteria. All publications had to be studies of inland freshwater lentic, pond or wetland habitats within an urban landscape (Figure 1). The title, abstract and key words were read to determine whether an article met these criteria. In some cases, the methods section of the paper was read to ascertain landscape and waterbody type**.** Reviews and studies that focused solely on the chemical assessment of water quality, constructed waste-water treatment wetlands (unless they are also managed or evaluated as biodiversity habitats), performance of wetlands (constructed or natural) in water treatment, aquaculture or coastal wetlands or brackish water habitats were excluded. The resulting set of publications was then categorized by the climate of the study region. Only studies undertaken in urban areas with tropical wet and monsoon climates were included in the review.

### *Data analysis*

For each paper, the geographical location (country and city name) of the study, and the type(s) of freshwater habitat (Table 1) were recorded. We also recorded the research objectives and spatial scale of each study to determine research scope, identify research focal points and understand the extent to which studies dealt with single or multiple wetlands. For studies that focused on understanding relationships between environmental conditions and taxonomic diversity, subject taxa and habitat type were recorded. Studies that were primarily concerned with ecosystem service provision or habitat distribution were categorized based on their research objectives.

To summarize research approaches and detect trends in the literature, each paper was characterized using eleven research attributes (Table 1). These data were then analysed using multiple correspondence analysis (MCA), using the package FactoMineR (Husson et al., 2016). MCA is a form of correspondence analysis for categorical datasets (Abdi & Williams, 2010) and enables the assessment of the multivariate similarity/dissimilarity of samples (in this case each paper was a sample), and the identification of attributes accounting for variation among samples (Abdi & Williams, 2010).

## Results

### Characteristics and focal points of tropical urban pond and wetland research

The systematic search identified 64 papers (Table S1) on ponds and wetlands that considered the biodiversity and distribution of lentic habitats in tropical urban areas from fifteen countries (Figure 2a). The earliest publication was from 1995 and the number of papers published in subsequent years ranged from three to eight until 2020 (Figure 2b). The year 2020 had the highest number of publications for a single year (n=13). An increasing trend in publications in the past decade is notable (about 70% of studies were published after 2011), reflecting global trends in wetland research (Oertli & Parris, 2019).

The majority of the 64 studies were from urban areas in India (45%, n=29). This is notable as the proportion of the national population that is urban is one of the lowest among the tropical countries included in the review (World Development Indicators, 2020). Studies from Brazil contributed 11% (n=7) of the articles reviewed. Sri Lanka and Singapore, with the highest and lowest urban populations respectively, contributed only four papers (6%) each; the remaining countries each contributed one to three papers (Figure 2a). Overall, the review indicates that a high proportion of published studies are from relatively few countries; there is a large number from India but very few from countries in Southeast Asia (n=11), tropical Africa (n=5) and South America (n=8) are represented.

In places with higher urban populations such as Singapore (n=4) and Brazil (n=7), larger, constructed waterbodies such as reservoirs (n=7) were often the focal point of studies, whereas in cities where urban populations are smaller (e.g., Sri Lanka (n=4)), studies tended to focus on remnant natural wetlands (Figure 2b). Overall, there was no bias towards larger metropolises. Although several megacities, including Manila, Dhaka and Kolkata, with urban populations greater than 10 million, were the focus of 37.5% (n=24) of the papers, cities with populations under 10 million (n=11) and under 5 million (n=29), consisting of either principle cities or smaller urban areas, were also well represented.

Based on habitat or ecosystem descriptions and classifications used by authors, the types of ponds and wetlands studied consisted of floodplain and park wetlands, lakes and lake wetlands, reservoirs and their littoral zones, and ponds. These included natural, modified, restored, and constructed systems (Table 2). Ecosystems described as ‘wetland habitats’ were the most widely studied (23 papers), followed by lakes (19 papers). Research focused on the ecology of reservoirs (7 papers) was almost exclusively limited to Brazil and Singapore. Notably, several papers included wetlands as part of multiple habitats in studies of urban blue-green spaces (Gandhi et al., 2015; Hayes et al., 2020; Mukhopadhyay & Mazumdar, 2019; Vallejo Jr et al., 2009; Zinia & McShane, 2021). Habitats categorized as freshwater wetlands were mostly natural wetlands, whereas lakes and ponds tended to include constructed waterbodies.

The papers included assessments of extent and/or change of pond and wetland distribution, biodiversity, bio-indicators of water quality, and ecosystem services provided by the ponds and wetlands (Figure 3a). The spatial scale of the study area was limited to one or two sites per urban area in half of the papers (n=32). The number of sites for the rest of studies ranged from 3-57 (Figure 3b), except for seven studies that mapped all ponds or wetlands within an urban area with aerial or satellite data. A common theme in the papers was the impact of formal and unregulated urban development on natural wetlands, especially in terms of loss in pond/wetland area to impervious land cover, and deterioration of water quality with increasing human use (Athapaththu et al., 2020; Campion & Venzke, 2011; Das & Basu, 2020; Das et al., 2020; Hettiarachchi, Athukorale, et al., 2014; Isunju & Kemp, 2016; Naigaga et al., 2011).

Multiple correspondence analysis (MCA) revealed some similarities in approaches and trends in the research. Papers on diversity (dv) tended to have positive values for dimension 1 and 2, while papers on ecosystem services, disservices and habitat use (es) and habitat cover/loss/expansion (hb) have positive values in dimension 1 and negative values in dimension 2. These suggest that there are few studies that integrate biological components of habitats (in terms of taxonomic composition and richness) with data on perceptions and value of habitats or habitat distribution (Figure 4a). The papers were arranged along dimension 2 according to the percentage of urban population (*pop*) in the study and type of pond or wetland (*type*). The variable-dimension correlation plot (Figure 4b) shows that *type* and *pop* are both correlated with dimension 2. This corresponds to the observation made above where studies from cities with greater urban populations tended to focus on constructed ponds and wetlands. There was no clear temporal ordering of studies (as defined using the 11 metrics) across the scatterplot (Figure 4a).

**Patterns of biodiversity**

Of the 64 papers reviewed, 40 addressed taxonomic diversity. Of these, 33 documented taxonomic diversity with a species inventory or the calculation of biodiversity metrics. The remaining seven assessed species diversity as a bio-indicator of water quality. Vertebrates were the most studied group (Figure 5a), with assessment of avian diversity a common focal point (n=9), followed by fish (n=3) and amphibians (n=2).

In total, 27.5% (n=11) of the 40 papers documented species presence/absence or relied on a single diversity metric, specifically richness and/or abundance of a taxonomic group. Another 30% of studies (n=12) used multiple metrics, mainly combining Shannon-Wiener and Simpson's indices for taxonomic diversity and density, in addition to species richness measures. Five studies documented functional diversity. Studies that carried out multivariate analyses and/or statistical modelling to describe relationships between diversity metrics and environmental factors made up 42.5% (n=17) of these 40 papers (Figure 5b). Besides these, there were another nine papers that focused on the feeding habits of birds in urban areas (Murray et al., 2018; Varner et al., 2014), introduced fish species presence (Kwik et al., 2013), and wetland plant species composition change (Hettiarachchi, Morrison, et al., 2014).

Several studies found urban habitats to be species-rich and characterized communities in terms of species composition, endemism, rarity or vulnerability status. For example, Clements et al. (2006) showed that distinct mollusc assemblages occupied different types of lentic water bodies in Singapore. Wakhid et al. (2020) found variation in aquatic insect assemblages among small lakes associated with differences in water quality and macrophyte cover. Razak and Sharip (2019) found that zooplankton diversity showed taxa-specific variation with degree of urban development, defined in terms of built environment density and human population density around the study site. Three studies assessed functional feeding group (aquatic macroinvertebrates) and dietary guild composition (urban wetland and non-wetland birds) and found that taxa distribution was associated with organic pollution (Wakhid et al., 2020) and type of urban blue-space (Hayes et al., 2020; Mukhopadhyay & Mazumdar, 2019). Phytoplankton functional group compositions and their correlation with water nutrient concentrations were examined in another three studies (Crossetti & Bicudo, 2008a, 2008b; Fonseca & Bicudo, 2010).

The relative contribution of urban wetlands and ponds to regional diversity was calculated in 10 of the 64 studies. Hayes et al. (2020), found about 10% of regional species (comprising wetland and non-wetland avian species) were present in wetlands within urban green spaces in Guyana. Similarly, Mukhopadhyay and Mazumdar (2019) found around 12% of regional bird species were represented in sub-urban areas, with wetland habitats supporting greater species richness than purely green spaces. Ansari (2017) produced an inventory of resident and migrant water bird species occurring at Surajpur Lake, and reported an occurrence of 95 species that included eight listed as Vulnerable or Near Threatened by IUCN. In contrast, Seshadri et al. (2008) reported low anuran species richness in urban freshwaters with only 14 species recorded in wetlands throughout urban Puducherry, India.

There was a limited number of studies (n=4) on problem or nuisance species (Kwik et al., 2020; Kwik et al., 2013; Reis et al., 2018; Sareein et al., 2019). Urban stormwater ponds in Singapore were found to be populated with tolerant, non-native fish species that were considered to potentially endanger native fish species if they spread to natural sites (Kwik et al., 2013). Sareein et al. (2019) examined the correlation between mosquito species, *Culex*, and predatory insect density; their findings suggest that predator diversity could provide a biological control for nuisance species in urban areas.

## Factors structuring biological communities

Some of the studies addressed spatial and temporal variation in species distribution and composition, primarily in relation to water quality. Figure 6 summarizes relationships between urban wetland diversity measures and the environmental variables considered in the published studies. Physical habitat characteristics of the wetlands were not commonly included as potential explanatory variables, nor were wider urban landscape characteristics. Generally, water quality variables and one or two physical characteristics at the site-level were the main correlates examined. Physical habitat characteristics examined included the area of the waterbody, substrate type, and presence of aquatic vegetation. The findings suggest species-specific responses to habitat features such as area (Clements et al., 2006; Razak & Sharip, 2019) and the importance of macrophyte density for odonate species richness and abundance (Wakhid et al., 2020). A positive correlation between plants and waterbird diversity was found in one study from India (Rajashekara & Venkatesha, 2018). Only one study looked at interspecies dynamics such as predator-prey relationships (Sareein et al., 2019). No papers assessed the influence of habitat origin or management practices on diversity.

Empirical studies of the relative effects of dispersal and connectivity in structuring biodiversity were absent from the literature. Similarly, quantitative assessment of local environmental conditions and spatial factors at a landscape-scale and their relationship with species diversity was largely absent. The three papers that included surrounding urban land use measures indicate that the importance of landscape variables varies between taxonomic groups (Clements et al., 2006; Rajashekara & Venkatesha, 2018; Razak & Sharip, 2019). Razak and Sharip's (2019) findings reveal negative correlations between the degree of urban development within a 1km radius of lentic waterbodies and zooplankton diversity. On the other hand, Clements et al. (2006) did not find isolation from areas of human development to be a predictor for mollusc richness. These findings highlight the need for more research before generalizable patterns in habitat biodiversity-environment relationships can be determined.

Few studies examined the impact of seasonal variation on diversity (n=4), especially responses to monsoon periods (Ansari, 2017; Koparde, 2016; Razak & Sharip, 2019; Yardi et al., 2019), but there were only two long-term investigations of diversity patterns and these focused on phytoplankton (see Crossetti et al, 2008a; Crossetti et al 2008b). While land cover studies reported wide-scale wetland habitat loss to urban expansion over time (Athapaththu et al., 2020; Mondal et al., 2017), there were no studies documenting changes in biodiversity as regions urbanised (but see Hettiarachchi et al. 2014).

**Biodiversity and ecosystem services**

Fifteen of the 64 studies addressed ecosystem services associated with urban ponds and wetlands. These included assessment of the provision of regulating or supporting services (n=12), perceptions of value (n=2), and inventoried ecosystem services (n=1). The study sites included urban parks (Baharuddin et al., 2017; Shafaghat et al., 2019), and natural wetlands that provided services for peri-urban and urban communities (Das & Basu, 2020; Hara et al., 2018; Hettiarachchi, Athukorale, et al., 2014). Research approaches often integrated land use and land cover changes with stakeholder surveys and interviews to assess changes in use for recreational and economic activities over time (D'Souza & Nagendra, 2011; Das & Basu, 2020; Hara et al., 2018; Hettiarachchi, Athukorale, et al., 2014). A combination of GIS and statistical tools were also applied to quantify ecosystem services use and analyse factors influencing stakeholders' preferences and attitudes (Bandyopadhyay et al., 2006; Das & Basu, 2020).

An inventory of urban ecosystems in Dhaka identified ponds and wetlands as providing food and water supply, regulating water flow, space for recreation and habitats for migratory birds (Zinia & McShane, 2021). Hara et al. (2018) reported that new ponds (from excavation activities) in urbanizing landscapes around Bangkok allow for economic activities (fishing and recreation) and increase wetland bird abundance. Other studies documented changes in wetland ecosystem use, and ecosystem service impairment, as a direct or indirect result of urbanization and over-exploitation (Hettiarachchi, Morrison, et al., 2014; Mombo et al., 2014). The extent to which urban communities rely on wetlands and ponds within the urban landscape are emphasized in studies that evaluate perceptions of the value of these habitats (Das & Basu, 2020; Mombo et al., 2014). Das and Basu (2020) showed that residents' satisfaction with the delivery of wetland ecosystem services varies with proximity to the wetland with those living nearer to the wetland area perceiving a greater need for habitat improvement. While all studies emphasized the importance of pond and wetland ecosystems for urban and peri-urban residents, quantitative or direct measurements of the relationship between ecological characteristics of urban ponds and wetlands and ecosystem functions or services were minimal. Thus, it remains unclear how important diversity might be in supporting ecosystem service provision in tropical urban areas.

## Discussion

Our review found that most urban tropical wetland research was concerned with the impact of urban growth on the extent of individual wetland areas, or changes to their water quality or diversity, rather than on patterns and trends across whole urban areas. Nevertheless, studies suggest that rapid and unplanned urban development is a major threat to freshwater habitats in tropical urban areas, and potentially undermines the provisioning and flood protection services they provide to urban residents (Brinkmann et al., 2020; D'Souza & Nagendra, 2011; Hettiarachchi, Athukorale, et al., 2014; Isunju & Kemp, 2016). There remain significant gaps in our fundamental understanding of the structure and functioning of urban lentic habitats at different spatial scales, limiting our capacity to develop effective and evidence-based conservation measures.

The findings of this review reveal geographical disparity among tropical regions, with over half of the research coming from a relatively small number of countries. This limits attempts to discern broad geographic patterns in tropical urban pond and wetland diversity. Oertli and Parris' (2019) review of the global urban ponds literature describes a range of design and management practices to support freshwater biodiversity. However, almost all the examples given in the review are from non-tropical countries and it remains unclear whether these practices are suitable for tropical urban ecosystems. Given the unique and different conditions prevailing in wetlands in tropical urban areas, establishing appropriate design and management practices is critical.

The total number of publications retrieved with our search terms suggests the tropical literature is growing, but is still small in comparison to temperate regions. Though the number of papers analysed as part of this review remains limited, the systematic nature of our search means that we have been able to address our questions. However, two caveats need to be emphasised. Firstly, we intentionally excluded brackish standing water systems. These systems are unique and important, and these things, together with the largely coastal nature of their distribution, brings a wider set of pressures that warrants its own review (Barnes, 1999; Basset et al., 2013). Secondly, our search excluded terms explicitly related to diseases and disease vectors, which are important issues in tropical cities. In some instances the control of vectors may influence the design, management practices and diversity of urban ponds and wetlands (Walton, 2012), and may affect public support for their conservation. This warrants some consideration and so discussed below (see point 3).

Discerning trends in biodiversity patterns and the conservation value of different types of lentic habitat in tropical urban areas will require baseline data on all components of biodiversity. Moreover, further studies of species responses to the environmental and social characteristics of tropical urban environments are needed, and of the relationships between biodiversity and ecosystem service provision. To help direct future research on tropical urban ponds and wetlands, we provide a series of recommendations in the section that follows.

## Key limitations in research approaches and recommendations for future research

1. Determining spatial distribution and characteristics of urban ponds and wetlands in tropical cities

   *Research limitations*: Detailed ecological or biodiversity studies of tropical cities tend to be limited to one or two major lakes, wetlands or reservoirs (Figure 3b), while landscape-scale studies tend to focus on basic mapping or assessment of the spatial distribution of wetlands. These approaches limit urban freshwater biodiversity assessments in two ways. Firstly, the ecological value of non-surveyed, often smaller habitats, is overlooked. For instance, cities such as Kuala Lumpur (Teo et al., 2021) and Singapore (Lim & Lu, 2016) have numerous constructed ponds as part of flood mitigation measures yet these are rarely the subject of ecological studies. This is significant since research findings suggest that small retention or storm-water ponds can be important ecosystems for freshwater species conservation and ecosystem services provision (Hassall, 2014; Hill et al., 2016; Holtmann et al., 2017; Johansson et al., 2019). Other anthropogenic standing water bodies that are common in urban areas such as fountains, golf course ponds and drainage ditches, with their distinctive environmental conditions, may also support taxa of conservation (Čerba & Hamerlík, 2022). Chester and Robson (2013) provide an inventory of the various types of anthropogenic water body found in urban areas, many of which have yet to receive significant research attention, especially in tropical cities. Secondly, there are limited field-based data and studies for characterization of urban wetlands at a level required to adequately understand the extent to which local and regional processes influence biodiversity. This is especially important as previous research has suggested that small lentic waterbodies contribute most to biodiversity at the landscape-scale, reflecting their wide environmental heterogeneity and connectivity (Hill et al., 2018). Moreover, along with the interchangeable use of terms for habitats, incongruent characterization limits the extent to which comparisons with other tropical cities or geographical regions can be drawn.

*Recommendations*: It is important to inventory and characterize all types of ponds and wetlands across an urban area to maximize ecological benefits and opportunities for biodiversity conservation. This will also help in the development of a typology of urban ponds and wetlands that can allow for targeted ecological studies and effective management for biodiversity. For example, if a given type of pond or wetland is found to support a taxonomic group of interest, it can be selectively managed or prioritised for biodiversity support. In heterogeneous urban landscapes, standardized collection of data on the extent of impervious surfaces, open areas, building and road type and density, and land use surrounding study sites may also be useful in classifying pond types, and provide insight into mechanisms underlying species assemblages (Jeanmougin et al., 2014). Additionally, this review found that even though land-use data derived from remote sensing methods are applied in mapping distributions of habitats, these are seldom applied in biodiversity studies that focus on specific sites. Detailed landscape-scale data can be combined with thorough physico-chemical characterization of sites (Table 3) to support ecological studies that aim at understanding how spatial distribution influences diversity patterns (Heino et al., 2017). Finally, considering the range of differences in urban profiles among tropical urban areas, consistent description of both wetland habitat characteristics and urban features (in terms of regulation and patterns of development, build-up density) will also be critical for building baseline data on ponds and wetlands in tropical urban areas, and allow for useful knowledge transfer among cities. Oertli and Parris (2019) note that this has been overlooked in pond studies globally as well.

2. Assessing the ecological value of tropical urban ponds and wetlands

*Research limitations*: Biodiversity measures used in the published papers were mostly restricted to taxonomic richness and alpha diversity metrics, with minimal compositional or trait-based assessments. Similarly, temporal variation in diversity and habitat conditions have yet to be examined in-depth. Studies of non-tropical regions suggest that urban pond habitats could be subject to temporal changes in quality as environmental conditions respond to urban pressures like nutrient loads and sedimentation (Briers, 2014). Long-term monitoring is needed to understand the responses of different types of ponds and wetlands to disturbances related to their intended anthropogenic roles (the use of wetlands as sedimentation ponds, for runoff retention or treatment, as recreational sites). In addition, natural and constructed wetland habitats are subject to rapid, inter-annual variability in habitat conditions as well as biological community structure (Jeffries, 2005; Ruhí et al., 2013). This warrants attention in tropical urban systems subject to frequent flooding events and concomitant surges in sediment and nutrient loads that continue to challenge conventional storage and treatment structures in tropical cities. In addition, without data from long-term monitoring of species populations or community structure, it is difficult to assess the risk of urban habitats becoming ecological traps (Hale et al., 2015).

*Recommendations:* Future research should focus on assessing multiple components of diversity for a range of taxonomic groups to determine the ecological value of urban habitats. All components of tropical freshwater biodiversity need more attention, including taxonomic and functional compositional variation (beta-diversity) which are important to understand mechanisms driving species distribution patterns in urban landscapes, and their role in maintaining these ecosystems, respectively (Petchey et al., 2009; Socolar et al., 2016). In addition, quantifying the variation in community composition among habitats (e.g., determining the contribution of nestedness and turnover to total beta-diversity, and the ecological uniqueness of individual sites) and the relative contribution of particular sites to broader-scale biodiversity is important for conservation prioritisation at the landscape-scale (Heino et al., 2017; Hill et al., 2021; Socolar et al., 2016). Taxonomic and functional diversity patterns are not necessarily congruent, and the predominant focus on taxonomic richness found in most literature potentially overlooks components of biodiversity (functional and phylogenetic) that are relevant to critical ecosystem processes, functioning, and resilience (Devictor et al., 2010; Hill et al., 2019; Strecker et al., 2011). For example, Heino et al. (2017) report a negative correlation between species richness of a habitat and the uniqueness of its species, demonstrating the importance of multiple measures of diversity in ponds in temperate regions. These assessments and monitoring of species distribution can be carried out periodically to obtain data over longer time periods, and assess long-term habitat viability and resilience to frequent hydro-meteorological disturbances. It may also be necessary and useful to rely on multiple tools, including environmental DNA (e-DNA) analyses, for documenting biodiversity. For many freshwater taxa in tropical regions, especially macroinvertebrates, ecological and taxonomic knowledge remains limited and this constrains diversity assessments and monitoring (Sundar et al., 2020). Developing the capacity and reference databases for e-DNA analyses take time, but this approach offers great potential for more efficient biodiversity assessments, surveys, and species mapping (Belle et al., 2019). Tropical cities may have abundant freshwater habitats (Teo et al., 2021) but the dramatic changes in these systems due to the pace of urban development means that tools such as e-DNA able to rapidly assess diversity for the purpose either of conservation prioritisation or monitoring would be particularly significant.

3. Identifying environmental correlates of biodiversity and community structure for multiple taxonomic groups

*Research limitations*: Besides water quality, there was limited documentation and examination of habitat characteristics at a site level (Figure 6). The nature and relative importance of physical habitat characteristics and surrounding land-use have not been examined in depth for different faunal and floral groups in the tropical urban context. Physical habitat characteristics and surrounding landscape can facilitate or impede species establishing populations in urban ponds and wetlands (Hamer & Parris, 2011; Hamer et al., 2011; Liao et al., 2020) and affect ecological processes such as feeding, reproduction, dispersal or shelter (Goertzen & Suhling, 2012; Thornhill et al., 2017). Surrounding land use characteristics can also play a role in determining community structure (Holtmann et al., 2018), especially where it facilitates or impedes dispersal. Dispersal mechanisms and habitat connectivity may be particularly important in urban ecosystems where built structures, along with species dispersal and colonization capabilities, can limit an organisms' ability to move to and establish populations in suitable freshwater habitats (Oertli & Parris, 2019; Parris, 2006; Ruhí et al., 2013; Smith et al., 2009).

*Recommendations*: Research will need to focus on environment-taxa relationships that assess the influence of local environmental and spatial variables (land-use, dispersal, connectivity) on target species populations or whole communities at larger scales. This is key to effective and targeted management of wetland habitats in different urban areas. For example, several design and management recommendations are available for the support of urban populations of amphibians and dragonflies in non-tropical regions (Goertzen & Suhling, 2012; Hamer et al., 2011). Similar approaches to biodiversity research are needed for tropical species. Urban habitats may provide opportunities for ecological studies of taxonomic groups such as freshwater macroinvertebrates that remain underrepresented in conservation literature (Sundar et al., 2020). The relevance and influence of environmental variables will vary depending on the taxonomic group in question (endemism, tolerance, dispersal capabilities), the component of diversity examined and the spatial scale of the research. Among the environmental variables that warrant further attention from tropical urban research are measures related to microhabitat conditions in tropical urban environments. Tropical urban environments are subject to higher temperatures (a combination of both climate and urban heat island effects) and greater volumes of surface runoff characterized by high sediment loads that can settle and alter substrate properties within ponds and wetlands. Thus, variables like shade availability, and substrate type may be important for understanding the distribution of taxa like macroinvertebrates and amphibians with life processes that are vulnerable to heat stress and fine sediment or debris in water or substrates. Furthermore, in lentic habitats from non-tropical regions, potential 'master' variables have been identified that have a large influence over the richness and composition of aquatic taxa, including surface area, hydroperiod, connectivity and aquatic macrophyte coverage (Hill et al., 2019; Parris, 2006; Scheffers & Paszkowski, 2013). Studies are needed from tropical regions that consider the importance of these variables for multiple taxonomic groups, to identify any congruency (or lack of) in lentic habitat biodiversity-environment relationships among tropical and non-tropical regions.

Examining the relationships between environmental conditions and nuisance species is necessary to address health risks associated with disease vector proliferation in water bodies in tropical urban areas. As part of such research, it will be important to also consider how established practices or design features that aim at discouraging vector proliferation. Hanford et al. (2019) found that mosquito species vary in their responses to specific aspects of urban wetland habitats and suggested that identifying specific design features that promote or discourage target vector species occurrence may be key to managing urban habitats for biodiversity while mitigating health risks associated with them. Management such as water level regulation, bank gradient, plant choice and growth control, and the use of larvicides (Knight et al., 2003; Zakaria et al., 2004) may impact non-target species and wetland community composition or diversity. In a review of wetlands and mosquito research, Dale and Knight (2008) note that ecological studies rarely include assessments of vector prevalence or competence and vice versa. Urban vector research in the medical or vector entomology literature tends to focus either on larval microhabitats and oviposition sites in buildings and residential areas, or (ii) the influence of social factors such as population density and infrastructure on disease prevalence (Carbajo et al., 2006; Li et al., 2014; Mint Mohamed Lemine et al., 2017; Samson et al., 2015), rather than how wetland habitats contribute to vector abundance. Constructed wetlands (for wastewater treatment or runoff management) are better represented in mosquito research but the effect of vector control design features and practices on non-target species still requires research attention (Dale & Knight, 2008). Overall, there is a need to quantify and assess the potentially differing vector risks associated with the various types of ponds and wetlands in urban areas (see Crocker et al., 2017) and to improve data available for assessing  trade-offs when multiple functions are expected from urban ponds and wetlands. Integrating understanding of infectious disease vectors and the risks they pose in urban areas with evidence from medical or public health literature, as well as constraints faced by city managers, in terms of maintenance costs and barriers to practical implementation (for example, number and sizes of wetland) will be integral to developing effective strategies and garnering support for urban freshwater biodiversity conservation.

Similarly, while connectivity may be important for maintaining biodiversity in urban habitats (Oertli & Parris, 2019), abundant and linked drainage systems may facilitate spread of invasive species capable of exploiting conditions in novel pond and wetland habitats or thriving in the warm, nutrient- rich waters (Kwik et al., 2020; Mansor, 1996). Research is needed to assess the risks posed by urban ponds and wetlands and to determine the specific species traits, connectivity factors and habitat characteristics that can be monitored or managed to control for invasion threats without compromising opportunities for biodiversity improvement (James S. Sinclair et al., 2020). Table 3 presents some potentially important environmental variables at local and landscape scales that require study to determine their importance for biodiversity patterns and function in tropical urban ponds and wetlands.

4. Identifying relationships between biodiversity and ecosystem services

*Research limitations:* The links between freshwater biodiversity and ecosystem services have gained increased research attention recently, and evidence suggests that species loss, especially within fragmented environments, compromises services (Durance et al., 2016). However, published studies from tropical urban areas examining the interaction between biodiversity, ecosystem service provision and urbanization are limited in number (but see Hettiarachchi, 2014). Major gaps in the current literature also exist for key urban ecosystem services which are important for tropical urban environments including mitigating hydro-meteorological disasters such as flooding and addressing urban heat island effects which are particularly prevalent in tropical cities and likely to increase in frequency and intensity with climate change (Lechner et al., 2020).

*Recommendations:* Integrate biodiversity and ecosystem service research. Assessing the capacity of urban lentic systems to undertake their primary function (e.g., stormwater retention or recreation) alongside an assessment of their biodiversity value, will enable management strategies to be developed that ensure these systems support both society and wildlife. For example, soil surveys of urban ponds and wetlands can quantify carbon content and assess their potential for atmospheric carbon sequestration (Moore & Hunt, 2012). Several studies in this review highlighted the role of governance and public perceptions and practices on the state of urban wetlands (D’Souza & Nagendra, 2011; Das & Basu, 2020; Hettiarachchi, Athukorale, et al., 2014). Many urban systems are primarily built for purposes other than biodiversity, and as a result management of these systems rarely considers the inhabiting fauna and flora. Management activities vary in methods (including vegetation selection and removal, water level manipulation, dredging) and intensity among pond and wetland types, and are directed by intended functions, landscaping practices or aesthetic choices (Holtmann et al., 2019; Schad et al., 2020). However, in many cases, small ecologically-focused changes to current management plans can maximise the biodiversity that is supported in urban lentic habitats, while not reducing the efficacy of their primary function, e.g., storm water/pollutant collection (Rosenzweig, 2003).

Urban ponds and wetlands are very often associated with parks or remnant areas of natural vegetation. This creates opportunities for their incorporation in the planning and design of urban blue-green spaces (Ahn & Schmidt, 2019; el-Baghdadi & Desha, 2017). This is typically accomplished within the framework of nature-based solutions, and allows the multiple functions of lentic systems to be explored (Lafortezza et al., 2018) and their cost-effectiveness relative to conventional ‘grey’ infrastructure to be assessed. The feasibility of using blue-green spaces for such purposes depends on the nature of the existing urban landscape, and the willingness and/or capacity of cities to adopt them plays a major role in their inclusion in city plans. Lechner et al. (2020) argued that the lack of data on the benefits of blue-green spaces from tropical areas limits their inclusion. The financial viability of replacing conventional built structures with natural systems is still a subject of research and debate, especially in terms of methods for economic valuation and ecosystem services assessment (el-Baghdadi & Desha, 2017; Wild et al., 2017). Fundamental biodiversity assessments and monitoring are essential to improve understanding of ecological processes and functions that underpin ecological services and value (Reid et al., 2019). Decision makers using  Nature-based Solutions to tackle problems faced by cities will need this ecological knowledge base, in addition to measures of social and economic values of wetlands (Durance et al., 2016; el-Baghdadi & Desha, 2017).

Finally, direct relationships between biodiversity patterns and management practices associated with social attitudes and urban societal needs and priorities also warrant exploration. This may be especially important for reconciling social preferences with management for conservation (Blicharska et al., 2017; Ngiam et al., 2017). Opportunities for education and public engagement can also be explored by assessing the efficacy of educational infrastructure like signage, and conducting participatory research and monitoring projects with urban residents (Simpson & Newsome, 2017; Soanes et al., 2020).

## Conclusions

As tropical urban areas expand, ponds and wetlands can provide refuge for freshwater organisms and a range of ecosystem services for urban residents. In order to determine the conservation value of these ecosystems and ensure management and/or design that promotes biodiversity, research will have to move beyond focus on single, prominent wetlands to an approach that examines large-scale patterns of biodiversity across urban areas. It will also be important to determine the response of different aspects of urban pond and wetland diversity to the distinct climate and hydrology of tropical urban areas, as well as the diverse range of lentic habitats that occur there, and how they respond to different management practices. While the number of publications on tropical urban ponds and wetlands is growing, there remains a need for more consistent descriptions of habitat and urban landscape characteristics to enable knowledge transfer among tropical cities. As the importance of green infrastructure for sustainable urban development becomes more apparent, sound ecological data are needed to maximize the potential of new and remnant pond and wetland habitats for biodiversity conservation. This is especially important for tropical freshwater taxa, long challenged by taxonomic and ecological knowledge gaps. Expanding the scope of tropical freshwater biodiversity research to urban areas and assessing links between biodiversity and ecosystem services can contribute to addressing these gaps and also aid tropical cities in creating, managing or restoring natural habitats for the benefits they provide to society and biodiversity.

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## Figure captions

**Figure 1** Summary of research paper screening and selection process (adapted from Moher et al., 2009)

**Figure 2** Types of urban ponds and wetlands studied in tropical urban areas by (a) country and (b) year

**Figure 3** Primary research focal points of papers by (a) type of study ecosystem and (b) number of study sites (n=64)

**Figure 4** (a) Multiple correspondence analysis (MCA) plot showing distribution pattern of papers (dots) based on similarities in research attributes. Papers are colour coded by main research focus (dv-diversity; es-ecosystem services, disservices, habitat use; hb-habitat cover/loss/expansion; ix-more than one; nn-none; wq-bio-indicators of water quality) (b) Dimension-variable correlation plot showing how eleven research attributes (variables) of studies are correlated to the first and second dimensions. The eleven research attributes are year (year), spatial scale (scale1), habitat type (type), taxonomic group (taxa), habitat origin (origin), research focus (focus), temporal scale (scale2), biodiversity measures (metric), variables examined as correlates of biodiversity (fct), ecosystem services (es) and urban population percentage (pop)

**Figure 5** Taxonomic groups examined in studies by (a) type of study ecosystem and (b) extent of analyses carried out for each taxonomic group (n=40)

**Figure 6** The number of studies that examined environmental factors influencing biodiversity patterns, by variable category and the specific environmental variable-taxonomic group relationships examined (n=40). For physical habitat characteristics and landscape characteristics, a maximum of one metric was measured in most studies (Note: total number of studies does not add up to 40 as some studies looked at more than one category of variables).

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## Tables

**Table 1** Research attributes used to characterize papers on urban ponds and wetlands in tropical urban areas (n=64)

| **Research attribute** | **Category** | **Description** |
|---|---|---|
| Year | Pre-2000 | Published before the year 2000 |
| | 2000-2004 | Published between 2000-2004 |
| | 2005-2009 | Published between 2005-2009 |
| | 2010-2014 | Published between 2010-2014 |
| | 2015-2019 | Published between 2015-2019 |
| | 2020 onwards | Published in the years 2020 and 2021 |
| Spatial scale | 1-2 sites | 1-2 habitats sampled |
| | 3-5 sites | 3 -5 habitats sampled |
| | 6-15 sites | 6 -15 habitats sampled |
| | More than 15 sites | More than 15 habitats sampled |
| | City wide | All pond/wetland water bodies across entire city mapped with remotely-sensed data |
| Habitat type | Wetland | Includes remnant floodplain wetlands, park wetlands, habitats primarily described as such by authors, natural and constructed |
| | Lakes | Lakes as described by authors, natural or constructed |
| | Ponds | Ponds as described by authors, natural or constructed |
| | Reservoirs | Reservoirs as described by authors, constructed |
| | Multiple | More than one of the above |
| Taxonomic group | None | No subject taxonomic group |
| | Aquatic vegetation | Includes emergent, submerged, and/or floating plants |
| | Plankton | Includes phytoplankton and/or zooplankton |
| | Macroinvertebrate | Includes aquatic and semi-aquatic macroinvertebrate groups |
| | Vertebrate | Includes birds, amphibians, fish |

| | | |
|---|---|---|
| | Multiple | More than one of the above groups |
| Habitat origin | Natural | Natural, modified habitats within an urban landscape |
| | Constructed | Ancient or modern constructed pond and wetland habitat |
| | Mixed | Both natural and constructed pond and wetland habitat |
| | Not mentioned (non) | Origin of the habitat not discussed in the paper |
| Research focus | Diversity | Habitat diversity or biodiversity |
| | Habitat cover/loss/expansion | Quantification of habitat cover within an urban landscape, or habitat loss or gain over years |
| | Bio-indicators of water quality | Assessing water quality with organisms as indicators |
| | Ecosystem services, disservices | Includes assessing value perception, disservices, provisional, regulating or supporting services |
| | More than one of the above | More than one of the above |
| | None | Other than the above, unique focus |
| Temporal scale | Single season | One season, one year |
| | Single year | Different seasons, one year |
| | Multiple years | Same/different seasons, multiple years |
| Biodiversity measures | None | No biodiversity assessment was conducted |
| | Inventory | Checklist of a specific taxonomic group occurrence |
| | Single measure | Single metric used (for e.g. species richness only) |
| | Multiple measures | Multiple metrics used (for e.g. richness, abundance, diversity) |
| | Multivariate analyses | Multiple diversity measures used and relationships with environmental or landscape variables examined with multivariate analyses or modelling |
| Variables examined as correlates of biodiversity patterns in wetlands | None | Biodiversity and/or correlates not assessed |
| | Water quality measures | For example pH, nutrient concentration levels |
| | Physical habitat characteristics | For example depth, substrate type, bank material |
| | Landscape composition | For example presence of roads, built structures, surrounding land cover type |

| | | |
|---|---|---|
| | Multiple | More than one of the above |
| Ecosystem services | None | Ecosystem services not assessed |
| | Mapping & Inventory | Mapping and/or inventory of ecosystem services provided by habitat |
| | Use or function assessment | Assesses habitat use by fauna or human communities, or the performance of ecosystem function |
| | Perception of value assessment | Documents attitudes and perceptions of human communities toward the habitat documents |
| Urban population % (of total country population) | Under 20 | Less than 20% |
| | 21-50 | 21-50% |
| | 51-80 | 51-80% |
| | 81-100 | 81-100% |

**Table 2** Description of systems covered in the reviewed literature (the proportion of papers that provide information on depth and area are shown in brackets)

| **Category** | **General characteristics** | **Total number of papers (percentage of total publications)** | **Depth range (m)** | | **Area range (ha)** | |
|---|---|---|---|---|---|---|
| Freshwater wetlands | Natural floodplain or constructed wetlands. Included perennial and seasonal wetlands within and around city borders. The term often encompassed different types of waterlogged or lentic habitats. | 23 (36%) | - | | 0.3 - 12500 | (10/23) |
| Lake and lake wetlands | Natural or constructed lakes, with the term sometimes used interchangeably with reservoirs. Some study sites are also described as wetlands surrounding major lakes. | 19 (30%) | 2 - 8 | (2/19) | 2.5 - 62.5 | (7/19) |
| Ponds | Mostly constructed lentic waterbodies. Included those built within temples, parks, and ponds with economic functions. | 9 (14%) | 1.5 - 8 | (2/9) | 0.029 - 104 | (2/9) |
| Reservoirs | Constructed water bodies. Term also used interchangeably with pond and lake | 7 (11%) | 2 - 5 | (6/7) | 0.5 - 59 | (6/7) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Multiple | More than one of the above categories | 6 (9%) | 1.67-4.81 | (1/6) | 0.06-488 | (1/6) |

**Table 3** Suggested metrics to aid characterization of tropical urban ponds and wetlands and identification of variables important for freshwater biodiversity. Adapted from Oertli and Parris (2019), Biggs et al. (1998), Biggs et al. (1998), Ehrenfeld (2000) and Briers (2014). (Metrics that are already consistently present in reviewed literature, like water quality variables, are not included)

| | **Metrics** | **Justification** |
|---|---|---|
| Urban setting, and sampling scales and location | Study area population size and density<br>Road density<br>Proportion and nature of built environment (regulated or unregulated urban development)<br>Function of ponds and wetlands<br>Pond and wetland density (proximity and number of ponds and wetlands around the site), and hydrological connectivity<br>Proportion and nature (natural, lawn park) of green spaces | Urban development patterns and features will vary among cities, and these metrics provide background information for comparable ecological studies. Studies can then compare diversity patterns among and between mega cities and smaller cities. Furthermore, the presence and proximity of other wetland and pond habitats can be important factors influencing community assembly in ponds, and along with information about site quality may help understand mechanisms driving biodiversity among multiple taxonomic groups and at multiple scales. |
| Physical habitat characteristics | Age, origin (constructed or natural) and type<br>Area, perimeter and margin complexity<br>Vegetation composition and structure (in and around site)<br>Source and depth of water<br>Type of bank and substrate<br>Degree of shading<br>Type and intensity of management<br>Intensity of use by urban residents | Depending on the taxonomic or functional group that is being examined, a range of factors will be significant in determining occurrence and distribution. Used consistently, these metrics can describe overall characteristics for comparing wetlands and, with additional physical variables specific to target taxa (e.g. margin slope, shade, microclimate, nesting trees, etc.) can help assess the quality of ponds and wetlands as habitats for freshwater taxa |