# Science of the Total Environment Review of Hydraulics of Floating Treatment Islands Retrofitted in Waterbodies Receiving Stormwater --Manuscript Draft--

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Abstract:	Stormwater pollution causes an excessive influx of nutrients and metals to the receiving waterbodies (stormwater ponds, lakes, and rivers), which can cause eutrophication and metal toxicity. One of the most cost-effective and eco-friendly solutions to stormwater pollution is constructing floating treatment islands (FTIs) within the waterbodies receiving stormwater runoff. Treatment efficiency of FTIs depends on many factors including plant species, temperature, detention time, and pollutant loading rate. Another important factor is FTI hydraulics, which determines the amount of inflow to the root zone and residence time, greatly impacting the treatment. However, only a few studies refer to the hydraulics of waterbodies retrofitted with FTIs. This paper reviews available literature on field-scale, laboratory-scale and numerical studies on the hydraulics of FTI retrofitted waterbodies. Because of limited knowledge on the factors affecting hydraulics of waterbodies rite with FTIs, current practices cannot ensure maximum hydraulic performance of this system. This review paper identifies different factors affecting the FTI hydraulics, investigates knowledge gaps, and provides future research direction for hydraulically efficient design of FTIs to treat stormwater. It was found that there is a need to investigate the impact of new design parameters such as FTI shape, FTI coverage, inlet-outlet configurations, and shape of waterbody on the hydraulic performance of FTI retrofitted waterbodies. A lack of dimensional analysis on FTI retrofitted waterbodies in existing literature revealed that field-scale values were not properly scaled down in laboratory experiments. Although a few short-circuiting prevention mechanisms (SPMs) were used in different field-scale studies, those mechanisms may be vulnerable to short-circuiting in the vertical dimension. It was revealed that studying the role of eddy diffusion and gap layer for vertical short-circuiting can help designing better SPMs. This review also identified that further
Response to Reviewers:	Response to the editor and reviewers' comments are attached in the 'Response to the editor and reviewers' document.

# <u>Highlights</u>

- Hydraulics influences treatment efficiency of Floating Treatment Islands (FTIs).
- Current FTI installation practices mostly ignore hydraulics of the waterbody.
- Existing flow short-circuiting prevention mechanisms may not be effective.
- Investigation on more design parameters will help to enhance hydraulic performance.
- Robust modeling tools are required to predict hydraulic performance.

1	Review of Hydraulics of Floating Treatment Islands Retrofitted in Waterbodies
2	<b>Receiving Stormwater</b>
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#### 6 ABSTRACT

7 Stormwater pollution causes an excessive influx of nutrients and metals to the receiving waterbodies 8 (stormwater ponds, lakes, and rivers), which can cause eutrophication and metal toxicity. One of the most 9 cost-effective and eco-friendly solutions to stormwater pollution is constructing floating treatment islands 10 (FTIs) within the waterbodies receiving stormwater runoff. Treatment efficiency of FTIs depends on many 11 factors including plant species, temperature, detention time, and pollutant loading rate. Another important factor is FTI hydraulics, which determines the amount of inflow to the root zone and residence time, greatly 12 impacting the treatment. However, only a few studies refer to the hydraulics of waterbodies retrofitted with 13 FTIs. This paper reviews available literature on field-scale, laboratory-scale and numerical studies on the 14 hydraulics of FTI retrofitted waterbodies. Because of limited knowledge on the factors affecting hydraulics 15 of waterbodies retrofitted with FTIs, current practices cannot ensure maximum hydraulic performance of this 16 system. This review paper identifies different factors affecting the FTI hydraulics, investigates knowledge 17 gaps, and provides future research direction for hydraulically efficient design of FTIs to treat stormwater. It 18 19 was found that there is a need to investigate the impact of new design parameters such as FTI shape, FTI coverage, inlet-outlet configurations, and shape of waterbody on the hydraulic performance of FTI retrofitted 20 21 waterbodies. A lack of dimensional analysis on FTI retrofitted waterbodies in existing literature revealed that field-scale values were not properly scaled down in laboratory experiments. Although a few short-circuiting 22 prevention mechanisms (SPMs) were used in different field-scale studies, those mechanisms may be 23 vulnerable to short-circuiting in the vertical dimension. It was revealed that studying the role of eddy 24

diffusion and gap layer for vertical short-circuiting can help designing better SPMs. This review also
identified that further investigation is required to incorporate root flexibility in the current modeling approach
of FTI retrofitted waterbodies.

28 **Keywords**: hydraulics, floating island, treatment, stormwater, waterbodies

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#### 30 1. INTRODUCTION

31 Urban waterways suffer from pollution during storm events due to washing off of pollutants from urban landscapes (Chance & White, 2018; Kumari & Tripathi, 2014). A high percentage of impervious surfaces in 32 33 urban areas yield more runoff volume and pollutant wash off compared to rural areas where surfaces are mostly pervious (Goonetilleke et al., 2017; Goonetilleke and Lampard, 2019). Stormwater runoff can carry 34 metals and nutrients to the watercourse and cause deterioration of water quality (Alam and Anwar, 2020; 35 36 Huber et al., 2016; Lai et al., 2011; Wijesiri et al., 2020). Pathogens in stormwater can pose a serious threat 37 to human health (Sauer et al., 2011; Sidhu et al., 2012). Pollutants in stormwater runoff can be both in particulate and dissolved forms (Al Mamun et al., 2020; Javarathne et al., 2017; LeFevre et al., 2014). 38 Governments, scientists, and engineers have devised policies, standards, and treatment technologies to 39 40 mitigate stormwater pollution (Daly et al., 2012). Cities around the world are pursuing sustainable stormwater 41 management practices under different names, such as Water Sensitive Urban Design (WSUD) (Liu et al., 2016) and Low Impact Development (LID) (Brown et al., 2013). Best Management Practices (BMPs) are in 42 use under these strategies to tackle the water quality issue during storm events (Liu et al., 2017). Non-43 structural BMPs may be divided into five categories: town planning controls, strategic planning and 44 institutional controls, pollution prevention practices, educational and participation practices, and regulatory 45 46 controls (Boulet et al., 2017; Taylor and Fletcher, 2007). There are also numerous structural measures or treatment systems to enhance stormwater quality such as bioretention systems, green roofs, permeable 47 48 pavements, infiltration trenches, constructed wetlands (CWs), and catch basin inserts (Alam et al., 2018b, 2018a, 2017; Lei et al., 2016). Floating Treatment Island (FTI), also known as Constructed Floating Wetland 49

50 (CFW) is a cost-effective and ecofriendly treatment device and is increasingly being used throughout the
51 world for stormwater treatment (Nichols et al., 2016; Schwammberger et al., 2020).

The mechanism of treatment by an FTI system is shown in Figure 1. In this system, aquatic plants are 52 planted in a floating bed and placed in the waterbody (e.g., lake, stormwater pond, and river). The plants take 53 up nutrients and metals in dissolved form through their root matrix directly from the water (Rezania et al., 54 55 2016). Velocity reduction by the FTIs enhances sedimentation and removes particulate pollutants. Sediments are trapped in the root matrix as well. Biofilms grow in the root matrix and the floating bed, contributing to 56 a further reduction of pollutant concentration through microbial activity (Lucke et al., 2019). Aquatic plants 57 58 have also shown the capability to inhibit algal growth in waterbodies (Jones et al., 2017; West et al., 2017). Aquatic plant roots have been reported to secrete exudates and release oxygen, both of which control the type 59 of microbial population in the root matrix and mitigate algal blooms (Bensch et al., 2015; Bi et al., 2019; 60 Shahid et al., 2018; Urakawa et al., 2017; Wu et al., 2016; Zhang et al., 2015). Inhibition of algal growth is 61 important because when algal death occurs after the growth phase, decomposition of dead algae consumes 62 63 Dissolve Oxygen (DO), causing fish death and harming the aquatic ecosystem.

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- 65

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#### Figure 1

One of the advantages of FTIs is that they can be retrofitted in existing waterbodies, making them a costeffective solution for stormwater treatment. Recently, FTIs are being used to treat eutrophic river or lake water in China, Italy, India, Singapore, and Bangladesh (De Stefani et al., 2011; Fang et al., 2016; Hu et al., 2010; Li et al., 2010; Ning et al., 2014; Pandey et al., 2013; Piro and Carbone, 2014; Saeed et al., 2019, 2016; Zhao et al., 2012). FTIs are also used to treat domestic, agricultural, and industrial wastewater (Abed et al., 2017; Chua et al., 2012; Rehman et al., 2012; Saeed et al., 2014).

73 There are many factors affecting the treatment efficiency of FTIs, which include FTI coverage area, type

of plants, water temperature, detention time within the FTI, and pollutant loading rate (Chance and White,

75 2018; Dunqiu et al., 2012; Pavlineri et al., 2017). One of the key factors enhancing the treatment capability of an FTI is the hydraulic performance of the waterbody (Khan et al., 2013). Hydraulic performance of a 76 pond refers to (1) the capacity to evenly distribute inflow across the pond width and (2) recirculation of water 77 within the pond or the degree of mixing of the water (Persson et al., 1999). Hydraulic performance of a pond 78 79 can be determined by tracer experiments and using hydraulic performance indices as outlined in Sections 2.1 80 and 2.2, respectively. Hydraulic performance will influence how much of the inflow will pass through the FTI root zone and residence time within the root zone and waterbody. In case of river channels, instead of a 81 tracer experiment, direct determination of inflow to the FTI root zone has been performed (Lei et al., 2016; 82 83 Liu et al., 2019). Since treatment occurs mainly in the root zone (Liu et al., 2019; Xavier et al., 2018), hydraulic performance affects the treatment efficiency of FTIs substantially. Hence, it is required to design 84 hydraulically efficient FTI systems considering the factors that affect the hydraulic performance of the 85 waterbody to achieve higher pollutant removal. However, few studies have been conducted to understand 86 what affects the hydraulics of the waterbody retrofitted with FTIs. 87

A survey of review articles on water treatment using FTIs revealed that no published review article focused 88 on the hydraulics of FTI retrofitted in waterbodies in detail (Bi et al., 2019; Chang et al., 2017; Colares et al., 89 2020; Headley and Tanner, 2012; Lucke et al., 2019; Masters and Technology, 2012; Pavlineri et al., 2017; 90 91 Samal et al., 2019; Shahid et al., 2018; Wei et al., 2020; Yeh et al., 2015). Most of the review articles on FTI focused on the mechanism of treatment, plant performance, efficacy of the system, and factors affecting 92 treatment performance, but did not include hydraulic performance. As such, there is a need to review the 93 94 current state of knowledge regarding hydraulic aspects of FTI systems. The only review article that reported on hydraulics is by Lucke et al. (2019), who discussed flow short-circuiting in FTI retrofitted waterbodies. 95 96 Flow short-circuiting occurs when a large proportion of the inflow exits the wetland before the mean 97 Hydraulic Residence Time (HRT) (Persson et al., 1999). The main focus of Lucke et al. (2019)'s study was to review experimental designs of FTI studies. The authors only reviewed field-based studies and ignored the 98 99 laboratory and numerical studies on FTI systems. The authors concluded that designing an FTI system 100 considering FTI percentage coverage might not be appropriate approach but suggested future studies should emphasize on the prevention of flow short-circuiting. However, the authors did not discuss about the 101 measurement of parameters for flow short-circuiting and other hydraulic performances. Lucke et al. (2019) 102 suggested prevention of flow short-circuiting either by better positioning of FTIs or through flow diversion 103 using curtains. However, the authors did not highlight proven or potential factors that may affect the hydraulic 104 performance of FTI systems, which would reveal other ways of preventing flow short-circuiting. Though the 105 review article of Lucke et al. (2019) identified few hydraulic aspects of FTI, there are many other issues 106 related to FTI hydraulics such as measurement of hydraulic performance of FTI retrofitted waterbodies, 107 108 factors affecting FTI hydraulics, lab and numerical studies and current field-scale practices that are not yet systematically reviewed. Therefore, this review paper systematically presents the up-to-date information on 109 the hydraulics of FTI retrofitted in waterbodies (stormwater ponds, lakes, and rivers), provides critical insight 110 and current understandings of the topic, identifies the gaps and puts together the idea for future research. 111

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#### 113 2. MEASUREMENT OF HYDRAULIC PERFORMANCE

#### 114 **2.1 Residence Time Distribution (RTD)**

The concept of residence time distribution (RTD) was originally developed to characterize chemical reactors (Danckwerts, 1953). Later RTD concept has been applied in ponds, considering them as chemical reactors (Kadlec, 1994). The RTD represents the various fractions of fluid spread within the reactor and their contact time distribution. This means, RTD can be represented by a probability density function for residence time in pond. The RTD function E(t) can be determined by the use of tracer experiments.

120 
$$E(t) = \frac{Q_e C(t)}{\int_0^\infty Q_e C(t) dt} = \frac{C(t)}{\int_0^\infty C(t) dt}$$
(1)

Where C(t) is the outlet tracer concentration (mg/L) and  $Q_e$  is the water flow rate (m<sup>3</sup>/min). The moments of RTD define the actual detention time and the spreading of concentration pulse due to mixing (i.e. variance). Hydraulic performance of a pond can be determined by RTD curves derived from tracer experiments (Farjood et

al., 2015; Khan et al., 2013; Persson et al., 1999; Wahl et al., 2010). In tracer experiments, inert tracer material 124 (e.g., Rhodamine WT, Lithium Chloride, or Sodium Chloride) is injected at the inlet and the tracer concentration 125 is measured at the outlet. From the experimental data, the RTD curve is plotted with outlet tracer concentration 126 and time after injecting the tracer (Khan et al., 2013) (Figure 2). RTD curves reflect the residence time of each 127 128 water particle and their average residence time, mixing among particles, and recirculation (Sonnenwald et al., 129 2016a). It can also detect the existence of any preferential flow path and dead zones within the pond. The hydraulic performance of waterbody can be deduced from the RTD curve. A sharp peak of an RTD curve means that flow 130 short-circuiting occurred and the system is hydraulically inefficient if the mean residence time is significantly 131 132 lower than the nominal residence time. Conversely, a flat RTD curve suggests mixing of flow, which is hydraulically efficient in case of an FTI retrofitted pond/lake. A typical RTD curve has a very long tail because a 133 small fraction of the tracer stays in the pond for a very long time. For practical use of the RTD curve, it is suggested 134 that sampling of the outlet concentrations should be performed until 95% of the initial injected tracer mass exits 135 the pond (Chang et al., 2016; Williams et al., 2013). RTD curve for a vegetated wetland or pond reflects most of 136 the flow characteristics as discussed above and in the next section. 137

138

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Figure 2

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#### 141 **2.2 Hydraulic Performance Indices**

Hydraulic performance of an FTI retrofitted pond/lake can be described by the use of different performance indices derived from the RTD curve. The performance indices may be classified in terms of different hydraulic phenomena in the FTI system, including short-circuiting, mixing and presence of dead zones and/or combination of all of them. The hydraulic performance indices, their hydraulic phenomena, and their mathematical expressions are given in Table 1. It is to be noted that these phenomena are not always independent of each other and one phenomenon may influence others.

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#### Table 1

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#### 151 **2.2.1 Flow short-circuiting**

The most common phenomenon, flow short-circuiting, occurs when a large portion of the flow exits the 152 153 system earlier than the nominal residence time through high-velocity preferential pathways to the outlet (Farjood 154 et al., 2015; Khan et al., 2013; Lightbody et al., 2009; Stovin et al., 2008; Thackston et al., 1987). It prevents the flow from accessing the entire volume of the system and limits mixing with existing fluid in the system. 155 Preferential flow paths can be created in both horizontal and vertical directions. The initial detection time  $(S_i)$ 156 157 describes the phenomenon most closely. However, reproducing the  $S_i$  value is reported to be difficult and it does not give the amount of tracer, limiting its applicability (Farjood et al., 2015; Teixeira and do Nascimento Siqueira, 158 159 2008). Different studies have used the normalized times ( $t_5$ ,  $t_{10}$ ,  $t_{16}$ , and  $t_{50}$ ) for different portions of the tracer (e.g. 5%, 10%, 16%, and 50%) exiting at the outlet to determine the level of short-circuiting (see Table 1). S<sub>10</sub> was 160 concluded to be the optimum index to describe short-circuiting (Guo et al., 2015). However, Farjood et al. (2015) 161 162 reported that a fraction of tracer closer to initial detection time can describe the short-circuiting better. It was suggested that  $S_5$  can detect the differences of different flow conditions better, which was also found more 163 reproducible than other short-circuiting indices (Farjood et al., 2015). A value close to 1 indicates substantial 164 165 short-circuiting for all the short-circuiting indices listed in Table 1 except  $S_i$ . A delay in  $S_i$  implies the mixing of 166 flow within the system.

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#### 168 **2.2.2 Mixing**

The mixing phenomenon can be described by the ideal plug flow condition. When flow exits the system as a single file with no mixing with the adjacent fluid on its way, it is called an ideal plug flow condition (Farjood et al., 2015; Guo et al., 2015; Levenspiel and Bischoff, 1964). In an ideal plug flow condition, the outlet tracer is represented as a pulse in an RTD curve (Figure 2) and the hydraulic residence time of all fluid particles becomes same equaling to the nominal hydraulic residence time (volume of the system divided by inflow rate). However, 174 an ideal plug flow condition is impossible in nature. In contrast, in a completely mixed flow condition, incoming fluid particles mix with existing fluid particles in the system, and the RTD curve is represented in an exponentially 175 decreasing trend. If a plug flow condition is found in an FTI retrofitted pond/lake, it simply means that the 176 FTI does not have any effect on the pond/lake at all. It implies that there has been no contact of flowing water 177 178 with the FTI, which is undesirable. As such, mixing in an FTI retrofitted pond or lake indicates flow passing 179 through FTI, which yields higher treatment efficiency. One of the problems with the mixing indices is that they are affected by a long tail of the RTD curve. Several authors tested the performance of the mixing indices and 180 recommended either Morril index  $(M_{\rho})$  or Dispersion index  $(M_{D})$  (Farjood et al., 2015; Guo et al., 2015; Teixeira 181 182 and do Nascimento Siqueira, 2008). Both Farjood et al. (2015) and Guo et al. (2015) concluded that  $M_o$  was better for distinguishing differences between different flow conditions. Teixeira and do Nascimento Siqueira (2008) 183 recommended using  $M_D$  when the mixing level is high and  $M_o$  when mixing level is low. This was because the 184  $M_o$  was found more reproducible at low mixing levels. A value of  $M_o$  close to 1 represents the plug flow condition 185 and it indicates mixing in the system with increasing value. For  $M_D$ , a value of zero suggests completely plug flow 186 condition and a value close to 1 implies complete mixing flow. 187

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#### 189 **2.2.3 Presence of dead zones**

Both short-circuiting and mixing indices do not take the effect of dead zones into consideration. Dead zones are referred to as the region within the system where velocity towards the outlet is much lower than average or no velocity at all and characterized by very long residence time within the region (Thackston et al., 1987). To describe the presence of dead zones in the system, numerous authors have used the effective volume ratio (e), which is the ratio of mean hydraulic residence time derived from RTD curve (tRTD) to the nominal hydraulic residence time (tHRT) (Guo et al., 2015; Persson et al., 1999; Sabokrouhiyeh et al., 2017; Thackston et al., 1987).

Hydraulic efficiency index is another type of index that reflects both short-circuiting and mixing (Farjood et al., 2015). The hydraulic efficiency index ( $\lambda$ ) is the ratio of time to the peak of RTD curve ( $t_{p1}$ ) to the nominal hydraulic residence time ( $t_{HRT}$ ). It reflects the distribution of RTD curve, but it also indicates the presence of any dead zone. However, since it is measured on a single point, it is susceptible to instantaneous variations of tracer concentration. Another useful hydraulic efficiency index proposed by Wahl et al. (2010) is the moment index  $(M_I)$ , which can reflect both mixing and short-circuiting. As  $M_I$  involves taking the moment of RTD curve before the nominal residence time (i.e., pre-nominal moment), it is not subjected to instantaneous variation and is not influenced by the long tail of the curve. Multiple authors have used this index and confirmed its applicability and performance in describing phenomena related to hydraulic performance (Farjood et al., 2015; Guo et al., 2020; Khan et al., 2019, 2013).

Peclet number (*Pe*) is also another hydraulic performance parameter, which reflects the dominance of advective transport over dispersive transport (Persson and Wittgren, 2003; Seeger et al., 2013). A value near zero indicates strong dispersion, which means a high degree of fluid mixing (Vázquez-Burney et al., 2015). Conversely, a higher value of *Pe* indicates advection-dominated transport of fluid and plug flow condition. Peclet number can also be affected by a long tail of the RTD curve.

Apart from the performance of indices in detecting differences in flow conditions and describing the 211 phenomena, these indices also need to be able to predict treatment efficiency. One of the numerical studies 212 concluded that for a water storage tank, short-circuiting index  $(S_{10})$  was able to correlate with disinfectant removal 213 efficiency (Xavier and Janzen, 2017). A modified moment index could not correlate well with disinfectant 214 215 removal in the same study. The authors used a post-nominal moment index instead of the pre-nominal moment index suggested by Wahl et al. (2010). Pre-nominal moment refers to the moment of the area under the RTD 216 217 curve between the start time and nominal hydraulic residence time. On the other hand, post-nominal moment 218 refers to the moment of the area of the RTD curve between nominal residence time and the end of the RTD curve. Bodin et al. (2013) concluded that effective volume ratio (e) predicts pollutant removal better than the number of 219 220 Continuously Stirred Tank Reactors (CSTRs) (N) for constructed wetlands. Kusin et al. (2014) found that the 221 Tank in Series (TIS) model for iron removal in constructed wetland requiring N value is better suited than the first-order kinetic equation. It was stated that since the first-order kinetic equation assumes a plug flow condition, 222

which was not the condition in the wetland, it failed to predict iron removal anywhere close to that of the TISmodel.

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#### 226 **2.3 Analytical and numerical models**

In the case of FTI in open channels, the vertical distribution of streamwise velocity will deviate from the usual logarithmic velocity distribution because of floating vegetation retarding the flow. This has been demonstrated by Huai et al (2012) by developing a three-layer analytical model dividing vegetated open channel into three zones of water such as a non-vegetated layer at the bottom, an intermediate vegetation layer, and an upper vegetation layer. The analytical models developed for these layers were checked with the experimental data given by Plew (2011), who used suspended canopies with floating vegetation. These analytical expressions may also be essential for the FTI design and subsequent performance assessment of pollutant removal.

Numerical modeling allows the determination of the flow field of the waterbody in question. Hence, the 234 fraction of total flow passing through the root zone and residence time within the root zone can be estimated 235 directly. Tracer experiments can also be run through numerical simulation. However, numerical simulations 236 require field or laboratory data for model validation. The widely adopted flow-field modeling approach is 237 Reynolds Averaged Navier-Stokes (RANS) equations for continuity (Eq. 22) and conservation of momentum 238 239 (Eq. 23), which numerous authors used to simulate hydraulics of vegetated constructed wetlands, ponds, and river channels (Ai et al., 2020; Choi and Kang, 2016; Sonnenwald et al., 2016b, 2016a; Sonnenwald et al., 2017a; 240 Xavier et al., 2018). 241

242 
$$\frac{\partial u_i}{\partial x_i} = 0 \tag{22}$$

243 
$$\rho \frac{\partial u_i}{\partial t} + \rho \frac{\partial u_j u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \rho \frac{\partial \overline{u_i' u_j'}}{\partial x_j} + f_i \quad (23)$$

where  $\rho$  is the fluid density; p is the pressure (N/m<sup>2</sup>);  $\mu$  is the dynamic viscosity (kg/m-s); i or j = 1, 2 or 3;  $x_1, x_2$ , and  $x_3$  are streamwise, cross-stream and vertical directions, respectively;  $u_1, u_2$ , and  $u_3$  are temporal averaged velocity components (m/s),  $\overline{u_i'u_j'}$  is the Reynolds stress with *u'* denoting the fluctuating part of the velocity;  $f_i$  is the drag force or momentum sink due to vegetation roots (N).

To close Equation 22 and 23, Ai et al. (2020) used Reynolds Stress Model (RSM) as given in the following equation (Eq 24) to simulate effects of vegetation in laboratory flume representing river channel.

250 
$$\underbrace{\frac{\partial \overline{u_{l}'u_{j}'}}{\partial t}}_{Time\ derivative} + \underbrace{u_{k}\frac{\partial \overline{u_{l}'u_{j}'}}{\partial x_{k}}}_{Convection} = \underbrace{\frac{\partial}{\partial x_{k}}\left(\mu_{k}\frac{\partial \overline{u_{l}'u_{j}'}}{\partial x_{k}}\right)}_{Molecular\ diffusion} + \underbrace{\frac{\partial}{\partial x_{k}}\left(\frac{v_{t}}{\sigma_{k}}\frac{\partial \overline{u_{l}'u_{j}'}}{\partial x_{k}}\right)}_{Turbulent\ diffusion} - \underbrace{\left(\overline{u_{l}'u_{k}'\frac{\partial u_{j}}{\partial x_{k}} + \overline{u_{j}'u_{k}'\frac{\partial u_{i}}{\partial x_{k}}}\right)}_{Stress\ production} + \underbrace{\frac{\varphi_{ij}}{\varphi_{ij}} - \underbrace{\varepsilon_{ij}}_{Dissipation} + \underbrace{\frac{C_{fk}\left(u_{i}f_{i} + u_{j}f_{i}\right)}_{Wake\ production\ due\ to\ vegetation}} - \underbrace{\left(24\right)}_{(24)}$$

where  $\mu_k$  is the kinematic viscosity (m<sup>2</sup>/sec),  $v_t$  is the turbulent viscosity (kg/m-s) and  $\sigma_k$  is a model constant = 0.82.

Choi and Kang (2016) also used the RSM model but did not consider the wake production term stating that low
vegetation density adopted in the study would not incur substantial drag to produce a wake.

To estimate the drag force exerted by the root zone, Ai et al. (2020) considered the following equation.

257 
$$f_i = -\frac{1}{2} \left( \frac{c_D a}{1 - \varphi} \right) \bar{u}_i \sqrt{u_i u_j} \qquad (25)$$

where  $f_i$  is the drag force,  $\varphi$  is the vegetation density calculated as  $\varphi = \pi a d/4$ , *a* is the frontal facing area per unit floating bed area (m<sup>2</sup>) = nd, n is the number of vegetation stems per unit bed area, *d* is root diameter (m)),  $C_D$  is the drag coefficient.

Ai et al. (2020) utilized the following expression (Eq. 26) given by Cheng et al. (2019) to estimate the drag force coefficient.

263 
$$C_D = \frac{3.07Re^{-0.168}a^{0.246}}{1.405\left(\frac{hg}{H}\right)^{0.288}}$$
(26)

where *H* is the depth of flow (m),  $h_{g=}H-h_c$  is the depth of water below vegetation stems (m),  $h_c$  is the length of vegetation stems along the depth of water (m). Sonnenwald et al. (2017a) represented vegetation zone as a porous media in ANSYS Fluent (2014) to model hydraulics of vegetated stormwater ponds. The drag force exerted by a porous media in ANSYS Fluent is expressed as follows (ANSYS Inc., 2013):

269 
$$f_{i} = -\left(\underbrace{\frac{\mu}{K_{perm}}u_{i}}_{viscous\,drag} + \underbrace{\frac{1}{2}C_{2}\rho|u_{i}|u_{i}}_{inertial\,drag}\right)$$
(27)

where  $K_{perm}$  is the permeability (m<sup>-2</sup>) and  $C_2$  is the porous zone inertial drag coefficient.

The value of  $C_2$  is defined by Equation 28.

$$C_2 = \frac{C_D a}{1 - \varphi} \qquad (28)$$

Sonnenwald et al. (2016b) analyzed the sensitivity of viscous and inertial drag on the flow field and concluded that the model is insensitive to  $1/K_{perm}$ , but highly sensitive to  $C_2$ . Sonnenwald et al. (2017a) neglected the viscous drag by assuming an infinite value of permeability. In contrast, Xavier et al. (2018) ignored the inertial drag of the porous media. The authors determined the value of  $K_{perm}$  to be  $10^{-7}$  m<sup>2</sup> by fitting the velocity profile data of Downing- Kunz and Stacey (2012), who conducted experiments in a laboratory flume with real plants.

To determine the value of  $C_D$ , Sonnenwald et al. (2017a) used the following expression:

280 
$$C_D = 2\left(\frac{\alpha_0}{Re_d} + \alpha_1\right) \quad (29)$$

where  $Re_d = Ud\mu^{-1}$  is the stem Reynolds number and *d* is the stem diameter (m). The values of  $\alpha_0$  and  $\alpha_1$  can be estimated by the following equations proposed by (Tanino and Nepf, 2008; Tinoco and Cowen, 2013).

283 
$$\alpha = 7276.43d + 23.55$$
 (30)

284 
$$\alpha_1 = 32.70d + 3.01\varphi + 0.42$$
 (31)

Tracer experiments can also be run through numerical simulations. The virtual tracer can be modeled using
the scalar transport equation (ANSYS Inc., 2015).

287 
$$\frac{\partial \rho C}{\partial t} + \frac{\partial \rho u_i C}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \frac{v_t}{Sc} \frac{\partial C}{\partial x_i} \right)$$
(32)

where *C* is the concentration of tracer (mg/L),  $S_c$  is Schmidt number (the ratio of momentum to mass diffusivity).

Equation 32 does not consider dispersion of tracer within porous media. Sonnenwald et al. (2017a) added a new 290 stem scale vegetation dispersion term  $(D_{ij})$  to reflect tracer dispersion within the porous media. However, the 291 modeling results of Sonnenwald et al. (2017a) were not further validated by experimental results. As such, it is 292 difficult to describe the benefit of adding new dispersion term to predict the experimental RTD curve accurately. 293 Xavier et al. (2018) validated the RTD curve modeled in the study using the data of Khan et al. (2013).  $R^2$ 294 295 value of Xavier et al. (2018) modeled vs. observed data was 0.87. However, it under-predicted the peak of RTD curve and over-predicted the tail of RTD curve. As such, it is recommended to validate the porous zone 296 297 modeling approach with an additional dispersion term proposed by Sonnenwald et al. (2017a).

298

#### 299 3. HYDRAULICS OF FLOATING TREATMENT ISLAND

#### **300 3.1 Article Selection Criteria**

Three criteria were used to select articles for review: (1) research where hydraulic performance indices were measured in a stormwater pond retrofitted with FTIs, (2) research studying the hydraulic characteristics (e.g., depth, velocity, inflow to the root zone) of rivers in laboratory flumes with FTIs and (3) field-scale research where flow short-circuiting prevention methods have been used in ponds, lakes or river sections retrofitted with FTIs. Laboratory investigations, field-scale investigations, and numerical simulations were all included in criteria 1 and 2. Only field-scale studies were considered for criterion 3. Features covered by the articles in criteria 1 and 2 are summarized in Table 2.

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309

#### Table 2

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#### 311 **3.2** Hydraulics of FTIs in Stormwater Pond (Criterion 1)

Bu and Xu (2013) evaluated the performance of four different plants in treating polluted river water in China 312 in mesocosms placed in the natural environment (Figure 3-a). Water was collected from the Linjiang River and 313 314 gravity fed to four pilot-scale pond units retrofitted with FTIs (2.7 m x 2.3 m x 0.8 m) that were planted with four different aquatic plants: Canna indica, Accords calamus, Cyperus alternifolius, and Vetiveria zizanoides. 315 Hydraulic performance was studied by tracer experiments using NaCl solution as tracer. RTD curves were plotted 316 317 and different hydraulic performance indices were calculated. Water quality parameters such as COD, TN, TP, Chl-a, and DO were measured. It was found that *C.indica* provided better treatment. The authors concluded that 318 319 the greater pollutant removal efficiency was due to the higher hydraulic performance shown by C. indica. The mean hydraulic retention time, Peclet number (Pe), and number of CSTRs (N) for C. indica treatments were found 320 higher than the treatment units with other plants. The variance and hydraulic efficiency of the unit planted with 321 322 C. indica were less than the other units, which demonstrates a contrasting finding in terms of hydraulic performance. Bu and Xu (2013) concluded that high treatment performance of C. indica compared to other plants 323 was achieved due to the high hydraulic performance of C. indica planted unit assuming that all the plants have 324 325 equal uptake rate. Uptake rate is specific to plant species and treatment performance is the combination of plant uptake rate and hydraulic performance of the system. So, the overall treatment performance of the system was 326 327 studied, but plant uptake rates for different plant species were not studied by Bu and Xu (2013). Measurement of 328 hydraulic performance and treatment efficiency of different treatment units planted with the same plant having different physical configurations could better explain the high treatment efficiency of C. indica planted unit. This 329 330 study also did not investigate root features, i.e., fibrous vs. thick roots. Root features could tell more about why 331 pollutant removal performance was higher for C. indica than other plants. Aquatic plants with fibrous root matrix have been reported more efficient in uptaking pollutants than the plants with thick roots (Lai et al., 2011). 332

333 Hydraulic performance of a laboratory-scale stormwater pond retrofitted with single FTI and multiple FTIs (using artificial roots made from nylon rope) arranged in series for different inlet arrangements was 334 investigated (Khan et al., 2013) (Figure 3-b). Seventeen cases of design configurations (FTI position and 335 orientation, inlet configuration) with rectangular FTIs were investigated using a Rhodamine WT tracer. 336 Short-circuiting index, hydraulic efficiency, moment index, and effective volume ratio were calculated from 337 338 the RTD curve. It was found that a single FTI placed at a position where the ratio of the distance of FTI from the inlet to the length of the pond equaled 0.125 for a side inlet and 0.25 for a centered inlet yielded maximum 339 hydraulic performance. Moreover, four inlets distributed uniformly over the width of the pond produced the 340 341 highest hydraulic performance due to the sloping side effects of the pond. It was also revealed that splitting a single FTI into two units arranged in series did not enhance the performance if the long side of the single 342 FTI was oriented parallel to the long side of the pond. Although this study investigated the inlet configuration 343 and positioning of the FTI, it did not study other important features such as FTI shape, depth of flow, 344 vegetation coverage, and density which may have greater potential to influence the hydraulic performance of 345 a pond retrofitted with FTI. In the Khan et al. (2013) study, the outlet location was fixed and it potentially ignored 346 the effect of outlet position relative to inlet position. Although it did not investigate other design aspects, it can be 347 taken as a pioneering study that demonstrated how FTI and pond design configurations impact hydraulic 348 349 performance.

A numerical modeling study was conducted to understand the nutrient removal performance of FTIs having 350 351 different configurations in a stormwater pond (Xavier et al., 2018) (Figure 3-c). This study was performed using 352 the data of Khan et al. (2013) and the model was set up to match Khan et al. (2013) measurements for model validation. ANSYS CFX 17.0 (ANSYS Inc., 2016) was used to determine the flow field with a 3D transient 353 354 simulation. The model represented the root zone as a porous media in a bulk approach, which was modeled using 355 Equation 27 as mentioned earlier in Section 2.3. RTD curves experimentally derived by Khan et al. (2013) were numerically simulated to validate the model. Extracted data of actual and simulated RTD curves by us revealed 356 that R<sup>2</sup> value was 0.87, which indicates satisfactory model validation despite slight under-prediction of the peak 357

of RTD curve by numerical simulation of Xavier et al. (2018). Further simulations were performed by Xavier et al. (2018) to understand treatment efficiency by adding the first-order kinetics term in Equation 32, which was activated for root zone. The results of this study revealed that the treatment efficiency was higher for FTI combinations in which a greater amount of flow passed through the root matrix. This study was also extended by simulating FTIs in parallel, which was not investigated in Khan et al. (2013). It was concluded that the FTIs in parallel could improve the nutrient removal performance better than the FTIs in series. However, Xavier et al. (2018) did not measure the hydraulic performance indices.

Khan et al. (2019) studied the design configuration parameters such as submergence depth ratio (ratio of root 365 366 length to water depth) and vegetation density, which were not covered by previous studies of Khan et al. (2013) and Xavier et al. (2018) (Figure 3-d). But Khan et al. (2019) used the same model tank of Khan et al. (2013) and 367 used similar hydraulic performance parameters. It was found that a submergence depth ratio of 0.5 yields optimum 368 hydraulic performance, which is surprising because Lucke et al. (2019) stated that short-circuiting underneath the 369 root zone is highly possible when root length does not cover the entire water depth. However, Khan et al. (2019) 370 did not explain what led to an optimum submergence depth ratio of 0.5. As such, this finding needs to be validated 371 by further experiments. The vegetation density was varied between 2.75 plants/m<sup>2</sup> to 11 plants/m<sup>2</sup> and the 372 optimum vegetation density was found 5.5 plants/m<sup>2</sup>. But it is not only the vegetation density but also the 373 374 arrangement of the root matrix that could affect the hydraulic performance. When the distance between plants in the transverse direction was half of that in the longitudinal direction at a vegetation density of 5.5 plants/m<sup>2</sup>, it 375 provided better hydraulic performance than a uniform distance between plants. However, similar to Khan et al. 376 377 (2013), this study also kept the outlet position fixed, potentially ignoring the impact of the outlet position relative to the inlet. 378

A field-scale study on the hydraulic performance of a pond retrofitted with FTIs was conducted in USA (Vázquez-Burney et al., 2015) (Figure 3-e). The pond had a surface area of 1.6 ha of which FTIs covered 7% of the area with twenty units placed in an array just before the outlet. A tracer study was conducted using Lithium Chloride to produce the RTD curve. Peclet number (*Pe*), variance ( $\sigma_{\theta}^2$ ), number of CSTRs (*N*), and effective

383	volume ratio (e) were determined from the RTD curve. The Pe of the pond was only 0.13 implying major short-
384	circuiting. A Pe near zero indicates a high level of short-circuiting and a value near to infinity indicates plug flow
385	condition (Vázquez-Burney et al., 2015), whereas typical values of Pe in ponds range between 5 and 20 (Kadlec
386	and Wallace, 2008). An <i>e</i> value of 0.63 substantiated the claim further. An <i>e</i> less than 1 indicates dead zone(s),
387	which promotes short-circuiting in the pond. However, only one tracer experiment was performed in this study,
388	keeping all design configurations constant. Therefore, the impact of design features on hydraulic performance and
389	subsequent impact on treatment efficiency could not be determined. The study commented that the nutrient
390	removal could be enhanced if <i>Pe</i> and <i>e</i> was improved.
391	
392	Figure 3
393	
394	3.3 Hydraulics of FTIs in Rivers (Criterion 2)
395	Correlating FTI hydraulics in river channel sections with treatment efficiency requires direct determination of
396	inflow to the FTI root zone. To the best of our knowledge, there has been no tracer study conducted in real or
397	artificial river channels estimating the hydraulic performance indices as listed in Table 1. Most of the studies
398	investigating the hydraulics of rivers retrofitted with FTIs measured inflow to FTI root zone, velocity profiles,
399	and depth profiles in laboratory flumes representing river channel.
400	An investigation to understand the influence of FTIs on channel hydraulics was performed in a laboratory
401	flume representing river channel by Rao et al (2014) (Figure 4-a). Floating beds planted with Iris tectorum were
402	placed in an open-channel flume. Flow velocity, FTI coverage, and FTI position were varied to determine the
403	change in velocity distribution and water level within the flume. Flow velocity was measured using a Doppler
404	Velocimeter. Flow through the root zone was modeled using Navier-Stokes equations (Temam, 2001). The

406 upstream of FTI can be substantial at flow velocities greater than 0.2 m/s. Flow velocities increased underneath

407 the FTI. The position of FTI with respect to the channel walls was important. When the FTIs were positioned

408 against the wall without any gap on both sides, flow could pass through the constricted channel without much resistance. In contrast, when there was a gap between the FTIs and channel wall, it created multiple channels 409 within the flume and flow became more non-uniform affecting water level distribution. This study focused only 410 on the hydraulic characteristics of the river due to the installation of FTIs and not on how to increase inflow to the 411 root zone to enhance treatment efficiency. Similar investigations were also performed by some other studies with 412 413 additional analyses (Fu et al., 2020; Huai et al., 2012). Huai et al. (2012) investigated the velocity profile of open channel flows with suspended vegetation. Fu et al. (2020) studied the turbulent flow structures in open channel 414 flows with floating vegetation. However, these studies were also focused on the impact of floating vegetation on 415 416 the flow characteristics rather than how inflow to the root zone can be enhanced for better pollutant removal.

The flow field and pollutant removal efficiency of the root system of FTIs installed in a channel were 417 investigated in a laboratory flume representing the river channel (Lei et al., 2016) (Figure 4-b). This study 418 investigated the impact of root system porosity on hydraulics and pollutant removal efficiency at different 419 velocities. To the best of our knowledge, this is the first experimental attempt to correlate hydraulics and 420 pollutant removal capacity of FTIs in river channels. A Particle Image Velocimetry (PIV) system was used 421 to determine the velocity distribution within the root zone. Position of FTIs, flow velocity, and root system 422 porosity were varied in estimating the pollutant removal efficiency. It was concluded that optimum 423 424 positioning of FTIs could enhance removal efficiency, which would vary depending on the velocity. A higher root system porosity (79.17%) leads to increased removal efficiency within a certain velocity range (0.007 – 425 0.055 m/s). Pollutant removal efficiency goes down as the velocity exceeds the above-mentioned range. 426 427 Though root system porosity was investigated, it was expressed in percentage and not in terms of the number of plants per unit area, making it difficult for designers to implement the outcomes of this study. Also, this 428 429 study did not investigate the influence of FTI coverage in the channel and the submergence depth ratio. 430 The effect of FTI spacing on pollutant removal rate in a river channel was investigated in a laboratory flume representing river channel (Liu et al., 2019) (Figure 4-c). The ultimate goal was to determine the 431

432 optimum spacing between FTIs in series to maximize pollutant mass removal per unit channel length.

433 Hydraulic experiments were conducted in a 16 m long open-channel flume to determine the velocity field, inflow rate to the root zone, and residence time in the root zone. Mass removal was estimated as a first-order 434 removal constant, k (day<sup>-1</sup>) within the root zone. The values of removal rate were considered in a 435 dimensionless form kT, where T is the time (day). The results suggested that mass removal can be maximum 436 437 for an FTI spacing equal to one to three times the root zone length for  $kT \ge 5$  when considering the whole 438 FTI retrofitted channel section. The study was conducted using rigid dowels, i.e., artificial rigid root analogs, and it was recommended that the proposed mass removal model should be validated by experimenting with 439 real plants. Vegetation density was kept constant in this study (Liu et al., 2019), meaning that the results only 440 441 apply for the specific density, which was not reported. The optimum spacing between FTIs arranged in series was recommended between one and two times the length of the root zone if kT < 1. For kT > 2, the optimum 442 spacing was suggested between one and three times the length of the root zone for maximum pollutant 443 removal per unit length of a river. The submergence depth ratio was kept constant at 0.5. It was stated that 444 this ratio affects inflow to the root zone and hence the treatment efficiency. Also, the flow velocity in the 445 flume was kept constant by a constant flow rate. But it was mentioned that the channel flow velocity might 446 alter the inflow rate to the root zone. Therefore, the findings are valid for the specific velocity (0.097 m/s)447 used in the study. Despite these limitations, Liu et al. (2019) was the first study that showed how the spacing 448 449 between FTIs in series could influence inflow to their root zones in a river channel.

Numerical analysis of flow with floating vegetation was carried out by Ai et al. (2020) using the data of 450 Plew (2011) who conducted experiments in a laboratory flume with vegetation (Figure 4-d). Reynolds-451 452 averaged continuity and momentum equations for incompressible fluid were used to describe flow through the root zone. Plew (2011) used rigid aluminum cylinders to represent the roots. As such, the numerical model 453 454 by Ai et al. (2020) represented the root zone with a set of rigid circular cylinders. Drag force term was added 455 in the momentum equation to represent the resistance exerted by the root zone. One of the key features of this study is the analysis of the impact of vegetation density on velocity profile, which was not done by Liu 456 457 et al. (2019). It was found that with the increase of vegetation density, a velocity reduction occurs within the

458 root zone. This study also detected two couples of secondary current in the stream-wise direction of the channel. One of which was within the root zone close to the centerline and the other one was at the bottom 459 of channel outside the root zone. The study revealed that the secondary current outside the root zone got 460 stronger with the increase of vegetation density. The findings of the study indicate that with the increase of 461 vegetation density, inflow to the root zone decreases. As this study was conducted with laboratory flume 462 463 data, it will be only applicable for river channels where the flow is predominantly turbulent (Bouchez et al., 2011; Gimbert et al., 2014; Mihailović et al., 2014). In a stormwater retention pond, flow is characterized by 464 a low Reynolds number (laminar flow) and the situation might be different. However, this is an interesting 465 466 study to conduct physical experiments in the laboratory on the impact of vegetation density in retention ponds and rivers. 467

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- 469

### Figure 4

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#### 471 **3.4 Flow Short-Circuiting Prevention (Criterion 3)**

There were six field-scale FTI systems found in the literature that took measures to prevent short-472 circuiting in stormwater ponds, lakes, or rivers retrofitted with FTIs (Borne et al., 2013a-b; De Stefani et al., 473 474 2011; Maxwell et al., 2020; Nichols et al., 2016; Revitt et al., 1997; Schwammberger et al., 2019). The use of different mechanisms in the above-mentioned studies is depicted in Figure 5. Near Heathrow airport, 475 London, a study was conducted on a 15  $m^2$  pond where the FTI covered the entire surface area and forced all 476 477 the flow through the root matrix (Revitt et al., 1997). A stormwater detention pond in New Zealand used the full-width FTI concept to prevent short-circuiting of flow (Borne et al., 2013b, 2013a). Full-width FTIs were 478 479 also used in Queensland, Australia in a lake (Schwammberger et al., 2019). Full-width FTIs on the Sile river 480 in Italy were used, where all the inflow had to pass through the FTIs (De Stefani et al., 2011). Another example of flow short-circuiting prevention method is using impermeable curtains to create a separate zone 481 482 where the FTI was placed and forced all the flow to pass through the FTI. This mechanism was used in a 483 stormwater detention pond in Bribie Island, Oueensland, Australia (Nichols et al., 2016; Schwammberger et al., 2017; Walker et al., 2017). One of the deficiencies of above-mentioned studies is that none of the studies 484 have measured the hydraulic performance indices of the waterbody. In the absence of this information, it is 485 difficult to pinpoint how effective the short-circuiting prevention mechanisms were. Studying the hydraulic 486 487 conditions before and after installing the FTIs would reveal the improvement of hydraulic performance due 488 to FTI installation and the effectiveness of the SPMs. Lucke et al. (2019) mentioned that flow short-circuiting below the root zone, i.e. vertical short-circuiting is possible even with the full-width or full-coverage FTI. 489 Only two studies reported both the root length and operational depth, which revealed that in one of the studies, 490 the submergence depth ratio (root length/water depth) was 0.53 (Borne et al., 2013b), implying that flow 491 short-circuiting beneath the root zone was possible. The other study had a submergence depth ratio of 1 492 (Schwammberger et al., 2019), eliminating the possibility of short-circuiting underneath the root zone. 493 494 However, a ratio of 1 is also not desirable in order to prevent roots from getting attached to the soil. These 495 two competing trends make it paramount to determine the submergence depth ratio to satisfy both 496 requirements. However, maintaining the optimum ratio always is not possible because of variation in water depth during a storm event. It will also depend on other factors such as flow velocity and design 497 configurations of the waterbody and FTI. In this circumstance, a range of possible scenarios should be 498 499 numerically simulated to get a better idea about hydraulic performance in different conditions.

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- 501

#### Figure 5

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# 5034. FACTORS AFFECTING HYDRAULIC PERFORMANCE OF FTI RETROFITTED504WATERBODIES

505 4.1 Proven Factors

• **FTI position:** Khan et al. (2013) investigated the optimum positioning and orientation of a single FTI through laboratory experiments. It was found that if the FTI was positioned at a distance equal to one-

508 eighth of the length of the pond from the inlet for an inlet positioned at the center, it produced maximum hydraulic performance. For a side inlet, the optimum distance was one-fourth of the pond's 509 length from the inlet. Orientation of FTI was also found to be affecting hydraulic performance. The 510 longer side of FTI oriented along the length of a pond proved to be hydraulically more efficient than 511 the smaller side orientation of FTI along the length of a pond. Appropriately positioning FTI will 512 513 force more water to flow through the root zone and performance can be enhanced without significant increase in FTI area. As such, the positioning of FTIs within the pond is an important factor affecting 514 hydraulic performance. 515

516 • **Spacing between FTIs:** Liu et al. (2019) demonstrated how the spacing between FTIs in series affects inflow to the root zone in a river channel based on laboratory flume experiments. The optimum 517 518 spacing was recommended between one and three times of the vertical length of the root zone depending upon pollutant removal rate. Both Khan et al. (2013) and Xavier et al. (2018) concluded 519 that FTIs arranged in series in a pond do not improve hydraulic and nutrient removal performance 520 521 compared to that of a single equivalent FTI. However, Xavier et al. (2018) numerically proved that nutrient removal was enhanced due to splitting a single FTI and arranging in parallel. But the authors 522 523 did not investigate the impact of spacing between FTIs in parallel. As such, it is paramount to 524 investigate the optimum spacing between FTIs in parallel in different FTI systems. Also, there is a 525 difference in the flow regime of rivers and ponds. As mentioned earlier, river flows are mostly turbulent (Re > 3200), whereas flow in a stormwater pond is predominantly laminar (Re < 1800). 526 Furthermore, flow in a river channel occurs throughout the width of the channel, whereas inflow to a 527 528 stormwater pond typically comes through a single pipe, which has a higher potential of creating 529 preferential flow paths. As such, optimum spacing between FTIs in a river channel and a stormwater pond will vary. 530

Submergence Depth Ratio: Khan et al. (2019) investigated the hydraulic performance of FTI retrofitted pond in a scaled-down model tank at different submergence depth ratios (0.25 - 0.71) by

tracer experiments. The authors concluded that a ratio of 0.5 yielded maximum hydraulic 533 performance. The authors offered no explanation regarding the process of how this particular ratio 534 yielded maximum hydraulic performance. Plew et al. (2011) varied the ratio between 0.125 and 0.75 535 and conducted experiments at a varying flow rate in a laboratory flume and velocity within the root 536 zone was measured. It was found that the inflow to the root zone increased with the increase of the 537 538 ratio, but no optimum ratio was reported. There is a need to resolve these conflicting findings through investigation in the same system (pond or river channel) under similar conditions. Submergence depth 539 ratio is a crucial parameter to prevent short-circuiting in the vertical dimension. 540

Vegetation density: In an FTI retrofitted model pond, Khan et al. (2019) experimented with 541 vegetation density ranging between 2.75 and 11 plants/ $m^2$ . The authors concluded that the optimum 542 vegetation density was 5.5 plants/m<sup>2</sup>. Anything above or below this density would yield lower 543 hydraulic performance. According to Equation 25, with the increase in vegetation density, there will 544 be an increase in vegetation drag reducing the velocity within the root zone, which implies higher 545 546 residence time within the root zone. However, this will also incur less inflow to the root zone (Ai et al., 2020). These two competing trends lead to an optimum vegetation density, which will maximize 547 548 inflow and residence time for high hydraulic efficiency.

549

#### 550 **4.2 Potential Factors**

• Inlet-Outlet Configurations: As demonstrated by Khan et al. (2013), changing the inlet configuration, position and orientation of the FTI, and splitting a single FTI into multiple units changed the hydraulic performance of an FTI retrofitted pond. Numerical simulation has shown that the inlet-outlet configuration changes the flow path, velocity, and thus the hydraulic performance of constructed wetlands (Sabokrouhiyeh et al., 2017). Hence, in addition to inlet position, it can be proposed that inlet-outlet configuration, i.e., the relative positions of inlet and outlet with respect to each other may also affect the hydraulic performances of an FTI retrofitted pond. However, no 558

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corroborating field or laboratory study has been conducted on how inlet-outlet configuration may affect hydraulic performance in an FTI retrofitted pond system.

• **FTI Coverage:** It can be anticipated from the studies discussed in Section 3 that vegetation coverage 560 may also have a substantial effect on the hydraulic performance because of additional root volume. 561 All things being equal, water will want to flow around an FTI rather than through it due to the higher 562 resistance to flow provided by the FTI's root system compared to the adjacent open water. At low 563 FTI coverage, most of the flow will bypass the FTIs. It is only with increasing FTI coverage that more 564 and more water will be forced through the roots. Furthermore, many studies suggested that vegetation 565 coverage affects the hydraulics of a constructed wetland (Bodin et al., 2012; Sonnenwald et al., 2019a; 566 Sonnenwald et al., 2019b). Hence, it is rational to argue that increasing the floating island coverage 567 568 in an FTI retrofitted pond will contribute to the hydraulic performance. Thus, FTI coverage is also a potential factor affecting the hydraulic performance of waterbodies retrofitted with FTIs. 569 570 Nevertheless, no study has been conducted to determine the impact of FTI coverage in an FTI 571 retrofitted waterbody. We hypothesize that there is a threshold value of coverage beyond which noteworthy improvement of hydraulic performance cannot be achieved. Therefore, it is crucial to 572 573 investigate the optimum FTI coverage in ponds and river channels to achieve maximum hydraulic 574 performance. It is also to be noted that FTI positioning is another key aspect of FTI systems. This is 575 touched on in several of the studies (Khan et al., 2013; Liu et al., 2019 and Xavier et al., 2018) and may assist in reducing coverage by appropriate positioning. 576

FTI Shape: The shape of FTI may affect the hydraulic performance of the system but this factor remains uninvestigated till now. The root zone of FTIs in a waterbody provides obstacle for flowing water as it occupies some spaces in the water column. Some water will pass through this obstacle based on the root porosity and some will be diverted from the root zone. It was demonstrated that in a pond, the shape and pattern of obstacles on the water can affect the flow path (Shih et al., 2016). Thus, FTI being an obstruction with varying porosity, the shape of FTI should have an impact on how

the water will be diverted by creating pathways for the flowing water according to the shape of waterbody and thus impacting its hydraulic performance. Hence, it can be proposed that FTI shape is a potential factor influencing the hydraulic performance of FTI retrofitted waterbodies and further investigation should be carried out on the degree of influence for different FTI shapes.

Waterbody Shape: Sabokrouhiyeh et al. (2017) investigated the impact of pond shape on its 587 hydraulic performance through numerical simulation. It was found that elliptical ponds have higher 588 detention time and more uniform velocity distribution compared to rectangular ponds. The presence 589 of dead zones is less prevalent in elliptical ponds than the rectangular ponds. It was also found that 590 591 an increase in aspect ratio (ratio of length to width of a pond) leads to a higher effective volume ratio (e) or reduces the presence of dead zones. The findings of this study (Sabokrouhiyeh et al., 2017) 592 593 imply that depending on the shape of the pond, optimum FTI positioning will also vary. As such, it can be proposed that waterbody shape is also another factor affecting FTI hydraulics. 594

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#### 596 5. CURRENT PRACTICES OF USING FTIS AT FIELD SCALE

Typical FTI configurations used in stormwater ponds, lakes, and rivers in different countries are listed in 597 Tables 3(a) and 3(b), respectively. All the FTI retrofitted ponds or lakes in Table 3(a) are for treating 598 599 stormwater where the flow rate depends on the runoff volume. Most of the waterbodies listed in Table 3(a) 600 are located in USA followed by Australia. These waterbodies were either rectangular (approximately) or irregular in shape. The surface area of the ponds and lakes varied between 100 and 26,000 m<sup>2</sup>. The median 601 602 surface area was 2,792 m<sup>2</sup>. The catchment area for FTI retrofitted ponds treating stormwater varied between 13,750 m<sup>2</sup> (1.375 ha) and 570,000 m<sup>2</sup> (57 ha). Aspect ratios (ratio of length to width) for most of the ponds 603 and lakes were not reported. The few reported aspect ratios ranged between 1 and 2.84. In most of these 604 waterbodies, the shape of FTI was rectangular. Some other shapes were also used, such as circular, kidney, 605 and hexagonal shapes. Irregular-shaped FTIs were not common but did occur in the study of Winston et al. 606 607 (2013). In a river channel in Singapore, a triangular-shaped FTI was used. Multiple FTIs were deployed in

most waterbodies, although some had only a single FTI. In most of the cases, FTI coverage was less than 608 10% of the total surface area. In a big lake, FTI coverage was as little as 0.2%. Conversely, one small pond 609 had 100% FTI coverage. FTI coverage area in rivers ranged between 39 and 786 m<sup>2</sup>. FTI vegetation density 610 in these studies varied between 3 and 30.2 plants/ $m^2$ , whereas the median vegetation density was 16.5 611 plants/m<sup>2</sup>. The water depth of the waterbodies varied between 0.75 and 2.5 m, while the median water depth 612 613 was 1.5 m. In several lab and field studies, maximum root length varied between 0.39 and 0.87 m (Borne et al., 2013a; Lynch et al., 2015; Wang et al., 2015; White and Cousins, 2013). It is recommended that water 614 level in a waterbody retrofitted with FTIs be maintained at a depth of at least 0.8 to 1.0 m to prevent the roots 615 616 from attaching to the sediments (Headley and Tanner, 2008). If FTI roots are attached to the bottom, it will not be able to float in variable water depth and can get submerged causing its destruction. Most of these 617 studies did not describe the inlet-outlet configuration of the ponds or lakes and potentially ignored the 618 hydraulic effect of installing FTIs. One of the stormwater ponds located in France had multiple inlets, but 619 they were not arranged in the way suggested by Khan et al. (2013). Multiple inlets (four) suggested by Khan 620 621 et al. (2013) were located on the same side of the pond; whereas, in the field study by Ladislas et al. (2014) in France, two inlets were located in two different sides of the pond at an approximately 90° angle. Other 622 studies had a single inlet and outlet placed on opposite ends of the pond along the centroidal axis. Among the 623 624 other features, one of the ponds used an artificial aerator for better treatment (Chang et al., 2013). The aerator was a fountain placed in the middle of the four FTIs, which formed a ring around the fountain. The fountain 625 blew the water into the air and thus the water was aerated. The aeration was confirmed by the increase of 626 627 nitrate nitrogen, which is a result of organic nitrogen converting into ammonia nitrogen, which then converts to nitrate nitrogen - all happens in the presence of oxygen. There were no short-circuiting prevention 628 629 mechanisms implemented in most of the ponds or rivers listed in Tables 3(a) and 3(b). Some of them had 630 such mechanisms as mentioned earlier in Section 3.4.

One of the limitations of our understanding of how effective current FTI designs and FTI retrofitted pond
 design configurations are in terms of hydraulic performance is the lack of dimensional analysis of laboratory

studies. Without a dimensional analysis, it is difficult to state that laboratory results will be applicable at a field scale (Xavier et al., 2018). Dynamic similarity is defined as the similarity of forces in the model and prototype (i.e. field-scale system). Both geometric and kinematic similarities should be maintained to achieve a true dynamic similarity of the system under investigation (Chanson, 2004). Geometric similarity is denoted by the ratios of model dimensions to the prototype dimensions (Eq. 33 and 34 for example):

$$\lambda_L = \frac{L_m}{L_p} \tag{33}$$

$$\lambda_A = \frac{A_m}{A_p} \qquad (34)$$

640 where  $\lambda_L$  is the scale factor for length, *L* is the length (m),  $\lambda_A$  is the scale factor for area, *A* is the area (m<sup>2</sup>), 641 and the suffixes *m* and *p* refer to the model and prototype, respectively.

The ratios of model flow parameters to prototype flow parameters, e.g., velocity and flow rate, are referred
to as kinematic similarity (Eq. 35 and 36, for example):

$$\lambda_{\nu} = \frac{U_m}{V_p} \tag{35}$$

$$\lambda_Q = \frac{Q_m}{Q_p} \tag{36}$$

646 where  $\lambda_{\nu}$  is the scale factor for velocity, *U* is the flow velocity (m/s),  $\lambda_Q$  is the scale factor for flow rate, and 647 *Q* is the flow rate (m<sup>3</sup>/s).

Dynamic similarity can also be represented using non-dimensional parameters such as the Reynolds number
(Eq. 37) and Froude number (Eq. 38).

650 
$$Re_m = \left(\frac{\rho U D_H}{\mu}\right)_m = \left(\frac{\rho U D_H}{\mu}\right)_p = Re_p \quad (37)$$

651 
$$F_m = \left(\frac{U}{\sqrt{gH}}\right)_m = \left(\frac{U}{\sqrt{gH}}\right)_p = F_p \qquad (38)$$

where *Re* is the Reynolds number (dimensionless),  $\rho$  is the density of water (kg/m<sup>3</sup>), *U* is the velocity of flow (m/s), *D<sub>H</sub>* is the hydraulic diameter (m), *F* is the Froude number (dimensionless), *g* is the gravitational acceleration (m/s<sup>2</sup>), and *H* is the depth of flow (m).

655 Xavier et al. (2018) conducted a numerical simulation of the model tank used by Khan et al. (2013) and then ran another simulation with the full-scale wetland maintaining flow similarity and obtained similar 656 657 results for model and full-scale wetlands. They used a geometric ratio of 1:10. It was stated by the authors that geometric and flow similarity confirmed the similarity of treatment performance between lab and field-658 scale FTI systems. But none of the FTI field studies have investigated the flow characteristics of the 659 660 waterbody and calculated the non-dimensional flow parameters listed above. However, it has been reported that wetlands including ponds and lakes are characterized by low Reynolds number (García et al., 2020; 661 Piercy, 2010; Schmid and Hengl, 2017; Shih et al., 2016), and therefore flow in FTI retrofitted ponds or lakes 662 can be considered to be laminar flow, i.e., Re < 2300 (Chow, 2008). In contrast, from the dimensions and 663 flow characteristics of the Khan et al. (2013) model tank, the Reynolds number was calculated to be 664 approximately 2,800, which falls in the transitional flow (2300 < Re < 3200) category in terms of Reynolds 665 number. The flow of the study was selected based on Froude number similarity, i.e., subcritical flow (F < 1), 666 which is typical for most open-channel flows. Despite Froude number similarity, the difference in flow 667 668 regimes based on Reynolds number may limit the applicability of the results of Khan et al. (2013). The same limitation holds for Xavier et al. (2018) since the numerical simulation was validated using the data of Khan 669 et al. (2013). 670

It is essential to match the flow characteristics of laboratory experiments based on field values and scale down the model tanks and FTIs representing prototype ponds and FTIs to ensure the results are valid at field scale. It is also of great importance to modify future FTI retrofitted pond design configurations based on the results of these experiments with dimensional analysis to ensure efficient treatment by FTIs. There is an information gap in this regard and future research should focus on this particular area. There is a maxim in 676 treatment wetland design that one cannot directly scale up the results of small-scale laboratory or mesocosm studies to the design of full-scale systems, which may raise suspicion on the need for dimensional analysis. 677 To clarify the doubt, two different things in the scaling up of results from model to prototype needs to be 678 understood: (1) hydraulics and (2) the treatment performance. Obviously, hydraulics will impact the 679 680 treatment performance but not the other way round. Dimensional analysis is done mainly for flow and 681 geometric parameters to ensure that the similarity in hydraulics is achieved in the laboratory-scale experiments with that of field-scale values. But in this instance, it is needed to understand the source of errors 682 for scaling up the laboratory results for treating wetlands in field scale. One of the sources of error, as 683 684 mentioned by Vymazal (2018), is the use of synthetic wastewater in laboratory experiments, which is more biodegradable than the actual wastewater or stormwater treated at field-scale. This lab-scale treatment 685 wetland may over-predict the treatment performances. Furthermore, in laboratory-scale wetlands, biofilm 686 growth is limited because experiments are usually conducted for a short period of time, which does not 687 replicate the actual biofilm growth in the field. Now the above-mentioned sources of errors are not related to 688 hydraulics and as such, are not applicable to the kind of analysis that is suggested in Section 5. 689

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Table 3 (a)

#### Table 3 (b)

#### 695 6. KNOWLEDGE GAPS AND FUTURE RESEARCH DIRECTIONS

696 **6.1 Investigation on Design Parameters** 

Discussions have been made in Section 4 on proven factors and potential factors affecting the hydraulic performance of FTI retrofitted waterbodies. There are numerous avenues where more research should be carried out to understand how those parameters influence hydraulic performance in different situations. For example, Ai et al. (2020) and Lei et al. (2014) studied the effect of vegetation density on inflow to the root 701 zone and velocity profile, respectively. However, it is difficult to correlate the terms ( $\varphi$  in Eq. 25, porosity) 702 used in those studies with the vegetation density ( $plants/m^2$ ) that the designers will use. Hence, experimented values should directly imply field scale vegetation density used by the designers. As mentioned earlier, 703 spacing between FTIs in parallel should be investigated in both ponds and river channels to help designers 704 selecting a suitable spacing to maximize hydraulic performance. Also, there is a discrepancy between the 705 706 findings of Khan et al. (2019) and Plew (2011) in terms of submergence depth ratio. It is to be noted that due to the flexibility of roots, bending of roots in the direction of flow will vary depending on flow velocity, slope 707 of the waterbody, type of plants, water temperature, etc., which makes it very difficult to reduce all the factors 708 709 into a single parameter and find the optimum. As such, robust modeling equations should be developed to reflect the real-world situation. Other potential factors such as inlet-outlet configuration, FTI coverage, FTI 710 shape, and waterbody shape as discussed in Section 4.2, which have been investigated for Constructed 711 Wetlands or ponds without FTIs should also be investigated for FTI retrofitted waterbodies. 712

713

#### 714 6.2 Dimensional Analysis

As discussed in previous sections, there is a paucity of information and discrepancies on flow characteristics 715 similarity in current studies on FTI retrofitted stormwater pond and lake, which limits the applicability of 716 717 those studies. For example, flow characteristics of Khan et al. (2013), Xavier et al. (2018), and Khan et al. (2019) were based on Froude number similarity and ignored Reynolds number similarity. Both Khan et al. 718 (2013) and Xavier et al. (2018) used a transitional flow ( $Re \sim 2800$ ) in terms of Reynolds number to conduct 719 720 experiments in ponds, whereas the flow regime in ponds is dominated by laminar flow. Khan et al. (2019) used a turbulent flow regime ( $Re \sim 4200$ ) in FTI retrofitted model pond. Furthermore, FTI coverage used by 721 722 Khan et al. (2013), Xavier et al. (2018), and Khan et al. (2019) was 15.3%, whereas the coverage in 75% of 723 the field studies in Table 3(a) was below 15% and the median value was 8%. The discrepancy between lab experiments and field-scale FTIs may lead to uncertainty in the applicability of the results of those studies. 724

As such, we recommend matching flow regimes both in terms of Froude number and Reynolds number and field-scale values of FTI design parameters (e.g., FTI coverage) in performing laboratory-scale experiments.

727

#### 728 **6.3 Effectiveness of Current SPM mechanisms**

Several short-circuit prevention mechanisms have been deployed (e.g., full-width FTI, full-coverage FTI, 729 730 impermeable baffle curtains), but their effectiveness has not been investigated. Future research can focus on the efficacy of these mechanisms and based on the results, new mechanisms can be explored. To prevent 731 hydraulic short-circuiting, the use of baffle curtains by Walker et al. (2017) was a novel approach, which was 732 733 supposed to minimize the disadvantage of having low FTI coverage. However, when the baffle curtains narrowed the channel in which the FTI was installed, velocity within the channel created by curtain likely 734 increased, thus decreasing the residence time of water within the root zone. Hence, it is a matter of 735 investigation that how much treatment efficiency is enhanced due to the use of baffle curtains. A control 736 experiment without the baffle curtains could do this. Additionally, it is to be noted that the installation and 737 maintenance of baffle curtains may also incur some additional costs. 738

739

#### 740 **6.4 Investigation on Modeling Parameters**

741 Since FTIs are retrofitted in existing ponds, it might be struggling to control or change a number of design configuration options. For example, changing the shape of pond including aspect ratio, altering positions of 742 inlet and outlet, keeping the depth of flow fixed are difficult due to land and financial requirements and the 743 744 nature of stormwater inflow. In this case, the objective should be to understand or predict how effective FTI retrofitting will be in that specific circumstance and how to exploit those few configurations that can be 745 746 manipulated, e.g., FTI coverage, vegetation density, shape of FTI, etc. This requires robust modeling tools 747 with a clear understanding of the key processes. As such, an understanding of current modeling techniques and their limitations will help to guide future research. The following sub-sections identify two important 748

modeling parameters that can help achieve higher prediction accuracies and realistic simulations of FTI
 retrofitted waterbodies.

751

#### 752 **6.4.1 Vegetation flexibility and buoyancy**

Previous modeling studies on FTI hydraulics in pond or river channel either represented the root zone as 753 a porous media or assumed rigid cylindrical stems, which do not account for flexibility of roots. Flexible 754 roots will bend in the direction of flow and buoyancy will try to lift the roots, which will reduce the effective 755 submergence ratio. In a pond where the flow is primarily laminar, the flexibility of roots is unlikely to have 756 757 an appreciable impact on modeling results due to low flow velocity. However, in a river channel where flow is mostly turbulent, roots are highly likely to bend substantially due to high flow velocity. Flow within 758 flexible vegetation differs from their rigid counterparts and such vegetation attributes cannot be ignored when 759 characterizing flow structure (Fathi-Moghadam et al., 2011; Huai et al., 2019, 2013; Liu et al., 2019). 760 Longitudinal and transverse mixing in pond with real emergent plants has been studied by Sonnenwald et al. 761 (2017b). The authors concluded that artificial rigid emergent vegetation was unable to simulate the mixing 762 and flow pattern of real vegetation. To date, there is no study modeling the flexibility of roots of an FTI 763 retrofitted in a river channel or pond. However, there are studies modeling the flexibility of submerged and 764 765 emergent plants, which mainly account for the flexibility of leaves or the upper part of a plant (Chen et al., 2011; Dijkstra and Uittenbogaard, 2010; Huai et al., 2013). Modeling the flexibility of roots of an FTI can 766 be inspired by those studies. For instance, Huai et al. (2013) used the bending moment theory to model 767 768 vegetation bending for open channel flow analysis with submerged vegetation (Supplementary Figure S1). To estimate the deflection of vegetation, the authors adopted the following equations and solved them through 769 770 iterative method.

771 
$$\sin\theta = \frac{P}{2EI} \left( \frac{z^3}{3h_v} - z^2 + zh_v \right)$$
(39)

$$P = \frac{\rho g i H}{m} \quad (40)$$

773 
$$s(h_{v}) = \int_{0}^{h_{v}} \sqrt{\frac{1}{1 - \left[\left(\frac{\rho g i H}{2mEI}\right)\left(\frac{z^{3}}{3h_{v}}\right) - z^{2} + zh_{v}\right]^{2}} dz}$$
(41)

774

where *P* is the total load on the vegetation stem normal to *z*-axis (N), *E* is the modulus of elasticity (N/m<sup>2</sup>), *I* is the moment of inertia (m<sup>4</sup>),  $h_v$  is the height of curved vegetation (m), *H* is the depth of flow (m), *s* is the length of curved vegetation (m),  $h_{v-s}$  is the height of straight vegetation stem (m).

778 Determining the height of deflected vegetation  $(h_v)$  requires an initial estimation of  $h_v$  and then iteration of 779 the value unless Equation 41 is solved. Huai et al. (2013) ignored the buoyant force of water in estimating the bending of vegetation for model simplicity. The buoyant force acting along the z-axis will help to lift the 780 781 vegetation height and as such, there will be less bending when it is considered into the calculation. Dijkstra 782 and Uittenbogaard (2010) considered the buoyant force in their study. However, the impact of buoyancy on 783 submerged vegetation and hanging roots will be completely different. As roots attached to the floating bed 784 hang from the water's surface, the buoyant force will lift the roots and thus reduce the effective length of 785 already bent roots. Future research can focus on modeling root flexibility, considering all the effects of all 786 forces in action.

787

#### 788 6.4.2 Submergence Depth Ratio

789 As mentioned in Section 4.2, the submergence depth ratio affects the hydraulic performance of FTIs 790 retrofitted waterbodies. Plew (2011) mentioned that velocity in the gap layer ( $U_b$ ) would be higher than the velocity in the root zone ( $U_c$ ) (Supplementary Figure S2). The opposite may happen, i.e.,  $U_c > U_b$ , if the 791 792 vegetation roots are sparsely located and bottom friction becomes greater than the root zone drag. Plew (2011) 793 found that at a high submergence depth ratio ( $h_c/H > 0.75$ ), bottom layer drag and shear between root zone layer and gap layer combined tend to restrict the velocity in the gap layer. It implies that when the 794 submergence ratio increases, inflow to the root zone increases. However, it has been mentioned that the gap 795 796 layer beneath the root zone plays a dual role by allowing the fluid to short-circuit below the root zone through <sup>797</sup> longitudinal advection, otherwise described as vertical short-circuiting and at the same time causing eddy <sup>798</sup> diffusion, which transports fluid vertically to the root zone from the gap layer (Li and Katul, 2020). The eddy <sup>799</sup> diffusion in the gap layer happens due to high velocity, which causes turbulence. Turbulent eddies may also <sup>800</sup> form due to bottom friction. Eddy diffusivity is expressed as given in Equation 42.

$$D_t = \frac{v_t}{s_c} \tag{42}$$

where  $v_t$  is turbulent viscosity (kg/m-s) and  $S_c$  is Schmidt number.

A value of unity for Schmidt number ( $S_c = 1$ ) is well accepted in the field of fluid mechanics. Xavier et al. (2018) also used  $S_c = 1$  in simulating tracer concentration. However, recent investigations have shown that the value of Schmidt number can deviate from unity, especially in the roughness sublayer of vegetation (Huang et al., 2015) and due to thermal stratification (Katul et al., 2016). Therefore, it is a matter of further investigation if a non-unity Schmidt number is applicable for FTI retrofitted waterbodies. Future research works can also focus on how eddy diffusion helps to prevent vertical short-circuiting and the role of the gap layer under the root zone.

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#### 811 7. CONCLUSIONS

Literature search revealed that there is a scarcity of studies on the hydraulics of FTI retrofitted waterbodies. Literature review on field-scale FTIs unfolded that hydraulic aspects were ignored in most of the studies, which implies that FTIs were operating at a lower efficiency. Review on available laboratory and numerical studies on FTI hydraulics identified the factors that may affect hydraulics of FTI retrofitted waterbodies. The following key conclusions are drawn from literature review on field, laboratory and numerical studies on the hydraulics of FTI retrofitted waterbodies:

Enhancement of hydraulic performance of the waterbody is paramount for higher treatment efficiency
 by an FTI. The hydraulic performance of FTI retrofitted waterbodies can potentially be improved if the
 FTI design configurations (e.g., shape and inlet-outlet configuration of the pond, FTI shape, FTI

821	coverage, FTI positioning, vegetation density, and submergence ratio) are derived through detailed
822	model experiments in the lab. Through proper dimensional analysis for similarity of model and
823	prototype, the design parameters may be replicated in the field trials.
824 •	Current practices of flow short-circuiting prevention mechanisms (e.g., full width FTI, full coverage
825	FTI, and impermeable curtains) may be undermined by short-circuiting below root zone, i.e. vertical
826	short-circuiting. As such, effectiveness of current short-circuiting prevention mechanisms should be
827	investigated in terms of hydraulic performance to ensure that vertical short-circuiting is not reducing
828	the treatment efficiency of FTI.
829 •	Since, FTIs are retrofitted in existing waterbodies, it might not be possible to change some of the design
830	configurations of the waterbody for improved hydraulic performance. In these cases, robust modeling
831	tools can help identify the best way of installing the FTIs in the waterbody. However, this requires
832	accurate modeling technique and development of modeling parameters to realistically model the
833	scenarios. This review paper identified that modeling parameters related to root flexibility and
834	turbulence due to root zone should be investigated to enhance the accuracy of existing modeling tools
835	capable of simulating FTI retrofitted waterbodies.
836	

## 837 List of Symbols

λ	hydraulic Efficiency
$\lambda_A$	scale factor for area
$\lambda_L$	scale factor for length
$\lambda_Q$	scale factor for discharge
$\lambda_V$	scale factor for velocity
A	area (m <sup>2</sup> )
а	frontal facing area of roots per unit bed area (m <sup>2</sup> )
С	concentration of the tracer measured at the outlet (mg/L)
$C_2$	inertial drag coefficient
$C_D$	drag coefficient
$D_H$	hydraulic diameter (m)
$D_{ij}$	dispersion coefficient
$D_t$	eddy diffusivity (kg/m-s)
е	effective volume ratio
E	modulus of elasticity (Nm <sup>-2</sup> )
$f_i$	vegetation drag force (N)
$F_m$	froude number
H	depth of flow (m)

$h_c$	length of root zone (m)
$h_g$	depth of water below root zone (m)
$h_v$	height of deflected vegetation (m)
$h_{v-s}$	height of straight vegetation (m)
Ι	moment of inertia (kgm <sup>2</sup> )
Kperm	permeability (m <sup>-2</sup> )
Ĺ	length (m)
M75-25	normalized time elapsed between $t_{75}$ and $t_{25}$
M <sub>90-10</sub>	normalized time elapsed between $t_{90}$ and $t_{10}$
$M_D$	dispersion index
$M_f$	first moment of normalized RTD curve
$M_I$	moment Index
$M_o$	morril Index
Ν	number of continuous stirred reactor
n	number of vegetation stems per unit bed area
Р	total load on vegetation due to fluid flow (N)
Pe	peclet number
Q	flow rate ( $m^3/min$ ).
Re	reynolds number
S	length of deflected vegetation (m)
$S_c$	schmidt number
$S_i$	initial detection time (min)
$S_5, S_{10}, S_{16},$	short-circuiting index for 5, 10, 16, 50,75 and 90 percent of tracer exit
$S_{50}, S_{75}, S_{90}$	
$t_c'$	normalized time to the centroid of the normalized RTD curve
<i>t<sub>HRT</sub></i>	nominal hydraulic residence time (min)
$t_{p1}$	time to the peak of RTD curve (min)
t <sub>RTD</sub>	mean residence time calculated using RTD curve (min)
t5, t10, t16, t50,	time when 5, 10, 16, 25, 50,75 and 90 percent of the tracer has flown out of the outlet
<i>t</i> <sub>75</sub> , <i>t</i> <sub>90</sub>	(min)
U	velocity (m/s)
$U_b$	velocity of fluid below root zone (m/sec)
$U_c$	velocity of fluid within root zone (m/sec)
$v_t$	turbulent viscosity (kg/m-s)
$V_w$	volume of waterbody (m <sup>3</sup> )
ρ	density of fluid (kg/m <sup>3</sup> )
$\sigma_{ heta}{}^2$	variance
$\varphi$	vegetation density (m <sup>2</sup> /m <sup>2</sup> )

### 839 List of Abbreviations

AC	Accords calamus
BMP	Best Management Practice
CA	Cyperus alternifolius
CFW	Constructed Floating Wetland
Chl-a	Chlorophyll-a
CI	Canna indica
COD	Chemical Oxygen Demand
FTI	Floating Treatment Island
HRT	Hydraulic Residence Time
IT	Iris tectorum
LID	Low Impact Development
MFC	Membrane Fuel Cell
PG	Pollutant in General
RTD	Residence Time Distribution
SPM	Short-Circuit Prevention Mechanism
TN	Total Nitrogen
TP	Total Phosphorus

VZ	Vetiveria	zizanoides	

WSUD Water Sensitive Urban Design

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- 846

#### 847 Conflict of Interest

- 848 The authors declare that there is no conflict of interest.
- 849

#### 850 References

- Abed, S.N., Almuktar, S.A., Scholz, M., 2017. Remediation of synthetic greywater in mesocosm—Scale floating
   treatment wetlands. Ecol. Eng. 102, 303–319.
- Ai, Y., Liu, M., Huai, W., 2020. Numerical investigation of flow with floating vegetation island. J. Hydrodyn. 32, 31–
  43.
- Al Mamun, A., Shams, S., Nuruzzaman, M., 2020. Review on uncertainty of the first-flush phenomenon in diffuse
   pollution control. Appl. Water Sci. 10, 1–10.
- Alam, M.Z., AHM, F.A., 2020. Nutrients adsorption onto biochar and alum sludge for treating stormwater. J. Water
   Environ. Technol. 18, 132–146.
- Alam, M.Z., Anwar, A.H.M.F., Heitz, A., 2018a. Stormwater solids removal characteristics of a catch basin insert using geotextile. Sci. Total Environ. 618, 1054–1063.
- Alam, M.Z., Anwar, A.H.M.F., Heitz, A., Sarker, D.C., 2018b. Improving stormwater quality at source using catch
   basin inserts. J. Environ. Manage. 228, 393–404.
- Alam, M.Z., Anwar, A.H.M.F., Sarker, D.C., Heitz, A., Rothleitner, C., 2017. Characterising stormwater gross
   pollutants captured in catch basin inserts. Sci. Total Environ. 586, 76–86.
- ANSYS Inc., 2016. CFX-Pre Users Guide Release 17.0. Ansys Inc.
- ANSYS Inc., 2015. User's Guide Release 16.1. ANSYS Fluent Theory Guide. 17.0.
- ANSYS Inc., 2013. Release 15. ANSYS Fluent Theory Guide.
- 868 Bensch, G., Grimm, M., Peters, J., 2015. Why do households forego high returns from technology adoption? Evidence cooking 869 from improved stoves in Burkina Faso. J. Econ. Behav. Organ. 116. https://doi.org/10.1016/j.jebo.2015.04.023 870
- Bi, R., Zhou, C., Jia, Y., Wang, S., Li, P., Reichwaldt, E.S., Liu, W., 2019. Giving waterbodies the treatment they need:
  A critical review of the application of constructed floating wetlands. J. Environ. Manage. 238, 484–498.
- Bodin, H., Mietto, A., Ehde, P.M., Persson, J., Weisner, S.E.B., 2012. Tracer behaviour and analysis of hydraulics in
  experimental free water surface wetlands. Ecol. Eng. 49, 201–211.
- Bodin, H., Persson, J., Englund, J.-E., Milberg, P., 2013. Influence of residence time analyses on estimates of wetland
  hydraulics and pollutant removal. J. Hydrol. 501, 1–12.

- Borne, K.E., Fassman, E.A., Tanner, C.C., 2013a. Floating treatment wetland retrofit to improve stormwater pond
  performance for suspended solids, copper and zinc. Ecol. Eng. 54, 173–182.
- Borne, K.E., Tanner, C.C., Fassman-Beck, E.A., 2013b. Stormwater nitrogen removal performance of a floating
   treatment wetland. Water Sci. Technol. 68, 1657–1664.
- Bouchez, J., Lajeunesse, E., Gaillarde, J., France-Lanord, C., Dutra-Maia, P., Maurice, L., Gualtieri, C., 2011.
  Turbulent mixing in the Amazon River: The isotopic memory of confluences. Earth and Planetary Science Letters,
  290 (2010), pp. 37–43. Earth Planet. Sci. Lett. 311, 448–450.
- Boulet, M., Ghafoori, E., Jorgensen, B.S., Smith, L.D.G., 2017. Behaviour change: Trialling a novel approach to reduce
   industrial stormwater pollution. J. Environ. Manage. 204, 272–281.
- Brown, R.R., Farrelly, M.A., Loorbach, D.A., 2013. Actors working the institutions in sustainability transitions: The
   case of Melbourne's stormwater management. Global Environ Chang. 23, 701–718.
- Bu, F., Xu, X., 2013. Planted floating bed performance in treatment of eutrophic river water. Environ. Monit. Assess.
   185, 6369–9651.
- Chance, L.M.G., White, S.A., 2018. Aeration and plant coverage influence floating treatment wetland remediation
   efficacy. Ecol. Eng. 122, 62–68.
- Chang, N.-B., Xuan, Z., Marimon, Z., Islam, K., Wanielista, M.P., 2013. Exploring hydrobiogeochemical processes of
   floating treatment wetlands in a subtropical stormwater wet detention pond. Ecol. Eng. 54, 66–76.
- Chang, T.-J., Chang, Y.-S., Lee, W.-T., Shih, S.-S., 2016. Flow uniformity and hydraulic efficiency improvement of
   deep-water constructed wetlands. Ecol. Eng. 92, 28–36.
- Chang, Y., Cui, H., Huang, M., He, Y., 2017. Artificial floating islands for water quality improvement. Environ. Rev.
   25, 350–357.
- 898 Chanson, H., 2004. Hydraulics of open channel flow. Elsevier.
- Chen, L., Stone, M.C., Acharya, K., Steinhaus, K.A., 2011. Mechanical analysis for emergent vegetation in flowing
   fluids. J. Hydraul. Res. 49, 766–774.
- 901 Cheng, W., Sun, Z., Liang, S., 2019. Numerical simulation of flow through suspended and submerged canopy. Adv.
   902 Water Resour. 127, 109–119.
- Choi, S.-U., Kang, H., 2016. Characteristics of mean flow and turbulence statistics of depth-limited flows with
   submerged vegetation in a rectangular open-channel. J. Hydraul. Res. 54, 527–540.
- 905 Chow, V. Te, 2008. Open-channel hydraulics. Caldwell.
- Chua, L.H.C., Tan, S.B.K., Sim, C.H., Goyal, M.K., 2012. Treatment of baseflow from an urban catchment by a floating wetland system. Ecol. Eng. 49, 170–180.
- Colares, G.S., Dell'Osbel, N., Wiesel, P.G., Oliveira, G.A., Lemos, P.H.Z., da Silva, F.P., Lutterbeck, C.A., Kist, L.T.,
   Machado, Ê.L., 2020. Floating treatment wetlands: A review and bibliometric analysis. Sci. Total Environ. 714,
   136776.
- Daly, E., Deletic, A., Hatt, B.E., Fletcher, T.D., 2012. Modelling of stormwater biofilters under random hydrologic
   variability: a case study of a car park at Monash University, Victoria (Australia). Hydrol. Process. 26, 3416–6087.
- 913 Danckwerts, P. V, 1953. Continuous flow systems: distribution of residence times. Chem. Eng. Sci. 2, 1–13.
- De Stefani, G., Tocchetto, D., Salvato, M., Borin, M., 2011. Performance of a floating treatment wetland for in-stream
   water amelioration in NE Italy. Hydrobiologia 674, 157–167.
- Dijkstra, J.T., Uittenbogaard, R.E., 2010. Modeling the interaction between flow and highly flexible aquatic vegetation.
   Water Resour. Res. 46.
- Downing- Kunz, M.A., Stacey, M.T., 2012. Observations of mean and turbulent flow structure in a free- floating
   macrophyte root canopy. Limnol. Oceanogr. Fluids Environ. 2, 67–79.
- Dunqiu, W., Shaoyuan, B., Mingyu, W., Qinglin, X., Yinian, Z., Hua, Z., 2012. Effect of artificial aeration,
   temperature, and structure on nutrient removal in constructed floating islands. Water Environ. Res. 84, 405–410.

- Fang, T., Bao, S., Sima, X., Jiang, H., Zhu, W., Tang, W., 2016. Study on the application of integrated eco-engineering
   in purifying eutrophic river waters. Ecol. Eng. 94, 320–328.
- Farjood, A., Melville, B.W., Shamseldin, A.Y., Adams, K.N., Khan, S., 2015. Evaluation of hydraulic performance
  indices for retention ponds. Water Sci. Technol. 72, 10–21.
- Fathi-Moghadam, M., Drikvandi, K., Lashkarara, B., Hammadi, K., 2011. Determination of friction factor for rivers
  with non-submerged vegetation in banks and floodplains. Sci. Res. Essays 6, 4714–4719.
- Fu, X., Wang, F., Liu, M., Huai, W., 2020. Analysis of turbulent flow structures in the straight rectangular open channel
   with floating vegetated islands. Environ. Sci. Pollut. Res. 27, 26856–26867.
- García, J., Solimeno, A., Zhang, L., Marois, D., Mitsch, W.J., 2020. Constructed wetlands to solve agricultural drainage
   pollution in South Florida: Development of an advanced simulation tool for design optimization. J. Clean. Prod.
   258, 120868.
- Gimbert, F., Tsai, V.C., Lamb, M.P., 2014. A physical model for seismic noise generation by turbulent flow in rivers.
  J. Geophys. Res. Earth Surf. 119, 2209–2238.
- Goonetilleke, A., Lampard, J.-L., 2019. Stormwater quality, pollutant sources, processes, and treatment options, in:
   Approaches to Water Sensitive Urban Design. Elsevier, pp. 49–74.
- Goonetilleke, A., Liu, A., Managi, S., Wilson, C., Gardner, T., Bandala, E.R., Walker, L., Holden, J., Wibowo, M.A.,
  Suripin, S., 2017. Stormwater reuse, a viable option: Fact or fiction? Econ. Anal. Policy 56, 14–17.
- Guo, C., Cui, Y., Luo, Y., 2020. Response of solute transport model parameters to the combination of multiple design
   parameters and their quantitative expression with hydraulic indicators of FWS-constructed wetlands. Environ.
   Sci. Pollut. Res. 27, 43283–43295.
- Guo, C.Q., Dong, B., Liu, J.J., Liu, F.P., 2015. The best indicator of hydraulic short-circuiting and mixing of
   constructed wetlands. Water Pract. Technol. 10, 505–516.
- Headley, T.R., Tanner, C.C., 2012. Constructed wetlands with floating emergent macrophytes: an innovative
   stormwater treatment technology. Crit. Rev. Environ. Sci. Technol. 42, 2261–2310.
- Headley, T.R., Tanner, C.C., 2008. Floating treatment wetlands: an innovative option for stormwater quality
   applications, in: 11th International Conference on Wetland Systems for Water Pollution Control, Indore, India.
- Hu, G.-J., Zhou, M., Hou, H.-B., Zhu, X., Zhang, W.-H., 2010. An ecological floating-bed made from dredged lake
   sludge for purification of eutrophic water. Ecol. Eng. 36, 1448–1458.
- Huai, W., Hu, Y., Zeng, Y., Han, J., 2012. Velocity distribution for open channel flows with suspended vegetation.
   Adv. Water Resour. 49, 56–61.
- Huai, W., Wang, W., Zeng, Y., 2013. Two-layer model for open channel flow with submerged flexible vegetation. J.
  Hydraul. Res. 51, 708–718.
- Huai, W., Zhang, J., Katul, G.G., Cheng, Y., Tang, X., Wang, W., 2019. The structure of turbulent flow through
  submerged flexible vegetation. J. Hydrodyn. 31, 274–292.
- Huang, C.W., Lin, M.Y., Khlystov, A., Katul, G.G., 2015. The effects of leaf size and microroughness on the branch scale collection efficiency of ultrafine particles. J. Geophys. Res. Atmos. 120, 3370–3385.
- Huber, M., Welker, A., Helmreich, B., 2016. Critical review of heavy metal pollution of traffic area runoff: Occurrence,
   influencing factors, and partitioning. Sci. Total Environ. 541, 895–9697.
- Jayarathne, A., Egodawatta, P., Ayoko, G.A., Goonetilleke, A., 2017. Geochemical phase and particle size relationships
   of metals in urban road dust. Environ. Pollut. 230, 218–226.
- Jones, T.G., Willis, N., Gough, R., Freeman, C., 2017. An experimental use of floating treatment wetlands (FTWs) to
   reduce phytoplankton growth in freshwaters. Ecol. Eng. 99, 316–323.
- Kadlec, R.H., 1994. Detention and mixing in free water wetlands. Ecol. Eng. 3, 345–380.
- 965 Kadlec, R.H., Wallace, S., 2008. Treatment wetlands. CRC press.
- 966 Katul, G.G., Li, D., Liu, H., Assouline, S., 2016. Deviations from unity of the ratio of the turbulent Schmidt to Prandtl

- numbers in stratified atmospheric flows over water surfaces. Phys. Rev. Fluids 1, 34401.
- Khan, S., Melville, B.W., Shamseldin, A., 2013. Design of storm-water retention ponds with floating treatment
  wetlands. J. Environ. Eng. 139, 1343–1349.
- Khan, S., Shoaib, M., Khan, M.M., Melville, B.W., Shamseldin, A.Y., 2019. Hydraulic investigation of the impact of
   retrofitting floating treatment wetlands in retention ponds. Water Sci. Technol. 80, 1476–1484.
- Kumari, M., Tripathi, B.D., 2014. Effect of aeration and mixed culture of Eichhornia crassipes and Salvinia natans on
   removal of wastewater pollutants. Ecol. Eng. 62, 48–53.
- Kusin, F.M., Jarvis, A.P., Gandy, C.J., 2014. Hydraulic performance and iron removal in wetlands and lagoons treating
   ferruginous coal mine waters. Wetlands 34, 555–564.
- Ladislas, S., Gerente, C., Chazarenc, F., Brisson, J., Andres, Y., 2015. Floating treatment wetlands for heavy metal
   removal in highway stormwater ponds. Ecol. Eng. 80, 85–91.
- Lai, W.-L., Wang, S.-Q., Peng, C.-L., Chen, Z.-H., 2011. Root features related to plant growth and nutrient removal of
   35 wetland plants. Water Res. 45, 3941–3950.
- Laurent, J., Bois, P., Nuel, M., Wanko, A., 2015. Systemic models of full-scale Surface Flow Treatment Wetlands:
   Determination by application of fluorescent tracers. Chem. Eng. J. 264, 389–398.
- LeFevre, G.H., Paus, K.H., Natarajan, P., Gulliver, J.S., Novak, P.J., Hozalski, R.M., 2014. Review of dissolved pollutants in urban storm water and their removal and fate in bioretention cells. J. Environ. Eng. 141 (1), 04014050.
- Lei, R.A.O., Wang, P.-F., Yang, L.E.I., Chao, W., 2016. Coupling of the flow field and the purification efficiency in root system region of ecological floating bed under different hydrodynamic conditions. J. Hydrodyn. Ser. B 28, 1049–1057.
- Levenspiel, O., Bischoff, K.B., 1964. Patterns of flow in chemical process vessels, in: Advances in Chemical
   Engineering. Elsevier, pp. 95–198.
- Li, S., Katul, G., 2020. Contaminant removal efficiency of floating treatment wetlands. Environ. Res. Lett. 15, 1040b7.
- Li, X.-N., Song, H.-L., Li, W., Lu, X.-W., Nishimura, O., 2010. An integrated ecological floating-bed employing plant,
   freshwater clam and biofilm carrier for purification of eutrophic water. Ecol. Eng. 36, 382–390.
- Lightbody, A.F., Nepf, H.M., Bays, J.S., 2009. Modeling the hydraulic effect of transverse deep zones on the
   performance of short-circuiting constructed treatment wetlands. Ecol. Eng. 35, 754–768.
- Liu, A., Guan, Y., Egodawatta, P., Goonetilleke, A., 2016. Selecting rainfall events for effective water sensitive urban
   design: A case study in Gold Coast City, Australia. Ecol. Eng. 92, 67–72.
- Liu, C., Shan, Y., Lei, J., Nepf, H., 2019. Floating treatment islands in series along a channel: the impact of island
   spacing on the velocity field and estimated mass removal. Adv. Water Resour.
- Liu, Y., Engel, B.A., Flanagan, D.C., Gitau, M.W., McMillan, S.K., Chaubey, I., 2017. A review on effectiveness of
  best management practices in improving hydrology and water quality: Needs and opportunities. Sci. Total
  Environ. 601, 580–9697.
- Lucke, T., Walker, C., Beecham, S., 2019. Experimental designs of field-based constructed floating wetland studies:
   A review. Sci. Total Environ.
- Lynch, J., Fox, L.J., Owen Jr, J.S., Sample, D.J., 2015. Evaluation of commercial floating treatment wetland
   technologies for nutrient remediation of stormwater. Ecol. Eng. 75, 61–69.
- Masters, B., 2012. The ability of vegetated floating Islands to improve water quality in natural and constructed
   wetlands: a review. Water Prac. and Tech. 7 (1).
- McAndrew, B., Ahn, C., Spooner, J., 2016. Nitrogen and sediment capture of a floating treatment wetland on an urban
   stormwater retention pond—the case of the rain project. Sustainability 8, 972.
- Maxwell, B., Winter, D., Birgand, F., 2020. Floating treatment wetland retrofit in a stormwater wet pond provides
   limited water quality improvements. Ecol. Eng. 149, 105784.

- Mihailović, D.T., Nikolić-Đorić, E., Drešković, N., Mimić, G., 2014. Complexity analysis of the turbulent
   environmental fluid flow time series. Phys. A Stat. Mech. Its Appl. 395, 96–104.
- Nichols, P., Lucke, T., Drapper, D., Walker, C., 2016. Performance evaluation of a floating treatment wetland in an
   urban catchment. Water 8, 244.
- Ning, D., Huang, Y., Pan, R., Wang, F., Wang, H., 2014. Effect of eco-remediation using planted floating bed system
  on nutrients and heavy metals in urban river water and sediment: a field study in China. Sci. Total Environ. 485,
  596–603.
- Olguín, E.J., Sánchez-Galván, G., Melo, F.J., Hernández, V.J., González-Portela, R.E., 2017. Long-term assessment at
   field scale of Floating Treatment Wetlands for improvement of water quality and provision of ecosystem services
   in a eutrophic urban pond. Sci. Total Environ. 584, 561–571.
- Pandey, P.K., van der Zaag, P., Soupir, M.L., Singh, V.P., 2013. A new model for simulating supplemental irrigation
  and the hydro-economic potential of a rainwater harvesting system in humid subtropical climates. Water Resour.
  Manag. 27, 3145–3164.
- Pavlineri, N., Skoulikidis, N.T., Tsihrintzis, V.A., 2017. Constructed floating wetlands: a review of research, design,
   operation and management aspects, and data meta-analysis. Chem. Eng. J. 308, 1120–1132.
- Persson, J., Somes, N.L.G., Wong, T.H.F., 1999. Hydraulics efficiency of constructed wetlands and ponds. Water Sci.
   Technol. 40, 291–300.
- Persson, J., Wittgren, H.B., 2003. How hydrological and hydraulic conditions affect performance of ponds. Ecol. Eng.
   21, 259–269.
- 1031 Piercy, C.D., 2010. Hydraulic Resistance due to Emergent Wetland Vegetation.
- Piro, P., Carbone, M., 2014. A modelling approach to assessing variations of total suspended solids (TSS) mass fluxes
   during storm events. Hydrol. Process. 28, 2419–2426.
- Plew, D.R., 2011. Depth-averaged drag coefficient for modeling flow through suspended canopies. J. Hydraul. Eng.
   137, 234–247.
- Rao, L., Qian, J., Ao, Y., 2014. Influence of artificial ecological floating beds on river hydraulic characteristics. J.
   Hydrodyn. 26, 474–481.
- Rehman, I.H., Kar, A., Banerjee, M., Kumar, P., Shardul, M., Mohanty, J., Hossain, I., 2012. Understanding the political economy and key drivers of energy access in addressing national energy access priorities and policies. Energy Policy 47, 27–37.
- Revitt, D.M., Shutes, R.B.E., Llewellyn, N.R., Worrall, P., 1997. Experimental reedbed systems for the treatment of
   airport runoff. Water Sci. Technol. 36, 385–390.
- Rezania, S., Taib, S.M., Din, M.F.M., Dahalan, F.A., Kamyab, H., 2016. Comprehensive review on phytotechnology:
   heavy metals removal by diverse aquatic plants species from wastewater. J. Hazard. Mater. 318, 587–599.
- Sabokrouhiyeh, N., Bottacin-Busolin, A., Savickis, J., Nepf, H., Marion, A., 2017. A numerical study of the effect of
   wetland shape and inlet-outlet configuration on wetland performance. Ecol. Eng. 105, 170–179.
- Saeed, T., Al-Muyeed, A., Afrin, R., Rahman, H., Sun, G., 2014. Pollutant removal from municipal wastewater
   employing baffled subsurface flow and integrated surface flow-floating treatment wetlands. J. Environ. Sci. 26,
   726–736.
- Saeed, T., Majed, N., Khan, T., Mallika, H., 2019. Two-stage constructed wetland systems for polluted surface water
   treatment. J. Environ. Manage. 249, 109379.
- Saeed, T., Paul, B., Afrin, R., Al-Muyeed, A., Sun, G., 2016. Floating constructed wetland for the treatment of polluted
   river water: A pilot scale study on seasonal variation and shock load. Chem. Eng. J. 287, 62–73.
- Samal, K., Kar, S., Trivedi, S., 2019. Ecological floating bed (EFB) for decontamination of polluted water bodies:
   Design, mechanism and performance. J. Environ. Manage. 251, 109550.
- 1056 Sauer, E.P., VandeWalle, J.L., Bootsma, M.J., McLellan, S.L., 2011. Detection of the human specific Bacteroides

- genetic marker provides evidence of widespread sewage contamination of stormwater in the urban environment.
   Water Res. 45, 1354–4081.
- Schmid, B.H., Hengl, M.A., 2017. Salt tracer experiments in wetland ponds: will density stratification spoil the
   outcome?, in: EGU General Assembly Conference Abstracts. p. 2314.
- Schwammberger, P., Walker, C., Lucke, T., 2017. Using floating wetland treatment systems to reduce stormwater
   pollution from urban developments. Int. J. GEOMATE 12, 45–50.
- Schwammberger, P.F., Lucke, T., Walker, C., Trueman, S.J., 2019. Nutrient uptake by constructed floating wetland
   plants during the construction phase of an urban residential development. Sci. Total Environ. 677, 390–403.
- Schwammberger, P.F., Yule, C.M., Tindale, N.W., 2020. Rapid plant responses following relocation of a constructed floating wetland from a construction site into an urban stormwater retention pond. Sci. Total Environ. 699, 134372.
- Seeger, E.M., Maier, U., Grathwohl, P., Kuschk, P., Kaestner, M., 2013. Performance evaluation of different horizontal
   subsurface flow wetland types by characterization of flow behavior, mass removal and depth-dependent
   contaminant load. Water Res. 47, 769–780.
- Shahid, M.J., Arslan, M., Ali, S., Siddique, M., Afzal, M., 2018. Floating wetlands: a sustainable tool for wastewater
   treatment. CLEAN–Soil, Air, Water 46, 1800120.
- Shih, S.-S., Kuo, P.-H., Fang, W.-T., LePage, B.A., 2013. A correction coefficient for pollutant removal in free water
   surface wetlands using first-order modeling. Ecol. Eng. 61, 200–206.
- Shih, S.-S., Hong, S.-S., Chang, T.-J., 2016. Flume experiments for optimizing the hydraulic performance of a deep water wetland utilizing emergent vegetation and obstructions. Water 8, 265.
- Sidhu, J.P.S., Hodgers, L., Ahmed, W., Chong, M.N., Toze, S., 2012. Prevalence of human pathogens and indicators
   in stormwater runoff in Brisbane, Australia. water Res. 46, 1354–6652.
- Sonnenwald, F, Guymer, I., Stovin, V., 2019a. A CFD- based mixing model for vegetated flows. Water Resour. Res.
   55, 2322–2347.
- Sonnenwald, F., Hart, J.R., West, P., Stovin, V.R., Guymer, I., 2017a. Transverse and longitudinal mixing in real
   emergent vegetation at low velocities. Water Resour. Res. 53, 961–978.
- Sonnenwald, Fred, Stovin, V., Guymer, I., 2019b. Estimating drag coefficient for arrays of rigid cylinders representing
   emergent vegetation. J. Hydraul. Res. 57, 591–597.
- Sonnenwald, F., Stovin, V., Guymer, I., 2016a. Computational fluid dynamics modelling of a vegetated stormwater
   pond, in: 11th International Symposium on Ecohydraulics (ISE 2016). Engineers Australia, p. 271.
- Sonnenwald, F., Stovin, V., Guymer, I., 2016b. Feasibility of the porous zone approach to modelling vegetation in
   CFD, in: Hydrodynamic and Mass Transport at Freshwater Aquatic Interfaces. Springer, pp. 63–75.
- Sonnenwald, F.C., Guymer, I., Stovin, V., 2017b. Computational fluid dynamics modelling of residence times in vegetated stormwater ponds, in: Proceedings of the Institution of Civil Engineers. Water Management. Thomas Telford.
- Stovin, V.R., Grimm, J.P., Lau, S.-T.D., 2008. Solute transport modeling for urban drainage structures. J. Environ.
   Eng. 134, 640–650.
- Tanino, Y., Nepf, H.M., 2008. Laboratory investigation of mean drag in a random array of rigid, emergent cylinders.
   J. Hydraul. Eng. 134, 34–41.
- Taylor, A.C., Fletcher, T.D., 2007. Nonstructural urban stormwater quality measures: building a knowledge base to
   improve their use. Environ. Mange. 39, 663–677.
- Teixeira, E.C., do Nascimento Siqueira, R., 2008. Performance assessment of hydraulic efficiency indexes. J. Environ.
   Eng. 134, 851–859.
- 1100 Temam, R., 2001. Navier-Stokes equations: theory and numerical analysis. American Mathematical Soc.
- 1101 Tharp, R., Westhelle, K., Hurley, S., 2019. Macrophyte performance in floating treatment wetlands on a suburban

- stormwater pond: Implications for cold climate conditions. Ecol. Eng. 136, 152–159.
- Thackston, E.L., Shields Jr, F.D., Schroeder, P.R., 1987. Residence time distributions of shallow basins. J. Environ.
   Eng. 113, 1319–1332.
- Tinoco, R.O., Cowen, E.A., 2013. The direct and indirect measurement of boundary stress and drag on individual and
   complex arrays of elements. Exp. Fluids 54, 1–16.
- Urakawa, H., Dettmar, D.L., Thomas, S., 2017. The uniqueness and biogeochemical cycling of plant root microbial
   communities in a floating treatment wetland. Ecol. Eng. 108, 573–580.
- 1109 Vázquez-Burney, R., Bays, J., Messer, R., Harris, J., 2015. Floating wetland islands as a method of nitrogen mass
   1110 reduction: results of a 1 year test. Water Sci. Technol. 72, 704–710.
- 1111 Vymazal, J., 2018. Do laboratory scale experiments improve constructed wetland treatment technology?
- Wahl, M.D., Brown, L.C., Soboyejo, A.O., Martin, J., Dong, B., 2010. Quantifying the hydraulic performance of treatment wetlands using the moment index. Ecol. Eng. 36, 1691–1699.
- Walker, C., Tondera, K., Lucke, T., 2017. Stormwater treatment evaluation of a constructed floating wetland after two
   years operation in an urban catchment. Sustainability 9, 1687.
- Wang, C.-Y., Sample, D.J., Day, S.D., Grizzard, T.J., 2015. Floating treatment wetland nutrient removal through
   vegetation harvest and observations from a field study. Ecol. Eng. 78, 15–26.
- Wei, F., Shahid, M.J., Alnusairi, G.S.H., Afzal, M., Khan, A., El-Esawi, M.A., Abbas, Z., Wei, K., Zaheer, I.E.,
  Rizwan, M., 2020. Implementation of Floating Treatment Wetlands for Textile Wastewater Management: A
  Review. Sustainability 12, 5801.
- West, M., Fenner, N., Gough, R., Freeman, C., 2017. Evaluation of algal bloom mitigation and nutrient removal in
   floating constructed wetlands with different macrophyte species. Ecol. Eng. 108, 581–588.
- White, S.A., Cousins, M.M., 2013. Floating treatment wetland aided remediation of nitrogen and phosphorus from
   simulated stormwater runoff. Ecol. Eng. 61, 207–215.
- Wijesiri, B., Liu, A., Jayarathne, A., Duodu, G., Ayoko, G.A., Chen, L., Goonetilleke, A., 2020. Influence of the
  hierarchical structure of land use on metals, nutrients and organochlorine pesticides in urban river sediments.
  Ecol. Eng. 159, 106123.
- Williams, M.D., Reimus, P., Vermeul, V.R., Rose, P., Dean, C.A., Watson, T.B., Newell, D., Leecaster, K., Brauser,
  E., 2013. Development of models to simulate tracer tests for characterization of Enhanced Geothermal Systems.
  Pacific Northwest National Lab.(PNNL), Richland, WA (United States).
- Winston, R.J., Hunt, W.F., Kennedy, S.G., Merriman, L.S., Chandler, J., Brown, D., 2013. Evaluation of floating
   treatment wetlands as retrofits to existing stormwater retention ponds. Ecol. Eng. 54, 254–265.
- Wu, Q., Hu, Y., Li, S., Peng, S., Zhao, H., 2016. Microbial mechanisms of using enhanced ecological floating beds for
   eutrophic water improvement. Bioresource Technol. 211, 451–456.
- Xavier, M.L.M., Janzen, J.G., 2017. Effects of inlet momentum and orientation on the hydraulic performance of water
   storage tanks. Appl. Water Sci. 7, 2545–2557.
- Xavier, M.L.M., Janzen, J.G., Nepf, H., 2018. Numerical modeling study to compare the nutrient removal potential of different floating treatment island configurations in a stormwater pond. Ecol. Eng. 111, 78–84.
- Yeh, N., Yeh, P., Chang, Y.-H., 2015. Artificial floating islands for environmental improvement. Renew. Sustain.
   Energy Rev. 47, 616–622.
- Zhang, J., Liu, B., Zhou, X., Chu, J., Li, Y., Wang, M., 2015. Effects of emergent aquatic plants on abundance and community structure of ammonia-oxidising microorganisms. Ecol. Eng. 81, 504–513.
- Zhao, F., Xi, S., Yang, X., Yang, W., Li, J., Gu, B., He, Z., 2012. Purifying eutrophic river waters with integrated floating island systems. Ecol. Eng. 40, 53–60.

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# **Tables**

Phenomena	Hydraulic Performance	Equation	Implications of value	Reference		
Short- Circuiting	Initial detection time $(S_i)$	First time tracer is detected at the outlet	$S_i \rightarrow 0$ sec: High short- circuiting	(Farjood et al., 2015; Thackston et al. 1987)		
	Short-circuiting index $(S_5)$	$S_5 = 1 - \frac{t_5}{t_{HRT}}  (2)$ $t_{HRT} = \frac{V_w}{Q}  (3)$	$S_5 \rightarrow 0$ : High short- circuiting $S_5 \rightarrow 1$ : No short- circuiting	(Farjood et al., 2015)		
	Short-circuiting index $(S_{10})$	$S_{10} = 1 - \frac{t_{10}}{t_{HRT}}  (4)$	$S_{10} \rightarrow 0$ : High short- circuiting $S_{10} \rightarrow 1$ : No short- circuiting	(Guo et al., 2015; Thackston et al., 1987)		
	Short-circuiting index $(S_{16})$	$S_{16} = 1 - \frac{t_{16}}{t_{HRT}}  (5)$	$S_{16} \rightarrow 0$ : High short- circuiting $S_{16} \rightarrow 1$ : No short- circuiting	(Khan et al., 2013; Ta and Brignal, 1998)		
	Short-circuiting index (S <sub>50</sub> )	$S_{50} = 1 - \frac{t_{50}}{t_{HRT}}  (6)$	$S_{50} \rightarrow 0$ : High short- circuiting $S_{50} \rightarrow 1$ : No short- circuiting	(Guo et al., 2015; Stovin et al., 2008; Thackston et al., 1987)		
Mixing	Morril index $(t_{90}/t_{10})$	$M_o = \frac{t_{90}}{t_{10}}$ (7)	$M_o \rightarrow 1$ : Plug flow $M_o > 1$ : Mixing	(Farjood et al., 2015; Teixeira and do Nascimento Siqueira, 2008; Thackston et al., 1987)		
	Time elapsed between $t_{10}$ and $t_{90}$ ( $M_{90-10}$ )	$M_{90-10} = \frac{t_{90} - t_{10}}{t_{HRT}}  (8)$	$M_{90-10} \rightarrow 0$ : Plug flow $M_{90-10} > 0$ : Mixing	(Farjood et al., 2015; Stamou and Noutsopoulos, 1994)		
	Time elapsed between $t_{25}$ and $t_{75}$ ( $M_{75-25}$ )	$M_{75-25} = \frac{t_{75} - t_{25}}{t_{HRT}}  (9)$	$M_{75-25} \to 0$ : Plug flow $M_{75-25} > 0$ : Mixing	(Farjood et al., 2015; Stamou and Noutsopoulos, 1994)		
	Dispersion index $(M_D)$	$M_D = \frac{\sigma_{\theta}^2}{t_{RTD}^2}  (10)$ $t_{RTD} = \frac{\int_0^\infty tCdt}{c^\infty att}  (11)$	$M_D \rightarrow 0$ : Plug flow $M_D \rightarrow 1$ : Completely mixed	(Teixeira and do Nascimento Siqueira, 2008; Thackston et al.,		
	Variance $(\sigma_{\theta}^2)$	$\sigma_{\theta}^{2} = \frac{\int_{0}^{\infty} t^{2}Cdt}{t_{RTD}^{2} \int_{0}^{\infty} Cdt} - 1  (12)$	$\sigma_{\theta}^2 \rightarrow 0$ : Plug flow $\sigma_{\theta}^2 \rightarrow 1$ : Completely mixed	1987) (Guo et al., 2015; Thackston et al., 1987)		
	Number of CSTR in series ( <i>N</i> )	$N = \frac{t_{RTD}}{\sigma_{\theta}^2}  (13)$	$N \rightarrow 1$ : Completely mixed $N \rightarrow \infty$ : Plug flow	(Bu and Xu, 2013)		

# Table 1: Hydraulic Performance Indices

Phenomena	Hydraulic Performance Indices	Equation	Implications of value	Reference
Dead zones	Effective volume ratio ( <i>e</i> )	$e = \frac{t_{RTD}}{t_{HRT}}  (14)$	$e \rightarrow 1$ : No dead zone $e \rightarrow 0$ : Dead zones present	(Guo et al., 2015; Persson, 2000; Sabokrouhiyeh et al., 2017; Thackston et al., 1987)
Hydraulic efficiency (Mixing.	Hydraulic efficiency index $(\lambda)$	$\lambda = \frac{t_{p1}}{t_{HRT}}  (15)$	$\lambda \rightarrow 1$ : Efficient $\lambda \rightarrow 0$ : Inefficient	(Persson et al., 1999; Shih et al., 2013)
Short- Circuiting, dead zones)	Moment Index $(M_l)$	$M_{I} = 1 - M_{f}  (16)$ $M_{f} = \int_{0}^{1} (1 - t_{c}')C'dt'$ $(17)$ $C' = \frac{C}{C_{0}}  (18)$ $C_{0} = \frac{Tracer \ volume}{Total \ water \ volume}  (19)$	$M_I \rightarrow 1$ : Efficient $M_I \rightarrow 0$ : Inefficient	(Khan et al., 2013; Wahl et al., 2010)
Advective and dispersive transport	Peclet number ( <i>Pe</i> )	$Pe = \frac{UL}{D}  (20)$ $D = \frac{\sigma_{\theta}^2 U^3}{2L}  (21)$	$Pe \rightarrow 0$ : Completely mixed $Pe \rightarrow \infty$ : Plug flow	(Laurent et al., 2015; Persson and Wittgren, 2003; Seeger et al., 2013; Vázquez-Burney et al., 2015)

#### Table 1: Hydraulic Performance Indices (Continued)

 $t_5$ ,  $t_{10}$ ,  $t_{25}$ ,  $t_{50}$ ,  $t_{75}$ ,  $t_{90}$ , is the time (min) for 5%, 10%, 16%, 25%, 50%, 75%, 90% of the injected tracer to exit,  $t_{HRT}$  = nominal hydraulic residence time (min),  $t_{RTD}$  = mean residence time calculated using RTD curve (min),  $V_w$  = volume of waterbody (m<sup>3</sup>), and Q = inflow rate (m<sup>3</sup>/min), C = concentration of injected tracer measured at the outlet at different times (mg/L),  $t_{p1}$  is the time to the peak of the RTD curve (min),  $M_f$  = first moment of the normalized RTD curve,  $t_c'$  = normalized time to the centroid of the normalized RTD curve, U is the velocity of flow (m/s), L is length (m), D is dispersion coefficient (m<sup>2</sup>/sec).

Type of Study	Method/ Equipment used	Waterb ody type	Plant	Hydraulic Parameters	Variation Features	Pollutant Parameter	Reference
Lab	Tracer Experiment, Electrical Conductivity measurement	Pond (Criterio n 1)	CI, AC, CA, VZ	$t_{HRT}$ , $t_{RTD}$ , Pe, e, $\lambda$ , N	-	COD, TN, TP, Chl-a	(Bu and Xu, 2013)
Lab	Tracer Experiment, Fluorometer		Syntheti c roots	S, e, λ, M <sub>I</sub>	Inlet-Outlet configuration, FTI position	-	(Khan et al., 2013)
Field	Tracer Experiment, Lithium ion measurement		18 different species	t <sub>HRT</sub> , t <sub>mean</sub> , Pe, e, N	None		(Vázquez- Burney et al., 2015)
Numerical	Simulation of tracer concentration		-	RTD curve	Inlet-Outlet configuration, FTI position	PG*	(Xavier et al., 2018)
Lab	Tracer Experiment, Fluorometer		Syntheti c roots	S, e, λ, M <sub>I</sub>	Root length, vegetation density, FTI position	-	(Khan et al., 2019)
Lab & Numerical	Velocity Field Measurement, Particle Image Velocimetry System	River (Criterio n 2)	IT	Water Level, Velocity	Coverage, FTI position	-	(Rao et al., 2014)
Lab & Numerical	Velocity Field Measurement, Particle Image Velocimetry System		Plastic plant	Flow velocity field	Root system porosity, Inlet position	NH <sub>3</sub> -N*	(Lei et al., 2016)
Lab	Velocity Field Measurement, Doppler Velocimetry System		Rigid dowel roots only	$t_{HRT}$ in the root zone, Velocity field, Inflow rate to the root zone	FTI spacing	PG*	(Liu et al., 2019)
Numerical	Flow field simulation		Rigid cylindric al roots	Velocity	vegetation density	-	Ai et al. (2020)

 Table 2: Features of studies on the hydraulics of waterbodies retrofitted with FTIs

 Covering criterion 1 and 2.

\* marked parameters were simulated/estimated only and not experimentally measured

PG = Pollutants in general (not any specific pollutant)

TN = Total Nitrogen, TP = Total Phosphorus, COD = Chemical Oxygen Demand, Chl-a = Chlorophyll-a

CI = Canna indica, AC = Accords calamus, CA = Cyperus alternifolius, VZ = Vetiveria zizaniodes, IT = Iris tectorum

Location	Catchme nt area (m <sup>2</sup> )	Waterbody shape	Aspect ratio	Waterbody Surface Area (m <sup>2</sup> )	FTI area (m <sup>2</sup> )	FTI coverage (%)	FTI shape	FTI arrangement	Vegetation density (plants/m <sup>2</sup> )	Water depth (m)	Inlet-Outlet configuration	Other feature	Reference
UK	245,000	Rectangular	-	30	30	100	Rectangular	Single	-	-	Center-Center	SPM	(Revitt et al., 1997)
USA	6,637	Irregular	-	340	30	8.7	Rectangular	Multiple	21.6		Left-Right*	AA	(Chang et al., 2012)
USA $1 \\ 2$	130,007 23,700	Rectangular Irregular	2.84 2.4	3,600 500	324 90	9.0 18.0	Irregular	Multiple	9.8	1.22 0.93	Left-Center* Left-Right*	-	(Winston et al., 2013)
New Zealand	17,000	Rectangular	3.66	100	50	50	Rectangular	Single	17	0.75	Center-Center	SPM	(Borne et al., 2013b, 2013a)
France	13,750	Rectangular	-	375	4.5	1.2	Rectangular	Multiple	21.5	-	Multiple inlet- Single Outlet	-	(Ladislas et al., 2015)
USA	-	Irregular	-	16,000	1122	7.0	Rectangular	Multiple	-	1.5	-	-	(Vázquez-Burney et al., 2015)
USA	570,000	-	-	5,689	11.1	0.20	Rectangular	Multiple	21.7	-	-	-	(Wang et al., 2015)
USA 2 3	-	Rectangular	-	2,363 1,263 2,792	118.2 63.2 179	5.0 5.0 6.4	Rectangular Rectangular Hexagonal	Multiple Single Single	-	-	-	-	(Hartshorn et al., 2016)
USA	550,000	Irregular	-	7,100	50	0.7	Kidney	Split into two	30.2	1.54	-	-	(McAndrew et al., 2016)
Australia	74,600	Rectangular	-	5,048	101.2	2	Rectangular	Single	3	1.5	-	SPM	(Nichols et al., 2016; Schwammberger et al., 2017; Walker et al., 2017)
Mexico	-	Irregular	-	15,000	50.5	0.34	Rectangular	Split into two	6 and 24	2.5	-	-	(Olguín et al., 2017)
Australia	450,000	Irregular	-	26,000	2088	8.03	Rectangular	Two	8.7	1.65	-	SPM	(Schwammberger et al., 2019)
USA	33,387	Rectangular	1.29	279	50.4	18.06	Rectangular	Multiple	8.89	2	-	-	(Tharp et al., 2019)
Australia	30,000	Irregular	-	1,270	147	11.57	Rectangular	Single	8.7	2	-	-	(Schwammberger et al., 2020)
USA	36,000	Rectangular	1.91	800	184	23	Rectangular	Multiple	15	0.6-1.2		SPM	Maxwell et al. (2020)

 Table 3(a): Field configuration of Stormwater Ponds or Lakes retrofitted with FTIs

\* Left-right implies that inlet is on the left and outlet is on the right of the centroidal axis of the pond standing on the inlet side facing the pond

# Table 3(b): Typical configuration of FTIs in rivers

Location	River	River width (m)	Flow Rate (m <sup>3</sup> /sec)	Remediat ion length (m)	FTI shape	FTI arrangement	FTI area (m²)	Vegetation density (plants/m <sup>2</sup> )	Water depth (m)	Other feature	Reference
India	Kshipra	-		40	Rectangular	Single	200	8	-	-	(Billore and Sharma, 2009)
Italy	Sile	8		-	Rectangular	Two	39	16	-	SPM	(De Stefani et al., 2011)
Singapore	Peng Siang	-		-	Triangular	Multiple	22.5	-	-	-	(Chua et al., 2012)
China	Chaizhibang	20 - 25	4	450	Circular and irregular	Multiple	786	-	1.5 – 2	-	(Ning et al., 2014)

SPM = Short-circuiting prevention mechanism, AA = Artificial Aeration



Figure 1: Schematic of a Floating Treatment Island



Figure 2: RTD curves depicting hydraulic performance characteristics of the waterbody (Khan et al., 2013)



Figure 3: Experimental features of hydraulic performance studies on stormwater pond retrofitted with FTIs (a, b, c, e -plan view) (a) Bu and Xu (2013), (b) Khan et al. (2013), (c) Xavier et al. (2018), (d) Khan et al. (2019) – Longitudinal section, (e) Vazquez-Burney et al. (2015)



Figure 4: Experimental features of hydraulic studies on rivers retrofitted with FTIs (a, c -plan view; b, d-longitudinal section view) (a) Rao et al. (2014), (b) Lei et al. (2016), (c) Liu et al. (2018), (d) Ai et al. (2019)



Figure 5: Flow short-circuiting prevention mechanisms used in different studies (a) full FTI coverage in pond (b) full-width FTI coverage in lake (c) full-width FTI coverage in river channel (d) impermeable baffle curtains. Figures not to scale.