A Tracer Study in a Vertical Flow Constructed Wetland Treating Septage

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Abstract

Purpose – This study aims to investigate the hydraulic behaviour of a pilot-scale, two-staged, vertical flow constructed wetland (VFCW) for septage treatment, in terms of factors such as hydraulic retention time and hydraulic loading rate, and its influence on the treatment dynamics. Due to intermittent feeding mode of VFCW systems and variation in its loading, its hydraulic behaviour is highly variable, and need to be understood to optimize its treatment performance.

Design/methodology/approach – Tracer test were carried out using bromide ion with varying hydraulic loading rates (HLR) of 6.82 cm/d, 9.09 cm/d and 11.40 cm/d (i.e. equivalent to 75 L/d, 100L/d, and 125 L/d respectively). Tracer data is then analysed using the Residence Time Distribution (RTD) method.

Findings – RTD analysis showed that the increase in HLR increases the average hydraulic retention time (HRT). Subsequently, the increase in HLR results in a lower recovery of effluent, resulting in poor productivity in treatment. The study also showed that the removal of nitrogen and organic matter improved with increasing HRT. However, observations shows no correlation between HRT and total solids removal.

Originality/value – A performance evaluation method (by tracer) is proposed to understand the hydraulics and dynamics of treatment in VFCWs treating septage.

Keywords hydraulic retention time; tracer test; hydraulic loading rate; vertical flow constructed wetland; residence time distribution, septage treatment

Paper type Research paper

1. Introduction

Domestic wastewater in Malaysia is mostly segregated into greywater and blackwater. Blackwater is mostly treated in individual septic tanks (ISTs) (Bradley and Dhanagunan, 2004). ISTs effectively prevent the direct discharge of sewage by providing primary treatment. However, to operate ISTs at optimum, the accumulated sludge in the tanks needs to be removed periodically. This is because the sludge contains high concentrations of solids, organic matter, and nutrient. Construction of conventional treatment plants to manage the significant amounts of generated sludge is possible, but tend to be expensive and impractical for smaller towns and cities. Hence, a sustainable solution such as the vertical flow constructed wetland (VFCW) is proposed for management of septage.

Constructed wetlands have been used in the treatment of a variety of wastewater including agricultural wastewater (Tanner et al., 1995), industrial wastewater (Vrhovšek et al., 1996), and septage (T Koottatep et al., 2001; Paing and Voisin, 2005; Jong and Tang, 2016). Septage treatment using VFCW systems is complex due to the contaminants in septage being at least 10 – 100 times

45 stronger (Cofie et al., 2006) than domestic wastewater. Unlike other typical VFCW systems treating
46 wastewaters (Kadlec and Wallace, 2008), the filters on VFCW systems treating septage do not
47 incorporate a sand filter layer at the top. Instead, the substrate consists of larger particles sizes
48 compared to typical VFCW systems (treating wastewater or stormwater) to prevent clogging issues,
49 due to high concentrations of solids from septage (Jong and Tang, 2016).
50   The hydraulic behaviour of the VFCW, which is subject to factors such as its hydraulic retention
51 time (HRT) and water distribution within its substrate, is important towards understanding its
52 treatment processes and optimizing its efficiency. The study of hydraulic behaviour includes the
53 study of the influence of the hydraulic loading rate (HLR) on treatment efficiency, and HRT of the
54 system (Ghosh and Gopal, 2010), whereas the treatment performance of the system relies on its ability
55 to maintain its hydraulics (i.e. liquid motion) over its life span. The pollutant removal mechanism is
56 an integrated system in which physical, chemical, and biological processes are involved. In VFCWs,
57 removal of solids mostly occur through filtration on the surface of the substrate (Vymazal et al., 1998;
58 Kadlec and Wallace, 2008). Furthermore, microbial degradation within the substrate media removes
59 organic matter, whereby the removal efficiency increases with extended hydraulic retention time
60 (HRT) (Sirianuntapiboon et al., 2006). Similarly, the removal of nitrogen increases with increasing
61 HRT resulting in a more complete nitrification process. HLR may be utilized instead of solid loading
62 rate (SLR) due to a high level of variation in solids content (Koottatep et al., 2005). This is because
63 controlling SLR would require monitoring and measurement of total solids (TS) content before each
64 loadings, whereas HLR requires measurement of volume, which is easily obtainable on site.
65   Usually, the VFCW system is fed intermittently with alternating feedings allowing drainage and
66 full emptying of the system, which makes its hydraulic behaviour highly dynamic. During the
67 acclimatization stage, a sludge deposit layer is formed over the top layer of the system due to the
68 accumulation of organic matter and solids through physical filtration as the influent infiltrates
69 through the substrate medium of the system (Lana et al., 2013; Molle, 2014). According to Molle
70 (2014), the sludge deposit layer enhances filtration and water distribution on the system's surface, by
71 reducing the wetland's effective porosity and permeability. However, the intermittent feeding regime
72 increases the system's oxygenation efficiency, which improves microbial degradation of organic
73 matter accumulated at the top layer of the filter, avoiding clogging (Molle et al., 2006). Also, increased
74 degradation and dewatering of the sludge deposit layer between feedings results in formations of
75 cracks (Jong and Tang, 2016), which would reduce the overall HRT caused by preferential flows.
76 Ultimately, the reduced contact time would deteriorate effluent quality. Furthermore, dead zones
77 may also form throughout the operation resulting in reduced HRT and treatment efficiency of the
78 system (Cota et al., 2011). Nevertheless, shorter resting periods between loadings coupled with high
79 hydraulic loads reduces the probability of cracks formation as dewatering and mineralisation of the
80 sludge deposit layer is reduced. This is because it decreases re-oxygenation in the system, which
81 reduces aerobic biodegradation of the sludge deposit layer (Molle et al., 2006; Jong and Tang, 2016).
82 As a result, HRT increases and the treatment efficiency of the system is enhanced. Therefore, the
83 understanding of the hydraulic behaviour and the effects of different operational parameters on HRT
84 is crucial in optimizing treatment.
85   Tracer testing can be conducted as a means to understand the hydraulic behaviour of water in
86 the VFCW system (Kadlec and Wallace, 2008). Testing involves tracing the progress of solute
87 transport through the wetland system by addition of substances such as salt ions, fluorescent dyes or
88 titrated water. From the test, the actual residence time distribution (RTD) in the system can be
89 obtained. The RTD curve is the probability density function for residence time of water in the wetland
90 (Kadlec and Wallace, 2008). In simple terms, the curve represents the time that various portions of
91 the fluid spend in the system. Additionally, the overall HRT of the system can be obtained from the
92 RTD analysis.
93   In many studies, the efficiency of VFCW system is evaluated based on an influent-effluent
94 monitoring procedure, where the overall treatment performance is determined according to the
95 difference between influent and effluent quality (Paing and Voisin, 2005; Sirianuntapiboon et al.,
96 2006; Lana et al., 2013). Hence, the design of such systems still remain at a "black-box" level, in which

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"rules-of-thumb" are still used as design criteria. Moreover, the overall removal efficiency is commonly used to determine the capacity and operational strategies of the wetland beds (Kumar and Zhao, 2011).

Therefore, this paper presents a study of the hydraulic behaviour of a pilot-scale VFCW, which was aimed at determining the correlation between treatment dynamics and hydraulic behaviour in a treatment cycle. In particular, the retention time analysis (RTD) is carried out by performing a tracer test to determine the influence of HLR on the hydraulic behaviour of the VFCW.

2. Materials and Methods

2.1. Experimental Setup

The experimental setup of the VFCW system is shown in Figure 1 below. Each VFCW cell consist of similar substrate configurations in which only two cells were planted with *phragmites karka*. Planted cells were expected to have high treatment efficiency. From literature, macrophytes play a vital role in enhancing treatment performance by providing surfaces and oxygen for microorganism growth in the rhizophere for better nitrification. In addition, they release carbon from photosynthesis, which optimizes denitrification and organic matter removal (Langergraber, 2005; Saeed and Sun, 2012). Hence, this paper presents results from planted cells.
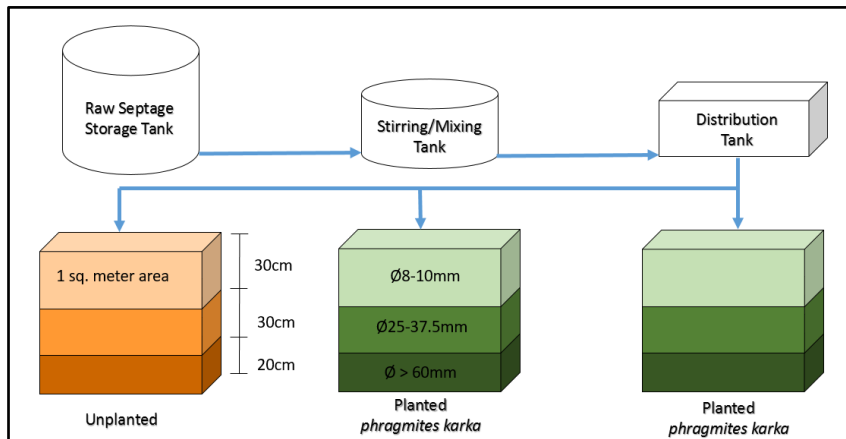
Figure 1 The design configuration of the first stage of the VFCW located in the university, which is the main focus in this study. Raw septage was obtained from residential sources and delivered to the raw septage storage tank. From the storage tank, septage is transferred to a stirring/mixing tank to be mixed homogeneously before transferring to a distribution tank and distributed to the individual VFCW beds via peripheral pumps.

Each cell consist of a 20 cm drainage layer built using large gravels ($\emptyset > 6.00$ cm) at the bottom of the bed. The main layers consist of two different sized crushed gravels ($\emptyset$ 2.5 – 3.75 cm and $\emptyset$ 0.80 – 1.00 cm), with the smaller-sized gravels stacked on top of the larger-sized gravels, each with a depth of 30 cm. The cells have a surface area of 1.1 m². Two vertical ventilation pipes were installed along the wetland beds to enhance reaeration. The septage used in this study was collected and delivered from residential sources by a local environmental servicer. The septage was filtered to remove any gross solids such as plastic material, clothing, hair, and others, to prevent clogging in the pipes without altering its original characteristics.

2.2. Experimental Tracer

The tracer test was carried out using sodium bromide (NaBr), due to its biological stability and conservative nature (Kadlec and Wallace, 2008). The tracer was injected into the septage and the mixture was homogenised before loading, similar to that of a step input injection, resulting in constant tracer concentrations in the influent (Fogler and Brown, 1986).

133 Intermittent feeds was utilized to ensure sufficient oxygen level in the wetland bed for enhanced
134 nitrogen and organic matter removal. Variations in the HLR was achieved by controlling the volume
135 of septage added. Low, medium, and high HLR (i.e. 6.82 cm/d, 9.09 cm/d, and 11.4 cm/d, equivalent
136 to 75 L/d, 100 L/d, and 125 L/d respectively) cases were studied. Due to high amounts of organic
137 content and solids in the septage, a resting period between loadings was required to prevent clogging
138 of the system.
139 Hua et al. (2014) states that for a resting period of 3, 6, and 10 days, the hydraulic conductivity
140 and effective porosity of the substrate media would improve significantly. However, for a resting
141 period of 10 days, a significant increase in effective porosity could occur, which would lead to short-
142 circuiting. Hence, the feeding regime incorporates a 6-day resting period between loadings. 3 days
143 resting is expected to be insufficient as the system would need longer time to recover due to the high
144 solids and organics content in septage. Table 1 below presents the HLRs used for this study. A total
145 of 12 experimental runs were conducted, with 4 runs conducted for each HLR case.

146 **Table 1** Feeding regime throughout operation of VFCW.

HLR (L/d)	HLR (cm/d)	Resting Period (days)
75	6.82	6
100	9.09	6
125	11.04	6

147 *2.3. Sampling and Testing*

148 The effluent flow rate was determined by measuring the volume collected at various time
149 intervals during each loading. A total of 200 mL of effluent was sampled for each time interval to
150 carry out the quality test. The concentrations of ammonium (NH_4^+-N), nitrate (NO_3^--N), dissolved
151 oxygen (DO), pH, and temperature were measured on site using an HQ40d portable multi-parameter
152 meter with specific probes. The laboratory analysis includes the measurements of Total Nitrogen
153 (TN) and Chemical Oxygen Demand (COD) using HACH DR2800 – spectrophotometer. The
154 concentration of total solids (TS) was determined using the oven drying method. The concentration
155 of bromide was measured using Hach® MM340 radiometer with bromide ion selective electrode.
156 Determination of the removal efficiencies is in accordance to (Liu et al., 2013) by comparing the
157 volume and concentration of the influent to the volume and quality of the effluent. However, a
158 conservative approach is conducted whereby the total volume of effluent replaces the volume of
159 influent. The removal efficiency equation is given as:

$$E = \frac{C_i \sum_{i=1}^{N} V_e - \sum_{i=1}^{N} C_e V_e}{C_i \sum_{i=1}^{N} V_e} \times 100\%, \tag{1}$$

160 such that, C_i and C_e are the influent and effluent concentrations [ML^{-3}] respectively, and V_i and V_e are
161 the volume of influent and effluent [L^3] respectively.

162 *2.3. Tracer Data Analysis*

163 This study utilized the method proposed by (Fogler and Brown, 1986) to analyse the tracer data
164 for step inputs. The variables determined from this method includes the average retention time,
165 variance, and tracer mass recovered to describe the effect of HLR on hydraulic behaviour of the
166 wetland system. Equations (2) to (4) below are equations for pulse input RTD analysis:

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt}, \tag{2}$$

$$\tau = \int_0^\infty tE(t) \, dt \tag{3}$$

$$\sigma^2 = \int_0^\infty t^2 E(t) \ dt - \tau^2 \tag{4}$$

167 such that, E(t) is the residence time distribution function [T^{-1}], C(t) is the concentration of tracer at
168 time, t [ML^{-3}], τ is the average residence time [T], σ^2 is the variance [T^2] and σ is the standard
169 deviation [T]. Equation (5) below relates the information to suit step input conditions:

$$E(t) = \frac{d}{dt}\left[\frac{C(t)}{C_0}\right]_{step} \tag{5}$$

170 such that, C_0 is the concentration of tracer in the feed [ML^{-3}]. Since flow is unsaturated in the VFCW
171 system, the varying flow rate patterns could significantly affect the tracer response curve (Headley
172 and Kadlec, 2007). Thus, to suit the unsaturated flow conditions, modifications to Equation (5) was
173 required. To easily compare and analyse tracer data from unsaturated flow, the tracer mass was used
174 instead of tracer concentrations (Headley and Kadlec, 2007). The new expression is given as:

$$E(t) = \frac{d}{dt}\left[\frac{m(t)}{M_0}\right]_{step} \tag{6}$$

175 such that, m(t) is the tracer mass at time t [M], and M_0 is the total recovered tracer mass [M].

3. Results and Discussion

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177 *3.1. Effect of Hydraulic Loading Rate (HLR) on Flow Pattern, Maximum Flow Rate, and Water Recovery*

178 The flow characteristics of the system with respect to variation in HLRs are presented here. Due
179 to space limitations, only one case was chosen and presented here. Furthermore, HLRs of 75 L/d, 100
180 L/d, and 125 L/d were examined to study the effects of low, moderate, and high HLR cases
181 respectively. Figure 2 below shows the typical effluent flow profile, which comprises of three stages
182 for all HLR cases. Also, a summary of the analysis are shown in Table 2.
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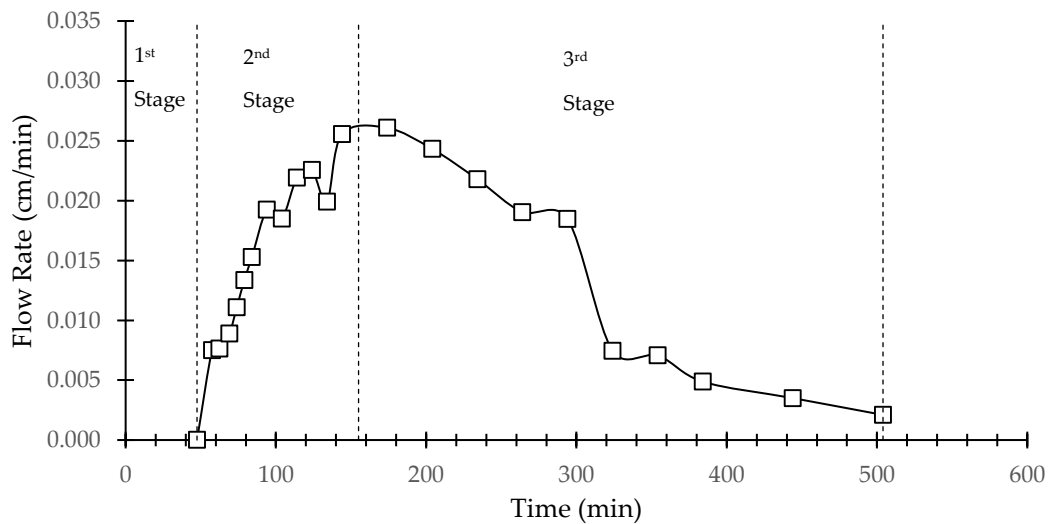
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185 **Figure 2** Typical effluent flow profile due to varying HLR cases, which consist of three (3) stages in
186 flow. The first stage is described by the delay in flow, followed by a transition to the second stage in
187 which a significant amount of flow was observed that increases to a maximum. The third stage is
188 observed as a steady decrease in flow after reaching a maximum flow.

189 **Table 2** Maximum effluent flow rate due to varying HLR and solids content.

HLR (L/d)	HLR (cm/d)	Average Sludge Thickness throughout operation (cm)	Total Solids Concentration (g/L)	Solids Content (g)	Maximum Flow Rate (cm/min)

75	6.82	5.00 – 6.00	2.00 – 5.00	150 – 375	0.015 – 0.065
100	9.09	4.00 – 7.00	8.00 – 12.80	800 – 1280	0.020 – 0.042
125	11.04	6.00 – 9.00	4.00 – 7.50	500 – 940	0.004 – 0.007

190   The first stage is determined as the period before effluent flow initiates. This delay may be
191   attributed to the time required for the influent to infiltrate the sludge deposit layer on the wetland
192   surface due to the low permeability of the layer before being discharged (Molle, 2014). It is during
193   this stage that significant water ponding was observed with negligible change in water depth. For
194   low, moderate, and high HLR cases, the duration of the first stage on average were 37 minutes, 59
195   minutes, and 29 minutes respectively. Comparison between low and moderate HLR cases shows that
196   the slower infiltration rate for moderate HLR cases is likely to be due to the difference in the solids
197   content of the septage, in which the highest solids content for the low and moderate HLR cases were
198   determined to be 375 gm and 1280 gm respectively. As a result, the effective porosity and
199   permeability reduces, resulting in a slower infiltration rate (Jong and Tang, 2016). On the contrary,
200   high HLR cases indicated the highest infiltration rate compared to the low and moderate HLR cases.
201   The increased infiltration rate may be driven by the significant hydraulic head difference (Molle et
202   al., 2006), although, solids content is generally high (as compared to the low HLR case), in addition
203   to having the greatest overall sludge deposit layer thickness throughout the operation. The first stage
204   in the effluent flow profile ends when a significant amount of effluent flow was observed, thus,
205   transitioning to the second stage of flow.

206   The transition into the second stage in the effluent flow profile occurs when a significant flow
207   rate was observed. It is during this stage that a rapid increase in flow rate was observed before
208   reaching a maximum outflow. Also, a significant change in water depth was observed compared to
209   that of the first stage in the flow profile. For low, moderate, and high HLR cases, the peak outflow
210   ranges from 0.015 – 0.065 cm/min, 0.020 – 0.042 cm/min, and 0.004 – 0.007 cm/min respectively. On
211   average, it was observed that low HLR cases have the highest flow velocity. Higher solids content as
212   well as a thicker sludge deposit layer may cause the slower flow velocity for moderate and high HLR
213   cases. The reduction in maximum flow rate indicated that the wetland is more susceptible to clogging
214   with a higher solids content, which was a result of increasing the HLR intensity (Molle, 2014). In
215   addition, the accumulation of the sludge deposit layer would increase the clogging tendencies in the
216   substrate medium, resulting in a reduced flow velocity (Langergraber et al., 2003; Rajabzadeh et al.,
217   2015). Moreover, the thicker sludge deposit layer would retain more water in the system, as well as
218   increase the capillary action, which would reduce the flow rate of water (Cota et al., 2011). In contrast
219   with the first stage of flow, in terms of controlling flow rate, the significance of solids content and
220   sludge thickness is more apparent than the hydraulic head difference for high HLR cases.
221   Nevertheless, the effect of hydraulic head difference reduces with decreasing water depth over time.

222   The third and final stage in the flow profile occurs when flow steadily decreases after reaching
223   a maximum outflow. This continues until no significant flow was visually observed. The steady
224   decrease of flow could be related to the decrease in hydraulic head over time, resulting in reduced
225   flow rate (Molle et al., 2006).

226   Furthermore, the results also indicated that the water recovery varied significantly for all HLR
227   cases. The average recovery for low HLR cases was approximately 76%, amounting to 57.1 L of
228   effluent. The percentage recovery for low HLR was the highest, followed by moderate, and high HLR
229   with 53% and 9% recovery (amounting to 53.0 L and 11.2 L) respectively. The low water recovery
230   may be due to the increase in sludge deposit and solids content. The higher solids content would
231   result in the system's tendency to clog due to reduction in effective porosity, hence, retaining more
232   water in the system (Langergraber et al., 2003). Nonetheless, higher hydraulic and organic loads
233   would decrease biosolids mineralisation of the sludge deposit layer, impeding the flow of water
234   through the system (Jong and Tang, 2016).

235   *3.2. Treatment Performance*

236   Table 3 below shows the overall treatment performance of the system throughout the study.
237   Firstly, the average removal of COD increases with increasing HLR intensity. This may be due to

enhanced filtration of particulate organic matter from the sludge deposit layer. The increasing solids
content with increased HLR intensity reduces the effective porosity of the sludge deposit layer,
resulting in enhanced filtration action (Molle, 2014). The increase in sludge deposit layer thickness
and solids content from increasing HLR intensity would result in reduced flow rate (Langergraber et
al., 2003; Rajabzadeh et al., 2015) resulting in increased HRT. The increase in HRT would enhance
aerobic degradation of organic matter. Aerobic degradation is more likely to occur due to the high
oxygen transfer of the VFCW system (Saeed and Sun, 2012). Similarly, total solids (TS) removal was
observed to increase with increasing HLR intensity. This would suggest enhanced filtration of solids
from the sludge deposit layer. The increase in solids content and thickness of the sludge deposit layer
would reduce its effective porosity, hence improving the filtration of solids. However, it should be
noted that removal of TS is highly dynamic with average removal percentages ranging from 42.9% -
87.5%, 78.1% - 91.3%, and 71.4% - 97.9% for low, moderate, and high HLR cases respectively. Large
fluctuations in TS removal would indicate that some of the filtered solids were flushed out of the
system due to size reduction from resting between loadings (Sharma and Yortsos, 1987). Hence, the
removal of TS is governed by the resting period and flow velocity.

Table 3 Summary of overall treatment performance for each experimental runs.

| HLR (L)	Influent (Inf.) and effluent (Eff.) contaminants mass (g), and removal efficiencies (RE) (%)											
	COD			TS			NH$_4^+$-N			TN		
	Inf.	Eff.	RE	Inf.	Eff.	RE	Inf.	Eff.	RE	Inf.	Eff.	RE
75	76.0	6.0	92.1	247.8	75.4	69.6	2.6	0.4	84.6	6.5	1.2	81.5
	85.2	5.5	93.5	86.1	10.8	87.5	1.9	0.4	78.9	2.4	0.7	70.8
	65.6	5.5	91.8	90.2	51.5	42.9	2.9	0.4	86.2	5.2	0.8	84.6
	56.0	4.2	92.5	78.6	11.2	85.7	2.0	0.6	70.0	4.4	1.1	75.0
100	528.0	15.5	97.1	902.8	197.5	78.1	4.4	1.5	65.9	17.1	2.0	88.3
	417.1	21.7	94.8	610.7	96.9	84.1	4.1	1.0	75.6	9.8	2.0	79.6
	294.6	11.9	96.0	322.5	28.0	91.3	3.4	1.0	70.6	10.5	5.1	51.4
	117.4	1.9	98.4	243.4	41.0	83.2	3.7	0.2	94.6	5.0	0.8	84.0
125	54.6	0.5	99.1	130.6	36.5	72.1	0.9	0.03	96.7	4.5	0.9	80.0
	29.5	0.3	99.0	67.0	6.8	89.9	0.3	0.01	96.7	2.0	0.1	95.0
	118.1	0.7	99.4	173.4	3.7	97.9	1.1	0.04	96.4	2.8	0.6	78.6
	33.7	0.5	98.5	52.5	15	71.4	0.9	0.02	97.8	1.6	0.2	87.5

Moreover, no significant differences were observed for the removal of NH$_4^+$-N between low and
moderate HLR cases. The average removal efficiencies for low and moderate HLR cases were
approximately 80%. However, high HLR cases was observed to have average removal efficiencies of
97%. The sludge deposit layer may favour NH$_4^+$-N adsorption and subsequently, nitrifying
ammonium during resting (Molle, 2014). A thicker sludge deposit layer, as that of high HLR cases
indicates that the adsorption site for NH$_4^+$-N is larger as compared to those of low and moderate HLR
cases. Nevertheless, a more complete nitrification of NH$_4^+$-N would have occurred due to the reduced
flow rate for high HLR cases as compared to that of low and moderate HLR cases (Sirianuntapiboon
et al., 2006). Likewise, low and moderate HLR cases show no significant differences for the removal
of TN with average removal efficiencies of approximately 77%, high HLR cases showed better
efficiency in TN removal with efficiencies of approximately 85%. Although removal of TN was highly
dependent on denitrification process in constructed wetlands (Saeed and Sun, 2012), denitrification
in VFCW is assumed to be insignificant due to the system's ability to provide high levels of oxygen.
Also, TN in septage is the sum of organic nitrogen and NH$_4^+$-N (USEPA, 1999). Therefore, the

269 concentrations of TN would be highly affected by the removal of NH_4^+-N. Hence, the decrease in TN
270 concentration over time was likely to be influenced by nitrification of ammonium, whereby the
271 removal is further enhanced with increasing HRT. Furthermore, the TN removal rate is comparable
272 to those in literature with removal efficiencies exceeding 80% (T. Koottatep et al., 2001; Paing and
273 Voisin, 2005).

274 *3.3. Retention Time Distribution (RTD) Analysis*

275 In addition to the established influent-effluent monitoring method, a better description of the
276 treatment performance of the VFCW can be obtained by studying the correlation between its
277 treatment performances with the hydraulic behaviour of the water in the system. This provides a
278 better insight to the mass loss of pollutant in the system. The relationship between the mass loss of
279 pollutant in the system is correlated to the HRT by RTD curves of pollutant concentration, where the
280 RTD curves represent the time which various portion of fluid spends in the system. Previous studies
281 have shown that increasing HRT would result in better treatment performance (Cota et al., 2011; Jong
282 and Tang, 2016; Molle et al., 2006)
283 Figure 3 below shows the RTD curve plots for low, moderate, and high HLR cases. The RTD
284 curves were observed to conform to the effluent flux profiles (as shown in Figure 2) for unsaturated
285 conditions. This was expected as the tracer concentration was injected using a step input method. As
286 the tracer is conservative in nature, its mass would be consistent, thus, the RTD curves produced
287 would be expected to have a similar profile to that of effluent flux curves for individual HLR runs.
288 The obtained RTD curves confirms the assumption that tracer is homogenised in the liquid, and
289 follows the same flow pattern, giving it a reasonable reflection of the hydraulic RTD (Headley and
290 Kadlec, 2007).
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(a)   (b)

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294 (c)
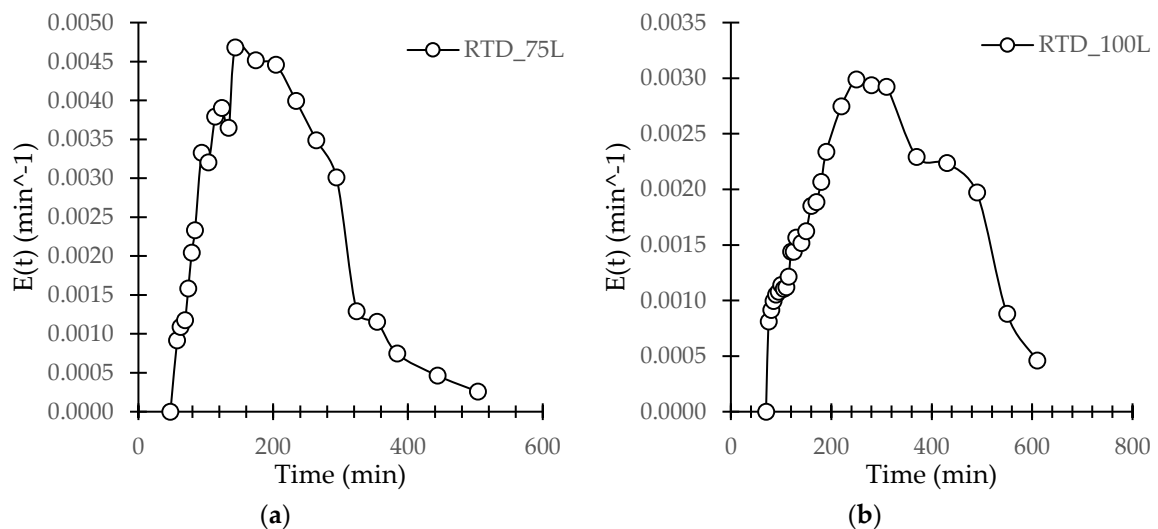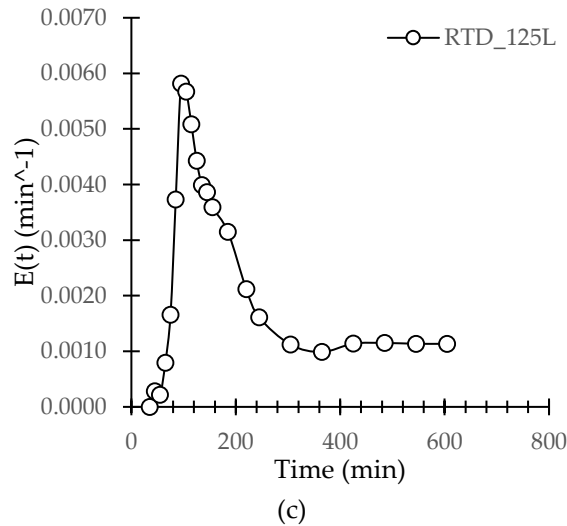
295 **Figure 3** Representative RTD curves presented for varying HLR cases: (a) low HLR; (b) moderate
296 HLR; (c) high HLR. The RTD curves observed conforms to that of the effluent flow profile of all HLR
297 cases.

298 Still, the RTD curves observed do not show a typical bell shaped curve as those found in
299 literature (Kadlec and Wallace, 2008; Giraldi et al., 2009). Instead, the asymmetry and long tail
300 observed is similar to those found in (Cota et al., 2011). Hence, it is in all likelihood that the
301 asymmetry and long tail observed in the RTD curves is due to diffusion of water into dead zones in
302 the system, which is gradually released over time. Also, the long tail may be related to the adsorption
303 of tracer in the biomass (Levenspiel, 2000).
304 Further analysis shows that the average HRT for low, moderate, and high HLR cases are 183
305 minutes, 263 minutes, and 288 minutes respectively. The increase of HRT may be related to the
306 increase in solids content and sludge deposit layer thickness, which would have reduced the flow
307 rate of effluent due to reduced effective porosity and capillary effect respectively (Molle, 2014).
308 Moreover, the effect of increased HRT for high HLR cases was observed with the increase in COD,
309 NH_4^+-N and TN removal.
310 Additionally, the degree of mixing (i.e. variance), which characterises a distribution of residence
311 times in the wetland (i.e. the parcel of water travelling through the substrate media of the wetland
312 reaches the output at different times) (Headley and Kadlec, 2007), increased as HLR increased. The
313 average variances of the low, moderate, and high HLR cases were 7047 min^2, 9062 min^2, and 17577
314 min^2 respectively. Similar observations were reported in (Giraldi et al., 2009), which stated that the
315 degree of mixing in the system is controlled by HLR intensities, in which higher HLR would
316 ultimately result in a more thorough mixing of fluid in the VFCW system. Therefore, resulting in
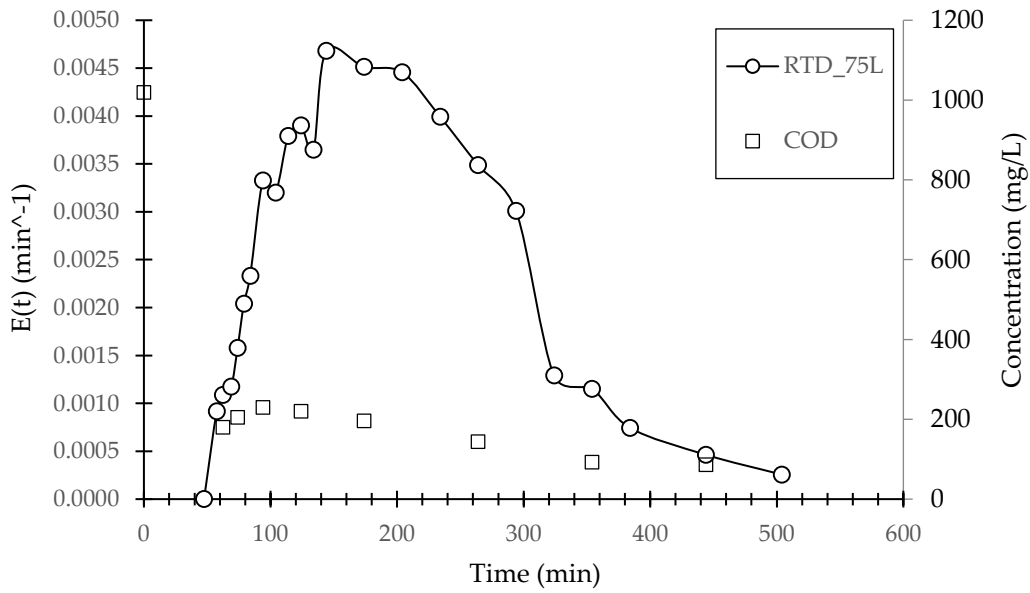317 greater treatment performance.
318 A correlation between treatment dynamics and hydraulic behaviour can be observed by plotting
319 RTD curves with the concentration of pollutants. Figure 4 below shows the concentration of
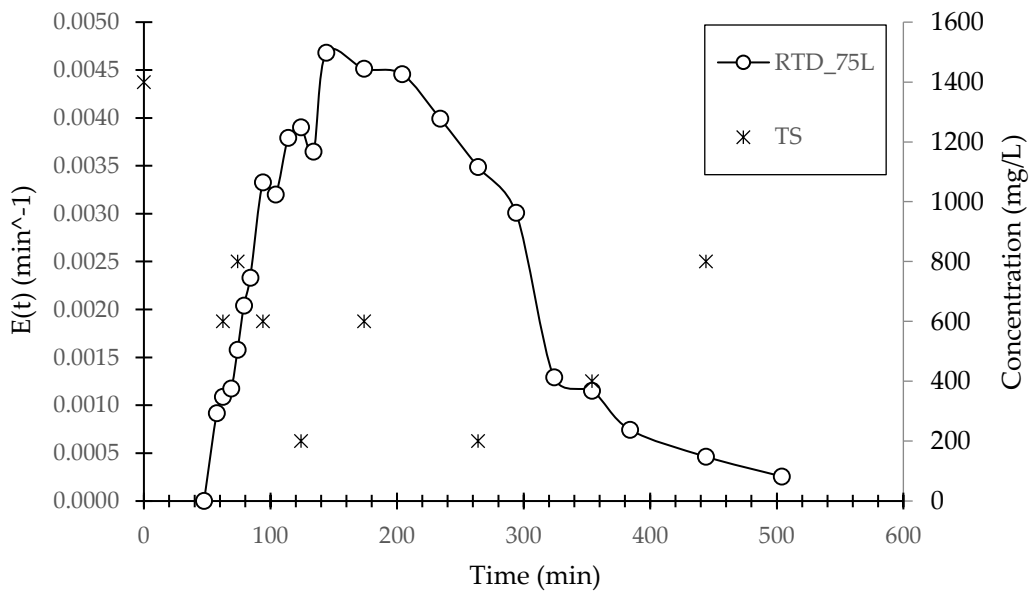320 pollutants, namely nitrogen compound, COD, and TS, plotted against RTD curves.
321
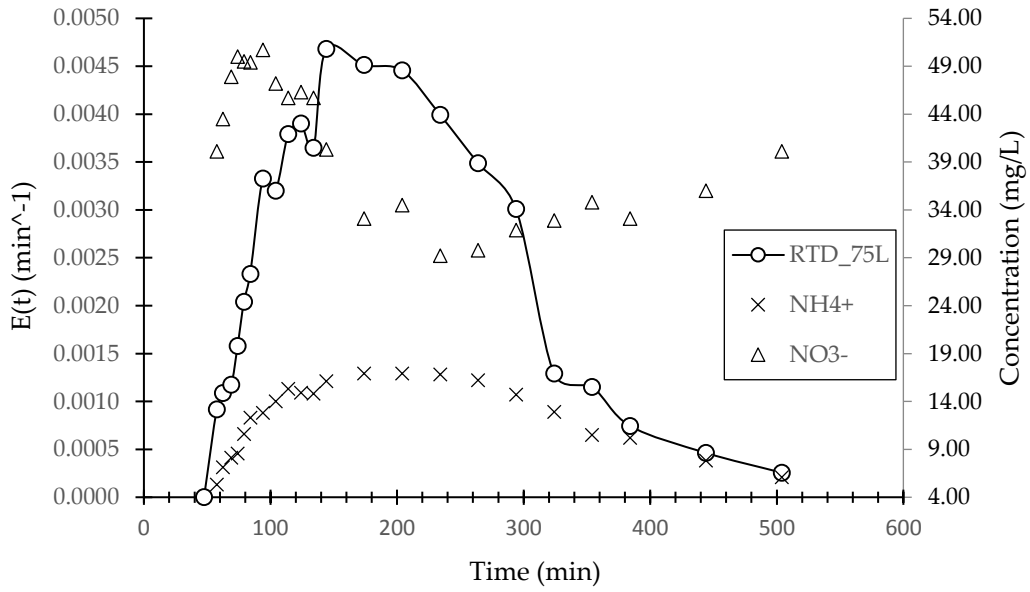
322
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(a)

324
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(b)

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327   (c)

331   Figure 4(a) indicates that the amount of time effluent spends in the system highly affects NH_4^+-N and NO_3^--N removal. The NH_4^+-N concentration decreases as the time spent by the effluent in the wetland system increases. However, it is interesting to note that at the initial stages of flow, the concentration of NH_4^+-N increases significantly with HRT before stabilizing and decreasing again. This could result from the flushing out of adsorbed NH_4^+-N in the biofilms. The lower concentrations of NH_4^+-N indicated that most of the adsorbed NH_4^+-N underwent nitrification during the resting period. Likewise, the increase in NO_3^--N concentration conforms that most of the adsorbed NH_4^+-N underwent nitrification. At the initial stages of flow, NO_3^--N concentration increases significantly which suggest that NO_3^--N is flushed out. Over time, the concentration of NO_3^--N decreases before increasing again with increasing HRT. The decrease would suggest that the flushing rate of nitrified NH_4^+-N adsorbed in the biofilm is greater than the rate of adsorption. Thus, the results are consistent with literature, which states that increasing HRT would increase nitrogen removal (Sirianuntapiboon et al., 2006).

344   The effect of HRT is also prominent in the removal of organic matter as seen in Figure 4(b). The concentration of COD showed significant reduction from its initial values, followed by a gradual decrease in concentrations with increasing HRT. The significant drop in concentration may imply enhanced filtration from the sludge deposit layer (Molle, 2014). Moreover, improvement in filtration efficiency may also result from a thicker sludge deposit layer as observed from the higher removal efficiency in high HLR cases. Subsequently the increased contact time between contaminants and the substrate would improve aerobic degradation (Saeed and Sun, 2012), resulting in the gradual decrease in concentration with increasing HRT.

352   Finally, no correlation between TS removal and HRT was observed. This is indicated by the degree of fluctuation in TS concentration with increasing HRT. However, as previously discussed, the removal of TS may be related to the resting period and flow velocity.

4. Conclusions

356   This study examined the effect of HLR on the hydraulic behaviour of VFCWs designed for septage treatment, and its correlation with the treatment dynamics. RTD analysis was conducted to understand the hydraulic characteristics of the system by means of analysing the average HRT as well as the treatment dynamics due to varying HLR intensity.

360   Effluent flow patterns for each loading resulted in a predictable trend, categorized by three stages of flow. The outflow velocity observed in all experimental runs suggest that solids content and thickness of sludge deposit layer was the controlling factor, with reduced outflow velocity as solids content and thickness of sludge deposit layer increases. Water recovery varied significantly for all HLR cases. A reduction in average recovery was observed with increasing HLR. The system's ability to recover water was observed to be related to the solids content and sludge deposit layer.

366   Overall removal of organic matter and nitrogen compound improved with increased HRT. However, no correlation between HRT and total solids removal was observed. The effects of HRT on treatment dynamics was further analysed by plotting RTD curves with pollutant concentrations. It was determined that the sludge deposit layer may have played a vital role in the removal of organic matter, nitrogen compounds and total solids. However, total solids removal was highly dynamic and easily influenced by resting periods between loadings and flow velocity.

372   It is expected that this study would contribute to a better understanding of the hydraulic behaviour and the treatment dynamics for a VFCW system designed for septage treatment as well as to support the modelling and calculation of pollutant removals. Further emphasis should be made to understand the role of sludge deposit layer in terms of hydraulics and treatment efficiency.

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