

Case studies investigating hydraulic parameters in full-scale constructed wetlands

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Abstract: Constructed wetlands and ponds are increasingly used worldwide for purifying various types of water effluents. The lack of current knowledge on how efficient they are hydraulically and how to maximise their efficiency is still a challenge. As water movement plays key role in the pollutants mitigation, understanding of the hydrodynamic processes and factors related to pollutants removal would improve the estimation of mixing coefficients, influence of vegetation, and system design. The majority of previous research investigating the effects of wetlands' hydrodynamics on mixing and pollutants removal rates, has been conducted either in pilot-scale units under controlled conditions or via computer simulations, which might introduce uncertainties in the establishment of rules, the prediction of coefficients, and in modelling. Empirical data obtained from full-scale studies are required to quantify the effects of hydrodynamic factors on mixing processes and hydraulic performance during a season. This paper presents results from tracer tests conducted during 2015-2016 in six full-scale systems in the UK under different flow regimes, water depths, and in-/outlet conditions. The aim is to quantify their hydraulic performance and mixing characteristics, trying to open the black box. Results indicate that deeper systems controlled from downstream allow for longer residence times and provide greater treatment efficiency, and that retrofitting using baffles in the system significantly improves the hydraulic performance.

Key words: Constructed Wetlands; Full-Scale; Longitudinal Mixing; Residence Time; Fluorescent Tests

1. INTRODUCTION – LITERATURE REVIEW

Within the best management practices (BMP) context, constructed wetlands (CWs) and constructed ponds are increasingly utilized for the treatment of a variety of contaminants, including agricultural, urban and highway runoff, wastewater, mine and other industrial water effluent types. They aim to moderate and control the impact of source and non-point source water pollution, affording environmentally friendly and promising infrastructure (Vymazal and Březinová, 2015). Beyond purification properties, CWs and ponds offer a variety of services, including flood moderation, ecological and recreational use.

The success of CWs in removing a diversity of pollutants is registered and ratified by numerous published studies internationally (most recently, including Diaz et al., 2012; Fia et al., 2013; Lee et al., 2015; Pappalardo et al., 2016; Rossmann et al., 2013; Selvamurugan et al., 2010; Tournebize et al., 2015). Nevertheless, a great deal of research in CWs and ponds has been directed towards treatment processes, i.e. biological and chemical, comparing in-/outgoing concentrations of pollutants. However, this approach treats the systems as black boxes, overlooking the hydraulics and the fact that water flow is the key factor of the overall system performance (Polprasert and Bhattarai, 1985; Kadlec, 1994; Min and Wise, 2009). As such, there has been less research dedicated to the hydraulic performance of systems, to the investigation of vegetation related to hydraulic processes, and to the interdependence between hydraulic and water quality processes, which is intended to be covered in this literature review.

Factors that importantly determine the performance of CWs involve hydrological and meteorological elements (Persson and Wittgren, 2003), and actual system shape (Persson, 2000). It is generally agreed that the hydraulic residence time (HRT) dictates the removal efficacy, and is principally connected to hydrological conditions (Dierberg et al., 2002). Furthermore, Lee et al.

(2015) highlighted that rainfall intensity, rainfall depth, and antecedent dry days are critical components in the diffused pollutants removal. The overall hydrodynamics of CWs are highly dependent upon the aspect ratio (A_R), the in-/outlet arrangement, and obstructions appointment and determination, i.e. vegetation, isles etc. (Persson et al., 1999). Importantly, Johannesson et al. (2015) noted high dependence between pollutants' retention and CW A_R , recommending higher aspect ratios. Therefore, it is apparent that the hydraulic design of a CW should not be ignored.

Several studies have investigated factors that influence hydraulic performance of CWs and ponds, and have tried to optimise the systems and to provide general design guidelines (Aguwamba, 2006; Bodin et al., 2012; Diaz et al., 2012; German et al., 2005; Holland et al., 2004; Jadhav and Buchberger 1995; Koskiahio, 2003; Persson et al, 1999; Persson, 2000; Somes et al, 1999; Su et al, 2009; Wörman and Kronnäs, 2005). Nevertheless, the majority of the studies was either conducted via simulations, or has neglected vegetation. In order to add further knowledge and rigour on the CW hydrodynamics, studies have been undertaken using empirical data (lab or field), and vegetation (synthetic, dowel, or real) (Chyan et al., 2014; Nepf et al., 1997; Nepf, 1999, 2012; Shucksmith, 2008; West, 2016).

This paper presents empirical data obtained in full-scale cells of free-water surface (FWS) CWs and lagoons across the UK, and aims to assemble, contrast and assess results from several case studies. The ultimate objective is to contribute to the current knowledge regarding various hydraulic performance parameters, vegetation, and longitudinal mixing, obtained in full-scale units through the application of tracer tests.

2. METHODOLOGY – EXPERIMENTAL SETUP

2.1 The cases studied

The six full-size studied sites included four CWs and two ponds/lagoons. The topographic map and details of each system are provided in this section. The geometric characteristics, influent type, and location of the systems are summarised in Table 1.

Table 1. Geometric characteristics of the investigated systems, influent type, and location.

	SW1	SW2	NW	A-WMTS	Control Lagoon (Clough Foot)	Baffled Lagoon (Clough Foot)
General shape	Trapezium	Trapezium	Trapezium	Rectangular	Rectangular	Rectangular
Length (m)	35	32	30	105	64.5	64.5
Width (m)	10	7	6	40	23.5	23.5
A_R	3.5	4.6	5	2.63	2.74	2.74
Mean water depth (m)	0.2	0.2	0.4	0.5	3.8	3.8
Surface area (m ²)	175	169	121	4,200	1,516	1,516
V_{tot} (m ³)	22.7	21.3	57.0	2,100	5,760	5,760
Vegetation	Phragmites	Phragmites	Phragmites	Phragmites	-	-
Other obstacles	-	-	-	-	-	Baffle Curtains
Influent type	Agricultural Runoff	Agricultural Runoff	Agricultural Runoff	Mine Water	Mine Water	Mine Water
Location	Cambridge	Cambridge	Cambridge	Derbyshire	Yorkshire	Yorkshire

2.2.1 South wetlands, RSPB farm

Two CWs are located in the RSPB farm, Cambridgeshire, and are in-series and connected via a 115m open channel, with South Wetland 1 (SW1) upstream, and South Wetland 2 (SW2) downstream, as illustrated in Figure 1. Both units are shallow and unbunded, with fully emergent vegetation, *Phragmites australis*. Flow depends on precipitation.

2.2.2 North wetland, RSPB farm

North Wetland (NW) is located at the north part of the RSPB farm, Cambridgeshire. This is

deep, banded downstream, with water discharged via a closed pipe (see Figure 2). Flow depends on the seasonal rainfall, and is intermittent. *Phragmites australis* is the main plant species.

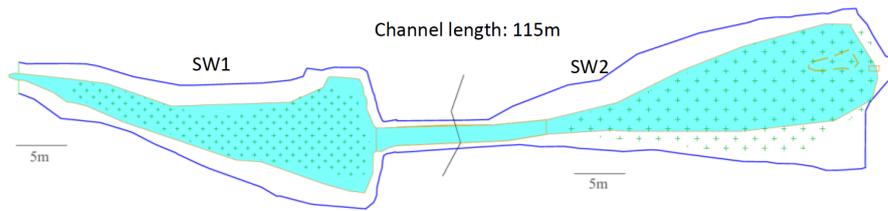


Figure 1. Schematic plan view for the in-series SW1 and SW2.

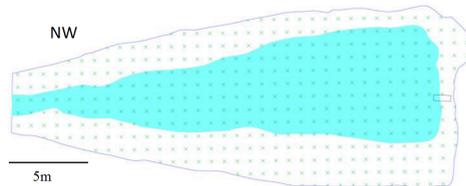


Figure 2. Schematic plan view for NW.

2.2.3 A-WMTS reedbed, Derbyshire

The A-Winning Minewater Treatment Scheme (A-WMTS) is a CW planted with *Phragmites*, in Derbyshire. It has two inlets, each of which receives water from an upstream lagoon, and two outlets, depicted in Figure 3. Water is pumped at a constant rate, and distributed along the inlet.

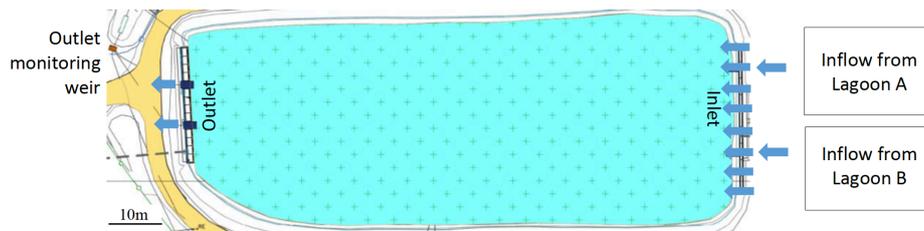


Figure 3. Schematic plan map for A-WMTS.

2.2.4 Clough Foot Lagoons, Yorkshire

Clough Foot minewater treatment scheme (Yorkshire), consists of two identically sized lagoons, operating in parallel arrangement. There is a control, and a baffled system, with the latter having been retrofitted by curtains to enhance lagoon hydraulics. The schematic of the baffled system is shown in Figure 4.

2.3 Hydraulic Tracer Tests

In order to derive residence time distribution (RTD), Rhodamine WT (RWT) was used as tracer, injecting an impulse at the inlet of each system. Fluorescent tracer concentrations were determined at the outlet using Cyclops-7 fluorometers.

2.4 Background on wetland hydraulic theory

Hydrodynamic transport parameters derived from the RTDs analysis are listed in Table 2.

In plug flow theory, it is customary to adopt the theoretical or nominal residence time, t_n . This is denoted as the fraction of wetland volume, V_{tot} , over discharge, Q . However, this basic standard rule

might not fit well in actual wetland conditions, due to: variations in flow velocity, heterogeneous mixing processes (i.e. bed topography and spatial vegetation distribution), and wind interference, all of which create a distribution of residence times in each water particle entering the system, ultimately leading to a distribution of travel times. Such deviations from the ideal pattern cause some water particles to depart earlier or later from the system resulting either in short-circuiting or dead zones (Thackston et al., 1987). The RTD function $E(t)$ is defined in:

$$E(t) = \frac{Q(t)C(t)}{\int_0^{\infty} Q(t)C(t)dt} = \frac{Q(t)C(t)}{\sum_{i=1}^n Q(t)C(t)dt} \quad (1)$$

where $E(t)$ =RTD function (s^{-1}); $Q(t)$ =outlet flow rate at time t ($m^3 s^{-1}$); $C(t)$ =outlet tracer concentration at time t (ppb); t =sampling time (s); dt =sampling time interval (s).

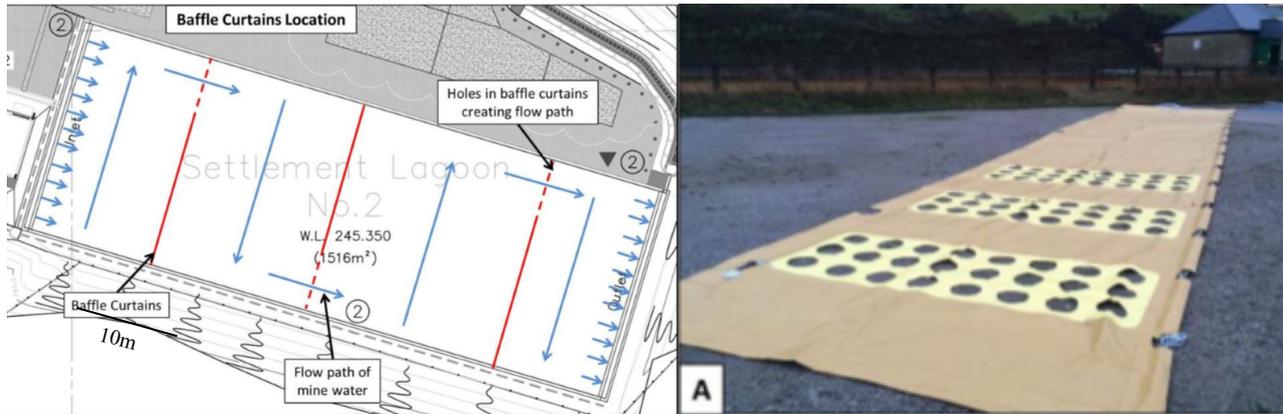


Figure 4. (Left) Clough Foot Baffled Lagoon, indicating curtain locations, orientations and flow path through the lagoon. (Right) Baffle curtains (taken from Chamberlain and Moorhouse, 2016).

Table 2. Hydrodynamic transport parameters obtained from RTD analyses.

	SW1	SW2	NW	A-WMTS	Control Lagoon (Clough Foot)	Baffled Lagoon (Clough Foot)
Q (l/s)	20	20	12	70	25	25
Vegetation configuration	F. EM. (Dec)	F. EM. (Dec)	F. EM. (Dec)	F. EM. (Dec)	No Veg	No Veg
t'_1	7.0 min	8.5 min	39 min	1.97 h	1.4 h	4.2 h
t_{10}	8.7 min	10.3 min	49.4 min	3.3 h	3.0 h	21.1 h
t_1/t_m	0.60	0.68	0.56	0.31	0.084	0.078
t_{50}/t_n	0.52	0.70	0.79	0.66	0.20	0.75
t_p	10 min	12.0 min	55 min	3.7 h	2.1 h	34.6 h
t_n	34 min	35 min	79 min	8.3 h	64 h	64 h
t_m	11.7 min	12.6 min	70.1 min	6.36 h	16.9 h	53.6 h
u_{mean}	0.047	0.044	0.010	0.0066	0.0011	0.0003
u_{max} (m/s)	0.079	0.065	0.017	0.021	0.013	0.004
σ^2 (h ²)	0.0036	0.0014	0.139	19.4	203.9	835.1
D_x (m ² /s)	0.073	0.023	0.019	0.236	0.025	0.003
$M_0=t_{90}/t_{10}$	1.69	1.40	2.00	5.09	12.45	4.42
Pe	21.2	63.3	19.61	4.17	2.79	6.88
N	10.6	31.64	9.80	2.08	1.40	3.44
V_{eff} (m ³)	17.4	15.4	50.5	1,604	2,258	3,439
e	0.58	0.74	0.89	0.76	0.26	0.84
λ	0.85	0.95	0.78	0.58	0.12	0.64

F. EM = Fully Emergent; No Veg = Unplanted

The mean residence time, t_m , is the average time that a tracer particle stays in the system, defined as the first moment of the RTD, given in:

$$t_m = \int_0^{\infty} tE(t)dt = \sum_{i=1}^n tE(t)dt \quad (2)$$

Variance, σ^2 (s^2), is a measure of the RTD spread and corresponds to the second moment, computed by:

$$\sigma^2 = \int_0^{\infty} (t_m - t)^2 E(t) dt = \sum_{i=1}^n (t_m - t)^2 E(t) dt \quad (3)$$

The hydraulic efficiency, λ , is a measure of the system's capacity to distribute the flow evenly within the occupying water volume, and also to achieve adequate mixing or recirculation. Persson et al. (1999) have classified λ into bands of good ($\lambda > 0.75$), satisfactory ($0.5 < \lambda \leq 0.75$), and poor ($\lambda \leq 0.50$). The λ in this paper was calculated by (Bodin et al., 2012; Chyan et al., 2014):

$$\lambda = \frac{t_p}{t_m} = e \cdot \left(1 - \frac{1}{N}\right) \quad (4)$$

in which t_p =peak concentration time (s) of RTD.

The shortest travel time, t'_1 , from the inlet to the outlet identifies a common index for short-circuiting. This refers to the quickest flow path in the system and corresponds to the first arrival time of the tracer at the outlet. Another commonly used index is t_{10} , which is the 10th percentile of the tracer having exited the outlet. Two further short-circuiting indices examined were t_{50}/t_n and t'_1/t_m .

3. RESULTS AND DISCUSSION

In this study, four CWs and two lagoons were assessed for their hydrodynamic properties through application of RWT. RTD curves are firstly analysed qualitatively to define the general hydrodynamic trends. Secondly, transport parameters obtained from the RTD analyses are compared (see Table 2). Lastly, discussion and general conclusions and rules are drawn from the empirical data, to add rigour and knowledge in the current operational and design CW/ponds considerations.

3.1 RTD curves

The obtained RTDs from the monitored tracer concentrations at the outlet of the systems are presented from Figure 5 to Figure 7, allowing assessment of the global flow trends. In particular, there is a strong correlation between the left Figures 5 - 7, suffering from strong short-circuiting. This type of RTD combines *plug flow*, with some *longitudinal mixing* for the long trailing edge according to Danckwerts (1953). The high short-circuiting in the control lagoon is attributed to the buoyancy effect from water temperature (stratification), where most of the dye was stuck at upper part of the water column, eventually preventing full mixing. The right Figures 5 - 7 indicate lower short-circuiting, higher e and greater dispersion, either due to more complete mixing, or due to prolonged tails.

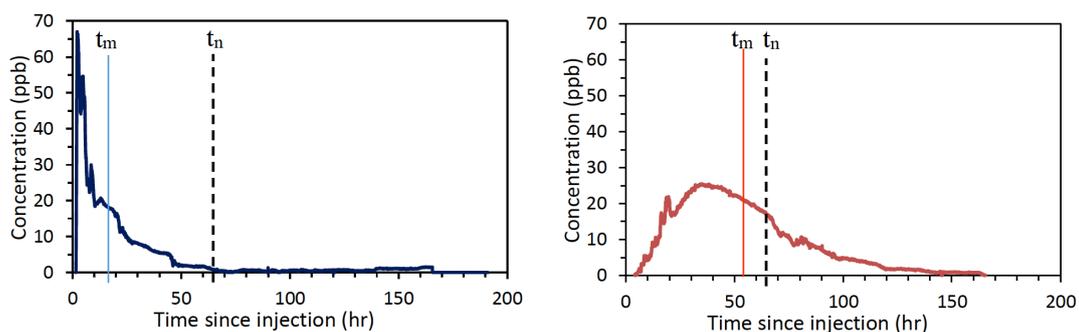


Figure 5. (Left) RTD in control Clough Foot Lagoon; (Right) RTD in baffled Clough Foot Lagoon.

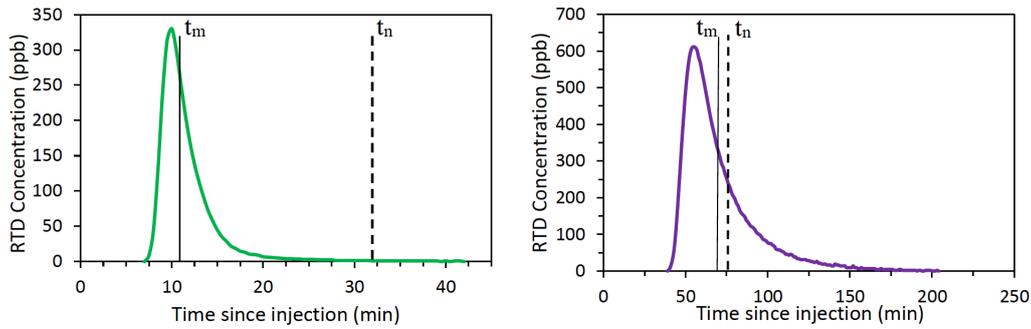


Figure 6. (Left) RTD in SW1; (Right) RTD in NW.

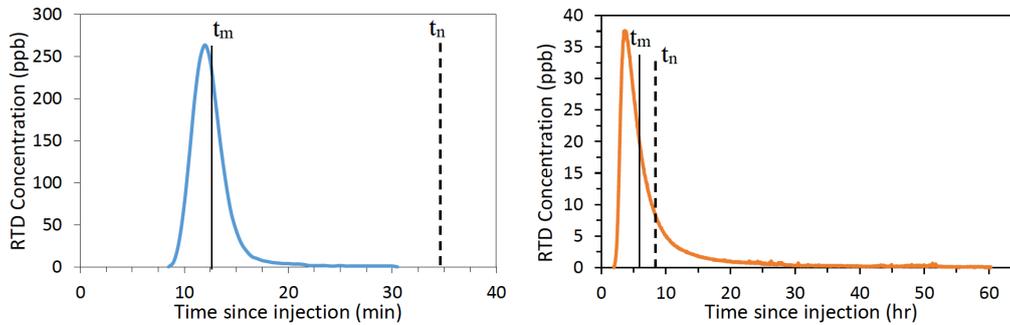


Figure 7. (Left) RTD in SW2; (Right) RTD in A-WMTS.

3.2 HRT, effective volume, hydraulic efficiency

HRT is an indication of the hydraulic performance, where longer HRT entails greater treatment (Dierberg et al., 2002; Lee et al., 2015; Stern et al., 2001; Pappalardo et al., 2016; Tournebize et al., 2016). HRT is dependent on the hydrology (i.e. water depth, flow rate), and hydraulics (i.e. obstructions, i.e. vegetation, and aspect ratio (system shape)) (Johannesson et al., 2015; Kadlec, 1990; Jadhav and Buchberger, 1995).

It is observed that for the same A_R the baffles retrofitting increased λ by 5 times, e by 3 times, and HRT by 7 times. Likewise, Su et al. (2009) recommended application of obstructions to enhance λ , if it is poor by construction. The authors furthermore found that the number of obstructions is not so important, as is their width, to enhance λ and reduce internal recirculations. It is recommended that A_R be at least larger than 1.88 to allow for $\lambda > 0.7$, which despite fulfilling this criterion for all the studied cases, it does not necessarily entail high λ . Furthermore, Su et al. (2009) recommend $A_R > 5$ to achieve $\lambda > 0.9$, case that is observed to apply merely for the NW. The divergence of Su et al.'s (2009) design recommendations should be dealt only as indicators, mainly because those results were produced through numerical simulations using ideal shapes, and because in reality this is rarely the case.

Good λ is noticed in the baffled lagoon, NW, SW1-SW2. However, by λ definition (Eq. 4, the high λ values obtained for SW1-SW2 are superficial, as the t_p and t_m values are very close to each other (Figure 6, left and right), inducing an erroneous outcome. To avoid seeming information, it would be advisable to consider additionally either e or V_{eff} values, which provide insights into the amount of volume actively used in the system.

3.3 Short-circuiting index

The short-circuiting indices used in this study included t'_1 , t_{10} , t'_1/t_m and t_{50}/t_n . Greatest short-circuiting was observed in SW1-2 and in the control lagoon. This is instantly observed in left Figures 5 – 7, where the t_n is substantially far from t_m , demonstrating advective flow as dominant pattern. However, NW, of similar shape and dimensions with SW1-2, retains the tracer 6 times

longer, dissipates maximum and mean velocities at least by 5 times, while t'_1 is 4-fold. This is particularly attributed to the deeper outlet layout conditions, providing a good reference for design construction.

Investigating the short-circuiting in the two identical lagoons, results suggest that the baffle curtains retrofitting attenuates the short-circuiting at least by 50%. Therefore, it is attested that simple system modifications using berms or baffles of long width can improve radically the short-circuiting.

Comparing between the four estimated indices, it is inferred that t'_1/t_m and t_{50}/t_n do not always represent the actual short-circuit conditions. To the contrary, t'_1 , t_{10} , showed more consistency and reliability. This is because the values of t_{50} and t_n , and t'_1 and t_m are very close to each other in the cases of SW1-2, thus producing erroneously high ratios of t_{50}/t_n and t'_1/t_m respectively. t_{50} is not a pure indicator of preferential paths, as it indicates the 50% percentile of the tracer removed at the outlet and also involves other physical phenomena, such as recirculations and dead regions. Therefore, both ratios do not find universal application to assess short-circuiting.

3.4 Comparative evaluation of the six investigated cases

Considering the highest t_m , the baffled lagoon probably affords the best removal efficiency. However, as its depth is 3.8m, it cannot be regarded suitable for CWs, because by design CWs' operational depth is up to 1m. Nonetheless, the curtains installation is an option that can be implemented in any system to improve internal hydraulics. NW would be deemed the best suited in terms of λ , where the impact of dead zones on removal mechanisms is minimised. This is attributed to the banded outlet layout. Greater dispersion occurs in the A-WMTS and control lagoon, while advective flow is pronounced in SW2 mainly due the irregular bed topography creating preferential path.

The differences in longitudinal mixing between the systems are further confirmed by the D_x , Pe and mixing index (M_0) values (see Table 2). There is a distinct alteration of flow regime after the baffles installation, with substantial increase of the HRT, effective volume utilisation, and λ .

4. CONCLUSIONS

The present study investigated full-scale case studies of different hydrodynamic properties and design considerations. Although the aspect ratio was similar or larger than what the literature recommends, the hydraulic efficiency and effective volume did not necessarily matched the expected results. Therefore, those design guidelines should yet be used as indicators, as they might not fully apply in reality. Furthermore, some studied cases demonstrated strong correlation in their RTDs and hydraulic performance, behaving like this due to high short-circuiting.

The various sizes and shapes radically influence hydrodynamic features of the systems and thus their removal capacities. Hence, the design of new systems should aim at the optimisation of shape, outlet conditions, and vegetation cover, as they all impact on the flow regime and dispersion levels. This could include for example: inlet and outlet layout optimisation, where entering water would be distributed evenly across to allow spread of the polluted inflow, and outlet would be banded/controlled to secure longer HRTs and greater hydraulic efficiency. For existing systems, retrofitting using obstacles would be an approved option to enhance hydraulic performance.

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