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RESEARCH ARTICLE

Mean residence time of lagoons in shallow vegetated floodplains

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Abstract

Lagoons interspersed within wetlands are expected to increase the residence time of the flow in the system which, in turn, will lead to enhanced pollutant removal thus ensuring a good ecological status of the ecosystem. In this study, lagoons interspersed in vegetated wetlands have been mimicked in the laboratory to develop a theoretical model to establish the impact three major driving parameters (the vegetation density surrounding a lagoon, the depth aspect ratio [length vs. depth] of the lagoon and the circulating flow – through the Reynolds number) have on determining the residence time of the flow in the lagoon. The results indicate that, according to the maximum free available area of the flow, the presence of vegetation (*Juncus maritimus*) decreases the residence time. In addition, an increase in the Reynolds number of the circulating flow in the wetlands also resulted in a decrease in the lagoon residence time. Nevertheless, lagoon residence times were found to depend on the depth of the lagoon, with deeper lagoons having higher residence times. The length of the lagoon, however, was found not to affect the residence time. High lagoon residence times in either natural or constructed wetlands are desirable because they enhance pollutant removal from the water. Although, if the residence times are too long, this may lead to anoxic water conditions that could in fact threaten the wetland's ecosystem.

KEYWORDS
constructed wetlands, lagoon aspect ratio, lagoon wetland, mean residence time, vegetation density

1 | INTRODUCTION

Constructed wetlands (CW) are nature-based, eco-friendly technologies that provide sustainable solutions to unique environmental problems such as removing sludge particles and organics resulting from microbial degradation (Vymazal, 2010; Vymazal, 2020; Yang et al., 2020). They have also been efficient in removing emerging contaminants such as antibiotics and antibiotic resistance gens (Chen et al., 2019; Ma et al., 2020), ibuprofen and caffeine (de Oliveira et al., 2019) and pesticides and nutrients from plant nursery runoff (McMaine et al., 2020) among others (Ilyas & van Hullebusch, 2020). CW can be integrated into conventional treatment plants to treat potable, waste or even industrial waters (Šereš et al., 2020; Vymazal, 2010). CW facilitate the removal of chemicals from wastewater and also homogenize the physical and chemical characteristics of the flow (Schaafsma et al., 2000). As such, they offer low-cost and low-maintenance processes of removing wastewater N and P through precipitation into the soil bottom, soil adsorption of chemicals, plant

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uptake with organic matter accumulation, and microbial immobilization (Margalef-Martí et al., 2019). In addition, they provide new habitats for aquatic organisms, refuges for wildlife, and can be used as recreational or educational facilities (Zhang et al., 2020). In other words, CW are eco-friendly water treatment solutions with added ecological values. CW mimic natural wetland areas, are rich in biodiversity and capable of improving the ecological status of the ecosystem via an optimal reuse of water. Although they usually require large areas of land, multilayer CW can provide a compact version that allows them to be integrated into urban areas (Nakamura et al., 2017).

Most CW present large shallow vegetated areas interspersed with deeper lagoons lower in vegetation density than the nearby shallow vegetated areas (Min & Wise, 2009). Lagoons provide physical and biochemical transformation processes that differ from other parts of the system, thus providing a more complete water treatment. The main function of a lagoon is to increase the permanence time of the water in the treatment process (Ruffino, 2015). Within lagoons, wastewater is treated following a series of physical, biological and biogeochemical natural processes, characterized by a high retention rate of algae, pH buffering and a further reduction of general sewage parameters (Steinmann et al., 2003). In ponds and wetlands, the length/width (length-to-width, L:W) aspect ratio of lagoons has been found to be critical for sediment and pollutant removal. While a high length/width aspect ratio will increase the flow path in the system and its effective retention flow time, it can also lead to overflow problems resulting from an accumulation of vegetation litter in time (Kadlec & Wallace, 2009). The U.S. Environmental Protection Agency (EPA) manual (1999) states that, in general, CW are built with width aspect ratios L:W ≤ 4:1 to avoid hydraulic problems. Persson et al. (1999) showed that for lagoons to perform efficiently, the width aspect ratio should be greater than 1.88 but less than 5. Although the width aspect ratio has been well studied, the depth of the system – despite being recognized as a principal design factor for efficient wastewater treatment – is still much of an unknown (Ioannidou & Pearson, 2018). Most of the research has been concentrated on determining the effect depth has on flooding in wetlands, which affects plant physiology because of soil oxygen concentration, soil pH, nutrients and toxic chemical concentrations (Tsihrintzis, 2004). However, as an increase in the depth (from 0.4 to 0.6 m) of CW has been demonstrated to increase nutrient removal (Song et al., 2019), the vertical length scale of the system therefore plays an important role in determining the retention time of the flow and should be studied to optimize the performance of the CW.

It is generally agreed that the hydraulic residence time (HRT) dictates the removal efficacy of deep wetland zones and is principally connected to hydrological conditions (Dierberg et al., 2002). HRT depends on the hydrology, (i.e., water depth and flow rate through the wetland system), and also on the hydraulics characterized by the vegetation and the shape of the wetland (Johannesson et al., 2015). The flow past a lagoon (deep zone) creates a shear layer at the interface between the flow and the deep zone which is characterized by the highest transport of momentum. In low aspect depth ratios, a main vortex dominates the flow (Jackson et al., 2013; Ouro et al., 2020; Sandoval & Mignot, 2019), while in high aspect depth ratios other secondary rotating structures can be formed. The secondary vortex is reported to increase the residence time of the flow within the deep zone (Jackson et al., 2013). Although shallow operational depths in CW lead to a flow-through regime, deep operational depths result in dissipated flow detention or ponding velocities (Ioannidou & Pearson, 2018). Consequently, it is worthwhile determining lagoon residence time in terms of flow velocity, as well as the lagoon length to depth ratio at the interface.

High nutrient loadings and their accumulation in ponds or deep zones of CW are expected to result in an increase in the pond phytoplankton stock (Aizaki et al., 1986), resulting in eutrophication. However, the role of vegetation in CW is to reduce the nutrient load not only via the direct uptake by plant roots and rhizomes, but also through microorganism action (Agudelo et al., 2012; McMaine et al., 2020). The flow through emergent vegetation in wetlands is determined by the Reynolds number for plants ($Re_p = ud/\nu$, where d is the plant diameter, u is the flow velocity and ν is the kinematic flow viscosity). For $Re_p < 200$, two eddies are generated behind the plants, thus increasing the retention time of any contaminant in the system. However, for $Re_p > 200$, eddies detach from the plants, producing a transport of momentum and mass downstream (Nepf et al., 1997). In addition, vegetation produces a lateral diffusion of contaminants in wetlands, consequently increasing the length of the paths that particles or contaminants will travel (i.e., increasing their residence time in the system) (Serra et al., 2004). The increase in the retention time of the contaminants around plant roots and rhizomes is expected to enhance the uptake of pollutants and the sedimentation of particles (Soler et al., 2017) and, therefore, increase the effectiveness of the treatment. The presence of macrophytes in the littoral areas of lagoons modifies the quality of the lagoon water, as well as the sedimentary rates observed (Pawlikowski & Kornijów, 2019). In contrast, and as shown in the case of the Vistula Lagoon in Russia, the low impact the littoral vegetation had was attributed to the low canopy density and also to the presence of bare soil areas interspersed within the vegetation (Viaroli et al., 2008). Vegetated areas in CW have been found to produce short-circuiting. This is due to fast flowpaths experiencing longitudinal dispersion but not producing flow exchange with dense surrounding vegetation (Lightbody, Nepf & Bays, 2009). Most of the research to date has concentrated on the type of vegetation that best optimizes the uptake of nutrients and the reduction of contaminants (Ghosh & Gopal, 2010) in CW. Deep zones situated transversally to vegetated marsh areas can offset short-circuiting by reducing flow velocity and producing lateral mixing, and by reducing the probability that certain flowpaths prevail along the whole wetland (Lightbody et al., 2009). Despite these studies, there is still a gap in the knowledge about the effects vegetation density has on modifying hydrodynamics and water quality in the different sized lagoons interspersed within the wetlands.

In this study, the mean residence time of a lagoon interspersed within a wetland has been evaluated in terms of the lagoon's structure (depth aspect ratio) and the flow regime (Reynolds number), along with the effect the emergent vegetation has on the residence time in the lagoon. The study has been performed using a laboratory-scale model that mimics scales and flow conditions found in actual wetland-pond systems. The results from the study provide a quantitative understanding of residence time in wetland lagoons in relation to wetland vegetation, flow, and shape which, in turn, may help engineers to design more efficient and cost-effective water systems.

2 | MATERIALS AND METHODS

2.1 | The experimental conditions tested

Experiments were carried out in a laboratory straight flume measuring 500 cm × 40 cm × 50 cm (Table 1). At the entrance to the flume, a honeycomb was used to straighten the flow produced at the inlet (Nepf et al., 1997), while at the outlet of the flume, an 18 cm high gate ensured a constant flow level. Two platforms measuring 120 cm long at the base, 100 cm long at the top and 10 cm high, were constructed and placed in the flume to create a deep zone between them that would represent a V-shaped lagoon (Figure 1(a)-(c)). Next, 100 cm × 40 cm × 1 cm perforated bases covered with 0.6 cm diameter holes, where the plant stems would be distributed, were placed on each platform. The height of the lagoon was considered to be from the top of the perforated platforms down to the bed of the flume. Two water heights were considered: H = 5 and 11 cm. To study the shallow lagoon with H = 5 cm, a new base was positioned inside the lagoon at a height of 6 cm from the bed of the flume. To study different lagoon lengths, the second platform was moved longitudinally along the flume to different positions along its main axis. The vegetation in the shallow areas consisted of stems of real *Juncus maritimus* vegetation (Figures 1(b),(c)), typical of river floodplain zones and saltmarshes, which was collected near the Ter river (Catalonia, North-East Spain). Seven canopy densities were considered (n = 0, 354, 707, 884, 1061, 1415, and 1768 plants m^{-2}) in accordance with the range in the canopy densities found in saltmarshes (Leonard & Luther, 1995; Leonard, Wren, Beavers, Lane, & Service NP, 2002). From the canopy density (*n*) and the value of the stem diameter, *d*, the percentage of the area covered by the vegetation in the shallow vegetated areas, (i.e., the solid plant fraction [$SPF = n\pi d^2/4$]), can be calculated (Pujol, Serra, et al., 2013). These canopy densities corresponded to solid plant fractions *SPF* = 0, 1, 2, 2.5, 3, 4 and 5, respectively. Next, the vegetation was randomly distributed using a computer function (Pujol, Casamitjana, et al., 2013; Ros et al., 2014; Serra et al., 2001) and stems were cut to 20 cm long to ensure that the vegetation was emergent. Three to four stems were attached and tied with tape to build a 0.6 cm thick plant that fitted into the holes that had been previously drilled into the platforms. The frontal area of the vegetation can be calculated as $(h_w - H)dN$ (where *N* is the total number of stems,

TABLE 1 Table with the experimental conditions considered in each experiment

Run	*SPF* (%)	*ad*	*H* (cm)	*L* (cm)	u_0 (cm s^{-1})	*H*/ (*L* + 2L_s)	Run	*SPF* (%)	*ad*	*H* (cm)	*L* (cm)	u_0 (cm s^{-1})	*H*/ (*L* + 2L_s)
1	0	0	5	31.5	2.63 ± 0.03	0.12	21	0	0	5	31.5	0.59 ± 0.03	0.12
2	0	0	11	20	2.53 ± 0.02	0.28	22	0	0	11	20	0.59 ± 0.02	0.28
3	1	0.013	11	20	2.53 ± 0.04	0.28	23	1	0.013	11	20	0.52 ± 0.05	0.28
4	2.5	0.032	11	20	2.55 ± 0.01	0.28	24	2.5	0.032	11	20	0.53 ± 0.04	0.28
5	0	0	11	100	2.82 ± 0.05	0.09	25	0	0	11	100	0.44 ± 0.04	0.09
6	1	0.013	11	100	2.83 ± 0.05	0.09	26	1	0.013	11	100	0.56 ± 0.04	0.09
7	2.5	0.032	11	100	2.98 ± 0.02	0.09	27	2.5	0.032	11	100	0.56 ± 0.03	0.09
8	0	0	11	50	2.52 ± 0.02	0.16	28	0	0	11	50	0.57 ± 0.07	0.16
9	2.5	0.032	11	50	2.61 ± 0.03	0.16	29	2.5	0.032	11	50	0.57 ± 0.06	0.16
10	5	0.064	11	50	2.56 ± 0.06	0.16	30	5	0.064	11	50	0.55 ± 0.03	0.16
11	0	0	5	31.5	2.10 ± 0.04	0.12	31	0	0	5	31.5	1.20 ± 0.02	0.12
12	0	0	5	31.5	3.75 ± 0.05	0.12	32	0	0	5	31.5	1.68 ± 0.04	0.12
13	0	0	5	31.5	3.75 ± 0.05	0.12	33	0	0	11	5	1.70 ± 0.04	0.44
14	0	0	11	5	4.01 ± 0.03	0.44	34	5	0.064	11	5	0.67 ± 0.05	0.44
15	5	0.064	11	5	4.17 ± 0.02	0.44	35	4	0.051	11	5	1.08 ± 0.03	0.44
16	4	0.051	11	5	4.88 ± 0.03	0.44	36	3	0.038	11	5	1.14 ± 0.02	0.44
17	3	0.038	11	5	3.89 ± 0.04	0.44	37	2	0.025	11	5	3.30 ± 0.01	0.44
18	2	0.025	11	5	5.43 ± 0.06	0.44	38	2	0.025	11	5	2.16 ± 0.05	0.44
19	2	0.025	11	5	3.20 ± 0.04	0.44	39	2	0.025	11	5	0.99 ± 0.04	0.44
20	1	0.013	11	5	4.32 ± 0.03	0.44	40	1	0.013	11	5	0.64 ± 0.04	0.44

Note: SPF is the solid plant fraction of the shallow vegetated areas, *ad* is the frontal area of the vegetation per unit volume, *H* is the depth of the lagoon, *L* is the length of the base of the lagoon, u_0 is the velocity at the inlet of the flume and $H/(L + 2L_s)$ is the aspect ratio of the lagoon, where L_s is the length of the slopes (Figure 1).

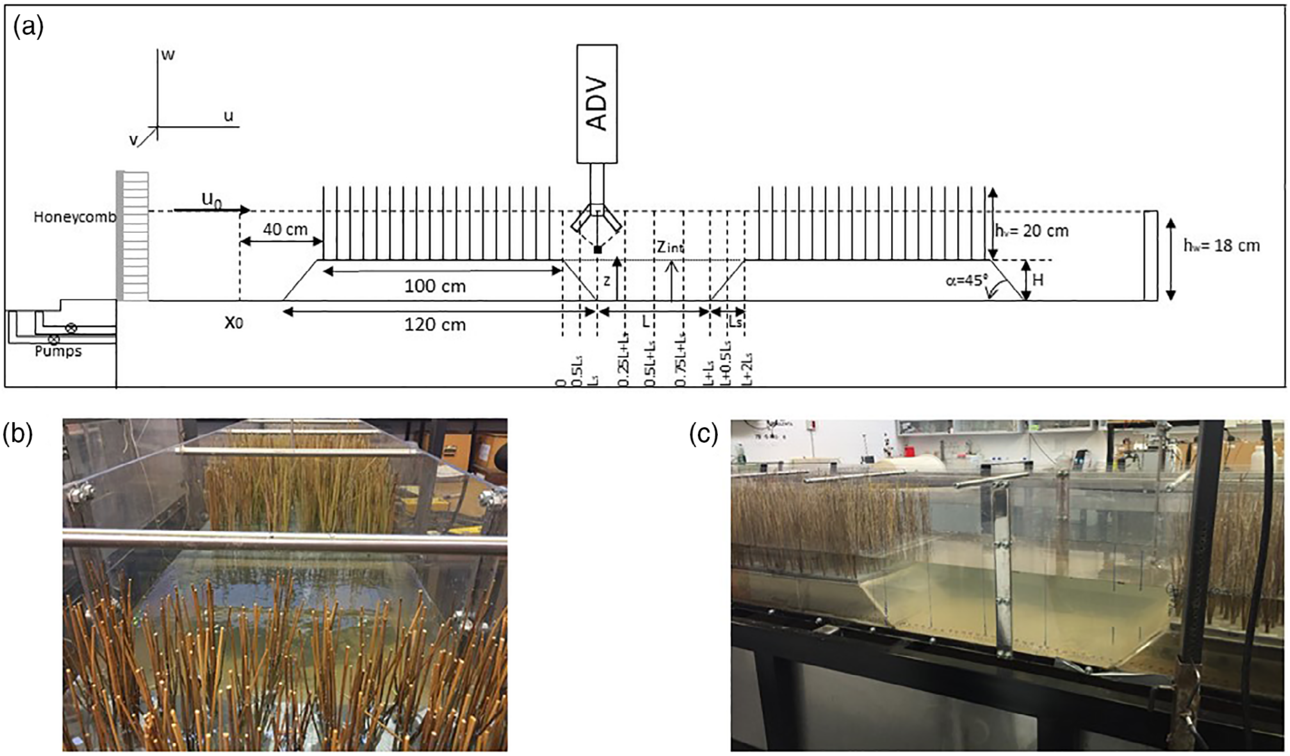

FIGURE 1 (a) Scheme of the experimental flume. (b) Photograph of the longitudinal view of the flume with the lagoon. (c) Photograph of the lateral view of the flume with the lagoon and the platforms

h_w is the water depth from the flume base, H is the lagoon depth and d is the stem diameter). The total volume in the vegetated region is $(h_w - H)A$ (where A is the area of the base of the flume in the vegetated region). Then, the frontal area per unit volume is $a = (h_w - H)dN/(h_w - H)A = (N/A)d$. If $n = N/A$, that is, the shoot density, then $a = nd$. The volume of the vegetation opposing the flow can be considered as ad (Nepf et al., 1997) (Table 1). Therefore, $1 - ad$ represents the porosity of the vegetated area, that is, the volume of the free void space available for the fluid.

Flow velocities were measured with a laboratory Doppler velocimeter (ADV, 16 MHz, SonTek Inc.). At each measurement position, the ADV calculated the three components of the velocity of the flow (u, v, w) using a frequency of 50 Hz for 5 min (giving 15 000 measurements). The ADV was moved manually along the vertical and horizontal directions and then fixed at the measuring point. Within the lagoon, eight horizontal locations were selected along the main axis of the flume ($x' = 0$, $0.5L_s$, L_s, $L_s + 0.25\ L$, $L_s + 0.5\ L$, $L + L_s$, $L + 1.5L_s$ and $L + 2L_s$, where $x' = 0$ cm at the beginning of the lagoon, and L_s is the length of the slopes of the lagoon walls, see Figure 1) and one location at the inlet of the flume (at $x' = x_0 = -140$ cm, Figure 1) were used to determine the hydrodynamics inside the lagoon and at the inlet, respectively. All measurements were taken at the centre of the flume ($y = 0$ cm, where y is the transversal direction of the flume). In the deepest part of the lagoon, 14 vertical measuring points along the vertical axis were selected at each x-location (from $z = 1$ cm to 14 cm, where $z = 0$ cm corresponds to the bed of the water column). At the slopes within the lagoon, nine vertical points evenly distributed were considered at $0.5L_s$ and four vertical points evenly distributed were considered at $x' = 0$, and $L + 2L_s$. The mean velocity at the entrance of the flume (u_0) was calculated from the vertical mean of the temporal mean x-velocity components at the three upper depths of the profile taken at x_0 ($z = 12$, 13 and 14 cm). The temporal mean velocity of each component at each position was calculated as the mean value of the 15 000 measurements taken for each component.

To cover a wide range of canopy densities, lagoon water lengths and depths and flow velocities at the inlet of the flume, a total of 40experiments (Table 1) were carried out.

2.2 | Residence time in the lagoon

The residence time in the lagoon (τ) was calculated from the vertical velocity components at the interface (z_{int}, Figure 1) following the method described by Weitbrecht and Jirka (2001), where τ could be determined from:

$$\tau = \frac{V}{Q_{int}} \tag{1}$$

where Q_{int} is the exchange volume per unit time through the interface and V is the volume of the lagoon. The exchange volume per unit time through the interface can be calculated by:

$$Q_{int} = EW(L + 2L_s) \tag{2}$$

where W is the width of the lagoon (equal to the width of the flume W = 40 cm), L is the length of the lagoon at the base, L_s is the length of the lagoon slopes (i.e., the length of the lagoon at the interface is $L + 2L_s$) and the volume of the cavity V can be determined by:

$$V = (L + L_s)HW \tag{3}$$

where H is the depth of the lagoon (Figure 1). E is the flux of water from the lagoon to the main stream through the interface and can be calculated as:

$$E = \frac{1}{2n}\sum_{i=1}^{n}|\overline{w_i}| \tag{4}$$

where n is the number of measuring points along the lagoon interface and w is the mean vertical velocity measured at each interface position. By putting Equations (2) and (3) into (1), we obtain the residence time in the lagoon τ as:

$$\tau = \frac{(L + L_s)HW}{EW(L + 2L_s)} = \frac{(L + L_s)H}{E(L + 2L_s)} \tag{5}$$

The residence time τ in the lagoon was calculated from Equation (5). To obtain a model that describes the dependence of τ with the main variables of the system, the Buckingham pi-theorem was applied. This theorem is based on the assumption that physical laws should be independent of the dimensions used to express the variables (Evans, 1972). The model is based on finding the relationship between the non-dimensional parameters of the problem, which can be expressed from the number k of dependent variables with m physical dimensions. According to the definition, in the present study there are six independent variables (τ, ad, u_0, H and $L + 2L_s$, W) and two physical dimensions (length and time). Therefore, four (k-m) non-dimensional parameters can be written $\left(\frac{\tau u_0}{(L+2L_s)}, 1-ad, \frac{H}{L+2L_s}, Re = \frac{Wu_0}{\upsilon}\right)$. Consequently,

$$\pi = \pi'\left(\frac{\tau u_0}{(L + 2L_s)}, 1 - ad, \frac{H}{L + 2L_s}, Re = \frac{Wu_0}{\upsilon}\right) \tag{6}$$

The first non-dimensional parameter represents the balance between the mean residence time and the time for a parcel of fluid flowing at the velocity of the main channel to travel a distance equivalent to the length of the interface ($L + 2L_s$). The second non-dimensional parameter is the porosity of the vegetated area, that is, the free area available for the flow. The third parameter corresponds to the aspect ratio of the lagoon and the fourth parameter to the Reynolds number that characterizes the regime of the fluid.

2.3 | Reynolds stress

The turbulent velocity components were obtained by subtracting the mean of the velocity from each instantaneous velocity as:

$$u' = u_i - \overline{u} \tag{7}$$

where u' is the turbulent velocity for the x velocity component, u_i is the instantaneous velocity and $\overline{u}$ is the mean velocity in the x-axis. The same expression can be applied to the y and z velocity components and the turbulent velocities in the y and z axis can be calculated as v' and w', respectively. The root mean square value of the turbulent velocities has been considered as the turbulent components of the velocity (u', v', w'). Therefore, the Reynolds stress can be calculated as $-u'w'$. In the plots, the temporal mean Reynolds stress $-\overline{u'w'}$ will be represented and named hereafter as $-u'w'$. The Reynolds stress averaged along different points of measurement will be named as $<-u'w'>$.

2.4 | Scaling of the model wetland

The parameters of model wetland studied here were scaled based on a CW in the field. A wetland is a shallow flooded area with vegetation and has deep zones interspersed within it. The Reynolds number was considered as the parameter for the similarity to a CW. Here, the CW considered for scaling was that at the Castelló d'Empúries Wastewater Treatment Plant (NE Spain). The field system is 160 m long, 50 m wide and has a mean depth of 0.5 m. The flow rate in the field case ranges from 0.23 L/s to 1.39 L/s. Based on the Reynolds similarity:

$$Re_{\text{model}} = Re_{CW} \tag{8}$$

$$\left(\frac{\rho v L}{\mu}\right)_{\text{model}} = \left(\frac{\rho v L}{\mu}\right)_{CW} \tag{9}$$

$$v_m L_m = v_{CW} L_{CW} \tag{10}$$

Therefore,

$$\frac{v_m}{v_{CW}} = \frac{1}{\lambda_L} \tag{11}$$

where λ_L is the ratio between the length scale of the CW and the model. The ratio between the flow rates can be also calculated as:

$$\frac{Q_m}{Q_{CW}} = \frac{A_m v_m}{A_{CW} v_{CW}} = {\lambda_L}^2 \frac{1}{\lambda_L} = \lambda_L \tag{12}$$

Considering the total length of the model formed by two shallow vegetated zones and a lagoon, the total length of the model in the flume ranged between 2.25 and 3.20 m. Considering the length of the CW as 160 m, λ_L ranges between 0.014 and 0.02. The flow rate of the CW ranged from 1000 m^3/day-6000 m^3/day (i.e., 11.57 L/s – 69.44 L/s). Therefore, considering Equation (9), the mean flow in the model should range between 0.16 and 1.39 L/s to behave like the CW system. Since the flow rate in the model ranged from 0.32 L/s to 3.90 L/s, parts of the model's results are considered to be representative of the field CW considered.

The aspect ratio of the lagoons studied ranged between 0.09 and .44 (Table 1). In the CW case considered, deep zones with different sizes can be found with aspect ratios in the range of 0.03 to 0.27, therefore, partially in the range of aspect ratios studied in the model.

3 | RESULTS

Within the lagoon, velocity profiles indicate that flow velocity decreased downwards, with its highest value being in the upper part of the water column and its lowest value at the base of the lagoon. Positive velocity values indicate that the flow is directed with the same direction like the main flow along the flume (i.e., from the inlet to the outlet of the flume), whereas negative velocity values indicate that the flow is directed opposite to the main flow along the flume (i.e., from the outlet to the inlet). From the profiles taken at the centre of the lagoon, a high velocity gradient was found for the small lagoon with an interface length of 40 cm (Figure 2(a)). As the lagoon length increased, so too did the velocity gradient. The greatest negative velocity values inside the lagoon were found for the small lagoon, decreasing as its size increased. Above the lagoon, the greatest velocity values were found for the small 40 cm lagoon, with $u/u_0 > 1$. When comparing the vertical profiles at the centre of the lagoon for the different solid plant fractions (Figure 2(b)), the velocity inside the lagoon slightly increased to more negative values from $u/u_0 = -1$ for *SPF* = 0% to $u/u_0 = -1.5$ for *SPF* = 2.5%. However, above the lagoon, u/u_0 increased from $u/u_0 = 2.8$ for *SPF* = 0% to $u/u_0 = 5$ for *SPF* = 2.5%.

The Reynolds stress varied along the interface of the lagoon with its greatest value being at the entrance to the lagoon (Figure 3). This decreased slowly in the first half of the lagoon and then presented a sharp decrease to 0 at a distance at approximately the beginning of the second slope of the lagoon (i.e., approaching the trailing edge of the lagoon), from whence it remained nearly constant thereafter. The highest Reynolds number was found for the densest canopy of 5% and decreased gradually with the *SPF*. For *SPF* = 0%, the Reynolds stress was constant with the smallest value along all the interface of the lagoon. In all the cases, the Reynolds stress was $-u'w' > 0$, indicating a negative transport of momentum through the interface and from the lagoon to the main channel of the flume.

The mean value of the Reynolds stress, $\langle -u'w' \rangle$, averaged among all the measuring points of the interface of the lagoon, increased with the flow velocity at the inlet of the flume u_0 (Figure 4(a)) almost following a linear trend ($\langle -u'w' \rangle = 0.508u_0^2 - 0.363, R^2 = 0.9705$, $p > 1$). The non-dimensional mean Reynolds stress, $\langle -u'w' \rangle / u_0^2$, increased with the volume occupied by plants (ad) in the shallow zone (Figure 4 (b)). In this case, the increase in $\langle -u'w' \rangle / u_0^2$ was linear for $ad > 0.012$ ($\langle -u'w' \rangle / u_0^2 = 1.101ad - 0.006, R^2 = 0.9585$, $p > 1$. However, for $0 < ad < 0.012$, $\langle -u'w' \rangle / u_0$ was constant. In addition, considering the error bars, the non-dimensional mean Reynolds stress along the interface, $\langle -u'w' \rangle / u_0^2$, remained constant with the aspect ratio of the lagoon $H/(L + 2L_s)$ (Figure 4(c)) with a mean value of 0.132 ± 0.002.

The non-dimensional vertical flow velocities (w/u_0) at the interface (z = 11 cm) were nearly 0 at the entrance of the lagoon and had the greatest negative values at the centre of the lagoon, thus indicating a flow towards the inner part of the lagoon (Figure 5). However, the vertical flow had positive values at the other end of the cavity, indicating a flow out of the lagoon. The vertical flow towards and outwards from the lagoon increased with the canopy density at the shallow zone.

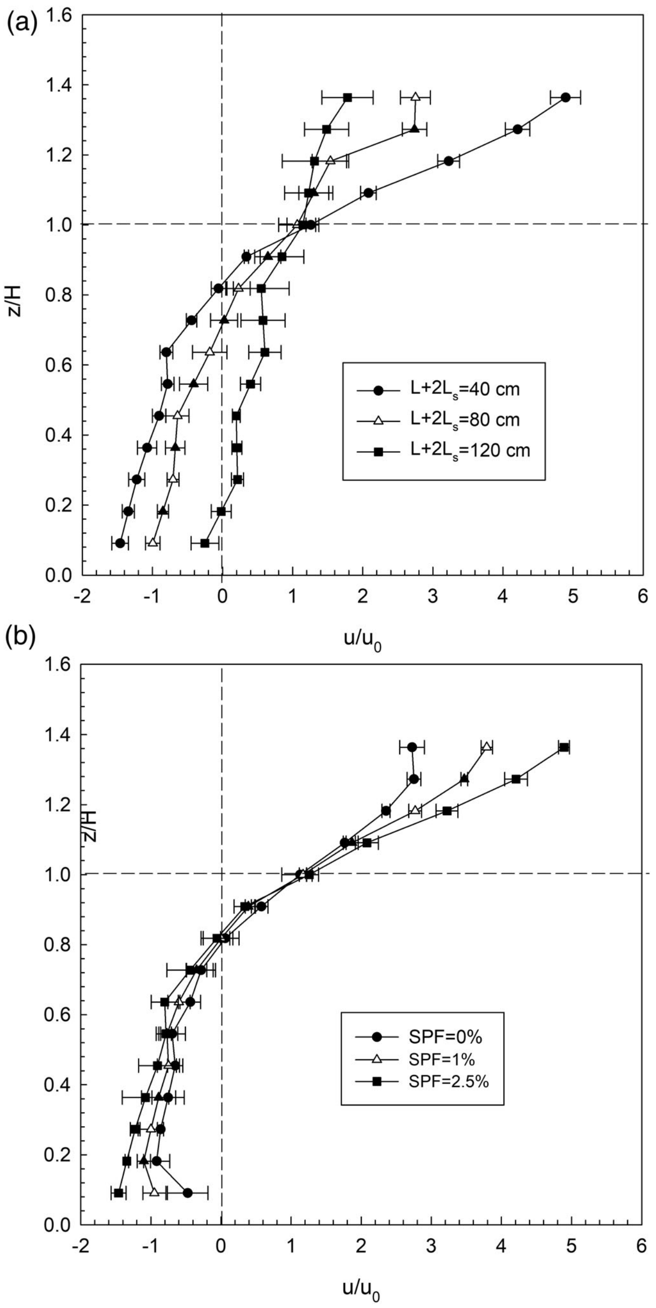

FIGURE 2 Vertical profiles of the ratio between the horizontal velocity in the x-axis (u) and the velocity at the inlet of the flume versus the non-dimensional depth (z/H, where H is the depth of the lagoon) for the case of *SPF* = 2.5% and different lengths of the lagoon (a) and for the lagoon of $L + 2L_s$ = 40 cm for three different *SPFs*. The profiles represented were measured at $x/(L + 2L_s) = 0.5$, at the centre of the lagoon. The horizontal dashed line represents the position of $z/H = 1$, that is, the position of the interface of the lagoon. The vertical dashed line represents $u/u_0 = 0$

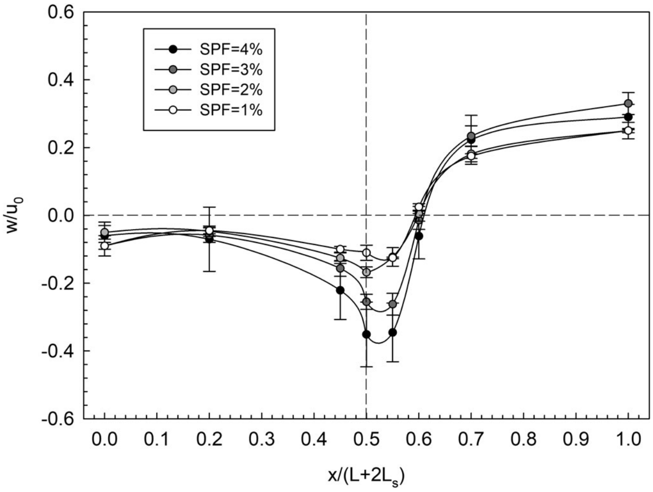

FIGURE 3 Ratio of the mean vertical velocity *w* and the horizontal velocity u_0 versus the non-dimensional position $x/(L + 2L_s)$ along the interface of the lagoon for different *SPFs* studied. The horizontal dashed line represents the value of $w/u_0 = 0$ and the vertical dashed line represents the x-position at the centre of the lagoon

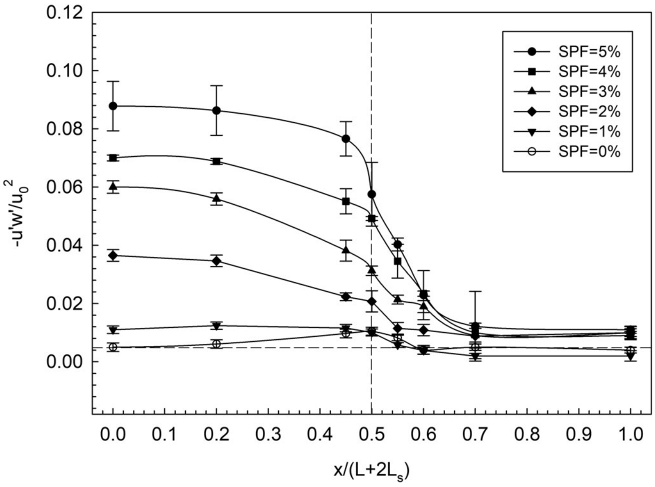

FIGURE 4 Ratio between the Reynolds stress and the square of the horizontal velocity at the inlet of the flume versus the non-dimensional distance along the interface of the lagoon ($x/(L + 2L_s)$). The horizontal dashed line represents $-u'w'/u_0^2 = 0$ and the vertical dashed line represents the $-u'w'/u_0^2$ value at the centre of the lagoon

For the non-vegetated experiments, the results of the Buckingham pi-theorem resulted in a linear trend between $\tau u_0/(L + 2L_s)$ and $(H/(L + 2L_s))Re^{0.3}$ (Figure 6(a)) with the equation,

$$\frac{\tau u_0}{L+2L_s} = 0.868\left(\frac{H}{L+2L_s}\right)Re^{0.3} \tag{13}$$

For the with-plants case, where $ad \neq 0$, the results of the Buckingham pi-theorem resulted in a linear trend between $\tau u_0/(L + 2L_s)$ and $(1 - ad)(H/(L + 2L_s))Re^{0.3}$ (Figure 6(b)) with the equation,

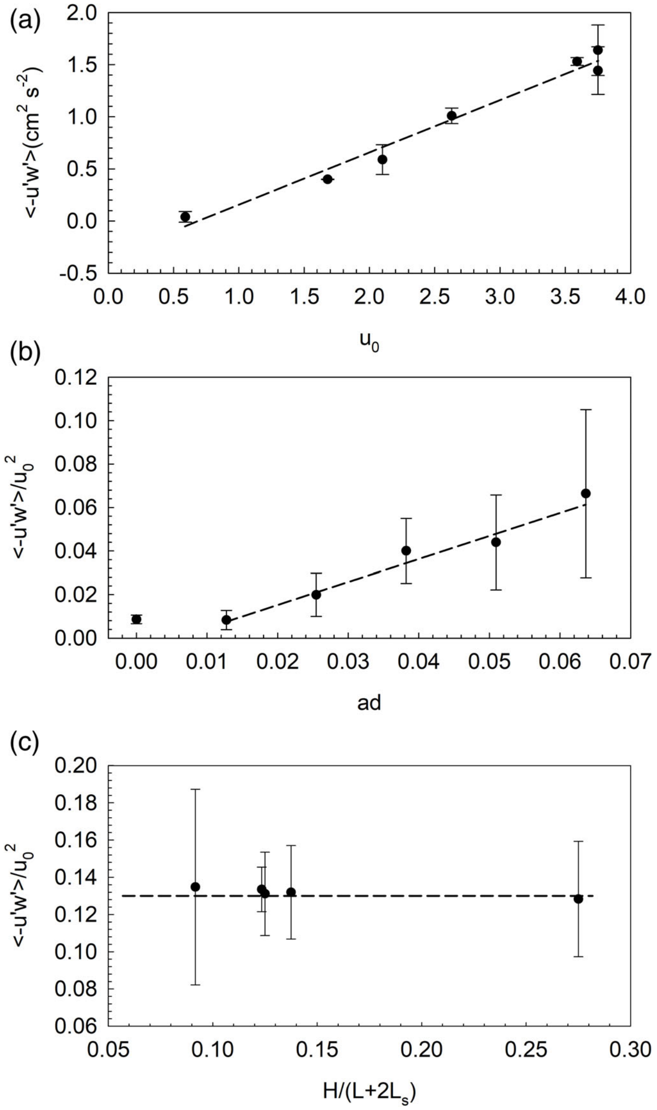

FIGURE 5 Spatial averaged Reynolds stress $<-u'w'>$ versus the horizontal velocity along the x-axis for experiments carried out with *SPF* = 0% (a). Ratio of the spatial averaged Reynolds stress $<-u'w'>$ and the square of the horizontal velocity at the inlet of the flume versus *ad* (b). Ratio of the spatial averaged Reynolds stress $<-u'w'>$ and the square of the horizontal velocity at the inlet of the flume versus the aspect ratio of the lagoon ($H/(L + 2L_s)$) (c). All experiments correspond to the case of the lagoon interface length of $L + 2L_s$ = 25 cm

$$\frac{\tau u_0}{L+2L_s} = 0.868(1-ad)\left(\frac{H}{L+2L_s}\right)Re^{0.3} \tag{14}$$

Therefore, the residence time in the lagoon can be solved from this Equation (14) and results in,

$$\tau = \frac{0.868(1-ad)H\left(\frac{W}{\upsilon}\right)^{0.3}}{u_0^{0.7}} \tag{15}$$

4 | DISCUSSION

The velocity profile in a lagoon interspersed within a wetland has been found to depend on both the structural characteristics of the lagoon, and the modification of water flows by the adjacent vegetation. From the velocity profiles at the centre of the lagoon, the velocity in the lagoon was greater for the smaller lagoon lengths, with a flow directed opposite to the flow direction of the main channel. Above the lagoon, and from the profiles taken at the centre of the cavity, the flow velocity was greater as the lagoon length decreased. This is because as the lagoon becomes smaller, its centre is situated closer to the shallow region where the velocity is greater than u_0 (measured at x_0, flume inlet), since the vegetated zone is shallower. In addition, plants produced an additional reduction in the free area available for the fluid through the vegetation and, in turn, an increase in the velocity of the flow in the lagoon, that is, short-circuiting. The increased flow effect due to the adjacent plants was also observed by Nepf et al. (1997) in the entire section of a channel with emergent vegetation.

While the Reynolds stress was constant along the interface of the lagoon for the non-vegetated experiments, the presence of vegetation in the shallow areas, however, generated an increase in the mean Reynolds stress in the lagoon. Consequently, the greater the canopy density is, the higher the mean Reynolds stress in the lagoon. The greatest Reynolds stresses were found at the leading edge of the lagoon decreasing towards the trailing edge. This can be partially due to the flow separation between the flow in the main channel and that in the cavity. However, the increase in the Reynolds stress is mainly attributed to the increase in the velocity of the flow in the vegetated cases due to the reduction in the available free area, (i.e., due to the short-circuiting for the flow in the shallow vegetated areas) as Lightbody et al. (2009) also found. This result is also in accordance with Folkard (2005) who performed experiments with a patch of flexible vegetation, although in this case, the increase in the Reynolds stress was found at the upper part of the vegetation, also coinciding with the increase in the velocity of the flow at this depth, which was attributed to a submerged patch of vegetation, contrary to the emergent patch used in the current study. The increase in the Reynolds stress at the lagoon inlet was attributed to the dissipation of the momentum of the flow path from the shallow vegetated areas. Therefore, the vegetation in the shallow zone adjacent to the lagoons is expected to enhance the mixing of the flow within it, producing a homogeneous flow at the entrance of the lagoon. In addition, an increase in the vegetation density *ad* is expected to produce a greater short-circuiting in the shallow zone. Greater flow velocities at the entrance of the lagoon will require a higher dissipation of the momentum, i.e., a higher mixing at the lagoon inlet. The mean value of the Reynolds stress along the interface increased with the velocity of the flow, which also coincides with the increase in the Reynolds stress found from low to high discharges following through a submerged patch of flexible vegetation (Folkard, 2005). This has also been observed in flow through lateral surface storage zones (Sandoval & Mignot, 2019). The increase in the Reynolds stress after a patch of emergent vegetation with the canopy density was also observed by Montakhab et al. (2015). In their work, the Reynolds stress after the vegetated patch decreased with distance which aligns with the findings of the present study. In contrast, Maji et al. (2017) found a decrease in the Reynolds stress after a patch of emergent vegetation. In their case, however, the vegetated patch did not cover the whole width of the flume, thus producing an increase in the velocity and the Reynolds stress in the lateral area free of plants and a decrease behind the plants where the velocity of the flow was also reduced. In the present study, low canopy densities ($ad \leq 0.012$) did not produce an increase in the Reynolds stress, whereas for $ad \geq 0.012$, the Reynolds

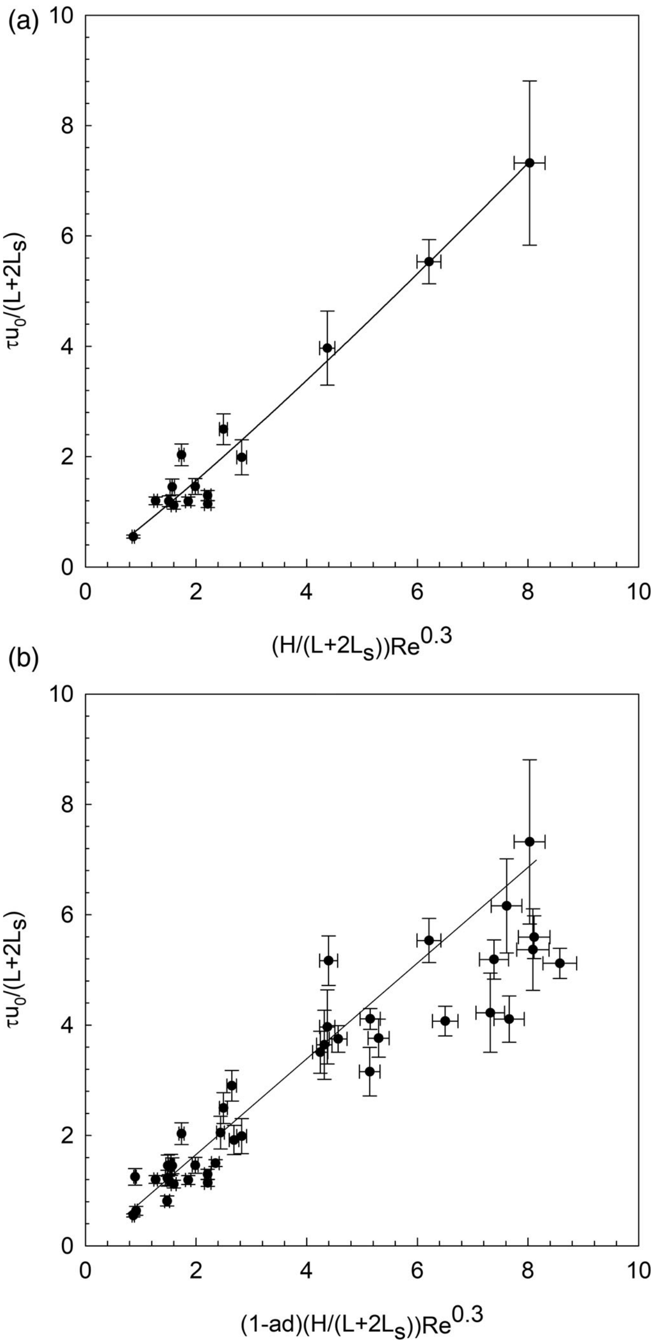

FIGURE 6 Non-dimensional residence time of the lagoon ($\tau u_0/(L + 2L_s)$) versus $(H/(L + 2L_s))Re^{0.3}$ for the cases without plants (a) and versus $(1 - ad)(H/(L + 2L_s))Re^{0.3}$ for the cases with plants (b). The line represents the best fit linear trend to the data represented in each plot

stress increased linearly with the canopy density. Therefore, density vegetation below 354 shoots m^{-2} (corresponding to $ad = 0.012$) produced similar behaviour to that of the non-vegetated case. In addition, the aspect ratio of the lagoon did not produce changes in the mean value of the Reynolds stress of the lagoon indicating, therefore, that a deeper lagoon did not affect the Reynolds stress at the interface compared to a shallower lagoon for the same lagoon depth. Hence, the main parameters determining the Reynolds stress were both the flow velocity and the canopy density.

The mean vertical flow velocity at the interface between the cavity and the water above increases from the leading edge of the cavity towards its centre, with negative velocities indicating that the flow enters the cavity zone in the first half of the lagoon. From $x/(L + 2L_s) = 0.55$ to the trailing edge of the cavity, the vertical velocity decreased progressively and increased to positive velocities towards the trailing edge, indicating that the flow was directed upwards, out of the lagoon. The pattern of the circulation of the flow within a cavity has been found to depend on its shape (Jackson et al., 2015; Weitbrecht & Jirka, 2001). For example, in squared lateral cavities, Ouro et al. (2020) found mean flow velocities across the cavity and directed outwards from the cavity at the leading edge and towards the cavity at the trailing edge, i.e., following a clockwise circulation. This is contrary to what has been found in the present study. This might be because the cavity studied here is vertical while in the other studies it was lateral. In a vertical cavity, it is expected that, due to gravity, the flow from the shallow region deepens as soon as it reaches the cavity, producing a counterclockwise circulation of the flow, that is, directed outwards at the trailing edge of the cavity and inwards at the leading edge of the cavity.

The non-dimensional mean residence time in the lagoon was found to depend on three parameters that characterize the lagoon system: the density of the vegetation surrounding the lagoon, the structural aspect ratio of the lagoon, and the Reynolds number of the flow in the flume. In all the cases studied, the non-dimensional residence time of the flow in the lagoon was $\tau u_0/(L + 2L_s) > 1$ (i.e., $\tau > t_{advection} = (L + 2L_s)/u_0$), indicating the relevant result that the presence of the lagoon increased the residence time of the fluid within the wetland system. When solving for the mean residence time (Equation (15)), an increase in the flow velocity at the inlet of the flume produced a decrease in the mean residence time, that is, an increase in the renewal of the flow in the lagoon. In addition, a relevant result of this study is that the residence time in the lagoon was found not to depend on the length of the lagoon. This result is in agreement with the results found in the lateral flow exchange in groins situated in river floodplains (Drost et al., 2014; Jackson et al., 2012). However, the residence time did depend on the depth of the lagoon in such a way that deeper lagoons are expected to have higher residence times. Nevertheless, in some cases climatic conditions such as air temperature or wind might result in a thermal stratification of the lagoon (Kellner & Pires, 2002). The presence of stratification has been found to reduce the volume of the active zones from winter (without stratification) to summer (with stratification) from 70% to 20%, respectively (Torres et al., 1997). Moreover, the mean residence time was dependent linearly on the available free area left by the plants in the shallow vegetated area ($1 - ad$). Nonetheless, the range of canopies studied produced a small variation in ad, resulting in a porosity of $1 - ad$ that ranged from 0.94 to 1. In this study, the mean residence time could be reduced by a maximum of 6% due to the presence of the vegetation compared to the non-vegetated case. In the case studied here, where plants were distributed all over the section of the flume, the flow velocity increased because of the presence of the plants and in such cases the increase in the flow resulted in a decrease in the residence time of the flow in the lagoon. In the field, typical porosities are in the range of 1–0.85 (Jadhav & Buchberger, 1995). In such cases, considering the linear relationship found here, the reduction in the residence time in the lagoon would be up to 15% due to the presence of plants. A reduction in the mean residence time could prevent the accumulation of pollutants in lagoons, thus maintaining the biodiversity and richness of macroinvertebrates thriving in the water column (Sun et al., 2019). The presence of vegetation has also been related to the increase in the biodiversity in ponds (Sun et al., 2019).

The results for the hydraulic residence time from the laboratory model mimicking field lagoons can be used to predict the experimental hydraulic residence times for the case of the Control and Baffled lagoons in the study from Ioannidou and Pearson (2018). In their study, both lagoons had the same structural dimensions of $W = 23.5$ m, $H = 3.8$ m and $L = 64.5$ m. The mean velocity in the Control lagoon was $0.0012\ m\,s^{-1}$ and $0.00034\ m\,s^{-1}$ in the Baffled lagoon. Therefore, the model here can be used to calculate the mean residence times, which results in 16.52 h and 39.96 h for the Control and Baffled lagoons, respectively. Ioannidou and Pearson (2018), however, calculated the experimental mean residence times of these lagoons were 16.7 h and 52.7 h, respectively, which are 1.01 and 1.32 times greater than that predicted by the model described herein. The discrepancy between the calculated and the experimental mean residence times might be due to the potential presence of dead zones in the experimental lagoon system caused by the presence of secondary eddies, which could further increase the residence times in the whole lagoon system.

Therefore, lagoons in wetlands and CW perform the role of increasing the residence time of the flow, thus favouring the removal of contaminants in the water. The residence time will, subsequently, depend on the characteristics of the vegetation and the flow velocity and lagoon depth. These parameters must be considered crucial in order to provide efficient water treatment for pollutants. In the case where the reaction time of the pollutants is greater than the mean residence time of the water in the system, pollutants will be only partially retained by the system (Gajewska et al., 2020). However, in the case where the reaction time is lower than the mean residence time of the water in the system, the pollutants will be retained in the system. Therefore, at first glance, a very long residence time could be desirable to provide the best efficiency of the system. However, many biological processes that take place in a lagoon and in the shallow areas rely on the activity of numerous aquatic organisms (bacteria, algae, zooplankton, plants, plant roots) that, in turn, require oxygenated water. Long residence times could lead to anoxic conditions within the lagoon that might, therefore, threaten the organisms that inhabit the ecosystem (Kennish & Paerl, 2010). Taking into account all these previous considerations, an appropriate mean residence time of the flow in the system is needed. One that will not only guarantee efficient wastewater treatment but also provide a safe environment for all the organisms living in the habitat.

The model presented here provides a tool for finding the mean residence time of the flow in a lagoon. This model would predict the residence time in lagoons with unimodal residence time distributions like in the Ioannidou and Pearson (2019) study. In cases where the residence time distribution is bimodal (Wanko et al., 2009), the model would not be able to predict the presence of dead zones where the flow is retained for a longer time. Neither would it be able to predict short residence times in other parts of the lagoon. To obtain this information, a new model would need to be studied. One that could account for the residence time distribution of the flow in the lagoon and from which more detailed information on the residence time distribution under different hydrodynamic conditions within the lagoon could be obtained.

5 | CONCLUSIONS

The presence of lagoons interspersed in wetlands and constructed wetlands has been found to increase the mean residence time in the lagoons themselves. A non-dimensional model based on three relevant parameters: the structural characteristics of the lagoon, the density of the vegetated zones surrounding the lagoon and the modified water flows due to the vegetation adjacent to the lagoon, revealed that the vegetation around the lagoon increased the flow velocity and reduced the residence time of the flow due to the presence of preferential flow paths generated in the vegetated shallow zones. The increase in the mean flow also produced a decrease in the residence time of the flow in the lagoon. In contrast, the deeper the lagoon, the greater the residence time of the fluid in the lagoon. The increase in the residence time of the flow in the lagoon was associated to the vertical velocity gradient within the cavity, with high velocities in the main channel decreasing with depth until the velocities reverse with respect to the main channel. The vertical distribution of velocities in the lagoon is related to the recirculation of the flow within the lagoon, with downward velocities at the leading edge of the lagoon and positive velocities at the trailing edge of the lagoon. The vertical velocity gradient at the centre of the lagoon was greater as the lagoon length decreased. This is due to both the greater proximity of this point to the vegetated shallow zones in small cavities and also to the smaller aspect ratio (length to depth) of the lagoon.

The mean residence time of the flow in the lagoon may be modified by changing the structural characteristics of the lagoons through the lagoon depth, the flow velocity through the vegetation or by regulating the presence of the surrounding vegetation. Indeed, the presence of vegetation could be used in different ways to avoid very high residence times that could result in anoxic conditions, which would imply a reduction of the vegetation around lagoons, or the contrary, to increase the ecological effect of vegetation surrounding lagoons to avoid extreme low residence times that could reduce the efficiency of the water treatment. Therefore, our study gives clear clues on how wetland landscape design can incorporate either engineering or ecological considerations, without compromising one or the other.

In addition, the presence of the vegetation in the shallow zone around the lagoon produced an increase in the mixing of the circulating flow in the vegetation, thus generating a homogeneous flow that might be potentially required for wastewater treatment purposes. That is, a homogeneous flow entering the lagoon would prevent the formation of preferential paths for chemicals in the lagoons. Finally, the aspect ratio of the lagoon did not change the Reynolds stress, that is, it did not produce any additional effect in the homogenization of the flow.

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NOMENCLATURE

H	lagoon water height (in m)
h_w	water height from the base of the flume (in m)
n	shoot density (in shoots m^{-2})
SPF	solid plant fraction, percentage of the area covered by the vegetation in the shallow area (in %)
d	stem diameter (in m)
N	total number of shoots or stems (in shoots)
A	area of the vegetated flume in the shallow vegetated area (in m^2)
a	frontal area per unit volume (in m^{-1})
u, v and w	three components of the velocity of the flow (in m s^{-1})
L_s	length of the slopes of the lagoon walls (in m)
L	length of the lagoon at the base (in m)
u_0	mean velocity at the entrance of the flume (in m s^{-1})
Q_{int}	exchange volume per unit time through the interface (in m^3 s^{-1})
V	volume of the lagoon (in m^3)
τ	mean residence time of the water in the lagoon (in s)
W	width of the lagoon (in m)
E	flux of water from the lagoon to the main stream (in m s^{-1})
Re	Reynolds number (non-dimensional)
ν, μ	kinematic and dynamic viscosities of water (in m^2 s^{-1} and Pa s, respectively)
u', v', w'	turbulent velocity components of u, v and w (in m s^{-1})
u_i, v_i, w_i	instantaneous velocity components (in m s^{-1})
$\overline{u}$,$\overline{v}$,$\overline{w}$	mean current velocities in the x, y and z directions, respectively (in m s^{-1})
$-u'w'$	Reynolds stress (in m^2 s^{-2})
ρ	density of water (in kg m^{-3})

L_m and L_{CW}	characteristic lengths of the model and constructed wetland, respectively (in m)
λ_L	ratio between the length scale of the constructed wetland and the model (non-dimensional)
Q_m, Q_{CW}	flow rates of the model and constructed wetland, respectively (in $m^3\ s^{-1}$)
A_m, A_{CW}	areas of the model and constructed wetland, respectively (in m^2)
$t_{advection}$	characteristic time for the advection process (in s)

DATA AVAILABILITY STATEMENT

This manuscript will have data available under request to the corresponding author.

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