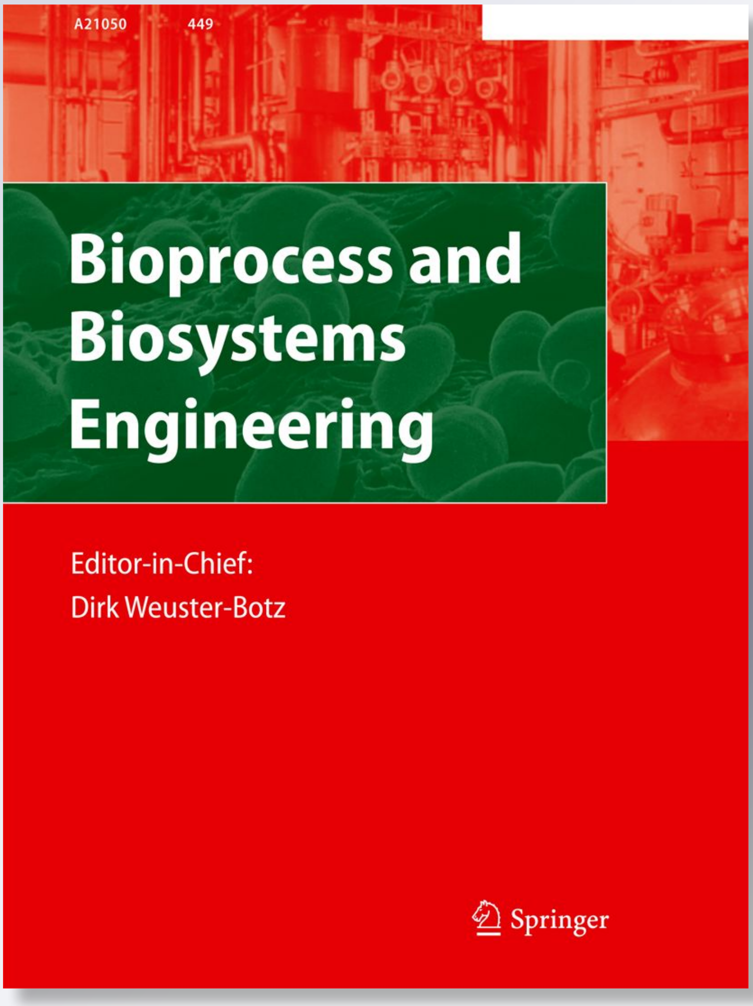
A tracer study for assessing the interactions between hydraulic retention time and transport processes in a wetland system for nutrient removal

Ni-Bin Chang, Zhemin Xuan & Martin P. Wanielista

Bioprocess and Biosystems Engineering

ISSN 1615-7591

Bioprocess Biosyst Eng
DOI 10.1007/s00449-011-0578-z



Springer

Bioprocess Biosyst Eng
DOI 10.1007/s00449-011-0578-z

ORIGINAL PAPER

A tracer study for assessing the interactions between hydraulic retention time and transport processes in a wetland system for nutrient removal

Ni-Bin Chang · Zhemin Xuan · Martin P. Wanielista

Received: 14 December 2010 / Accepted: 22 July 2011

Abstract In this study, a new-generation subsurface up-flow wetland (SUW) system packed with the unique sorption media was introduced for nutrient removal. To explore the interface between hydraulic and environmental performance, a tracer study was carried out in concert with a transport model to collectively provide hydraulic retention time (7.1 days) and compelling evidence of pollutant fate and transport processes. Research findings indicate that our pollution-control media demonstrate smooth nutrient removal efficiencies across different sampling port locations given the appropriate size distribution conversant with the anticipated hydraulic patterns and layered structure among the sorption media components. The sizable capacity for nutrient removal in this bioprocess confirms that SUW is a promising substitute for an extension of traditional on-site wastewater treatment systems.

Keywords Constructed wetlands · Tracer study · Transport model · Biogeochemical science

Introduction

Constructed wetlands have been widely applied for a variety of wastewater treatments because of their low construction, operation, and maintenance costs, excellent pollutant removal performance, and lower energy consumption. As promising sustainable infrastructure alternatives for wastewater treatment in the twenty-first century, constructed wetlands can remove pollutants with the aid of the complex interactions among water, substrate, plants, and microorganisms through a variety of physical, chemical, and biological mechanisms. Physical functions are mainly filtration by the substrate layer, plant-root zone, and sedimentation. Chemical reactions consist mainly of chemical precipitation, adsorption, ion exchange, and oxidation–reduction (REDOX) reactions. Biochemical reactions mainly refer to microorganisms degrading and removing pollutants in aerobic, anoxic, and anaerobic conditions. The performance of constructed wetlands relies on many factors. In addition to wetland dimension, waste loading and other external conditions, hydraulic retention time (HRT) and flow patterns have a significant influence on removal efficiency. A tracer study is the most direct approach to obtain the information of internal hydraulics in constructed wetlands.

Tracer studies are used to determine the direction and velocity of water movement by monitoring the matter or energy carried by water. They can also indirectly identify other hydraulic parameters such as dispersivity, porosity, and hydraulic conductivity through further analyses. An ideal tracer should be representative, meaning it follows the same path as the water and is easily detected, inexpensive to analyze, and has low toxicity, high solubility, and low background concentration in the natural environment. The three most popular choices for tracers are isotopes, ions, and dyes. Isotope technology is a common tool used to determine the fate and transport of isotopic nitrogen in nutrient treatment. Kadlec et al. [1] used the stable isotope ^{15}N introduced as ammonium in two subsurface-flow (SSF) wetlands receiving primary meat processing water and found little of the tracer in gas emissions ($\sim 1\%$). The majority of the tracer was found in plants (6–48%) and sediments (28–37%). Ronkanen and Kløve

---

N.-B. Chang (✉) · Z. Xuan · M. P. Wanielista
Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, FL 32816, USA
e-mail: nchang@mail.ucf.edu

[2, 3] used the stable isotope ^{18}O/^{16}O ratio and tracer tests to help prevent or reduce short-circuiting and dead zones in peatlands. Although isotope technology has high accuracy, it is expensive. Ionic compounds, especially bromide, have been widely used as groundwater tracers [4, 5]. Małoszewski et al. [6] used instantaneously injected bromide to evaluate hydraulic characteristics for a duckweed pond in Mniów, Poland. The tracer study result showed that the wastewater flowed along three different flow-paths to the exit. But the concentration of bromide in natural waters may be present well above detection; thus, large quantities of ionic tracers would be required to surpass the background levels. Another shortcoming is that, bromide is typically analyzed in a laboratory; portable probes available for direct measurements in the field are less reliable. In comparison, dyes have advantages of low detection limits, zero natural background, and relatively low cost. One of the most popular dyes is Rhodamine WT (RWT). Dierberg and DeBusk [7] compared RWT and lithium chloride (LiCl) for their suitability as hydraulic tracers in wetlands and found that both tracers returned more than 95% of the injected amount in submerged aquatic vegetation-dominated mesocosms. They concluded that although RWT was not as stable as LiCl at initial concentrations less than 60 mg/L, the reduction in the recoveries did not affect the accuracy of key hydraulic parameters. Lin et al. [8] performed hydraulic tracer tests in California, USA, to evaluate the suitability of RWT as a tracer for wetland studies and to determine HRT distribution of the wetlands. They evaluated the performance of RWT by comparing the breakthrough curve (BTC) of RWT to that of bromide in a pilot-scale test and found that the BTCs of RWT and bromide were equal. Giraldi et al. [9] used RWT as a square input signal to develop their numerical wetland model.

In addition to a tracer test that is able to track down the overall hydraulic pathways, another important consideration is the fluid dispersion function to help illuminate local transport behavior in the constructed wetlands. Two theoretically ideal reactors, the plug flow reactor (PFR) and continuously stirred tank reactor (CSTR), represent the two extreme flow patterns, the "no mixing" in PFR versus "perfect mixing" in CSTR. Zero mixing of PFR will result in an unchanged tracer spike flowing out of the system after one nominal HRT. In a CSTR reactor, however, the tracer is assumed to uniformly distribute throughout the entire cell immediately after entering the system. As a result, an exponentially declining tracer output curve will be observed at the outlet. Obviously, constructed wetlands are neither PFR nor CSTR, but somewhere in between. A particular skewed bell-shaped response curve observed in constructed wetlands can be possibly depicted by a tanks-in-series (TIS) model [10]. This type of model provides a more flexible way to simulate the hydraulic performance in constructed wetlands with varying internal structures. In addition to TIS, three other flow models, including plug flow with dispersion [11, 12], one-dimensional transport with inflow and storage [13, 14], and computational fluid dynamics [15–17] also appear in the wetland literature. With less complexity, the hydraulic parameter number of tanks in series model (NTIS), an extension of the TIS model, is deemed as the most popular flow model in this field.

A thorough review of the HRT determination and TIS quantification for free water surface (FWS) wetlands and horizontal subsurface flow (HSSF) wetlands can be found in Kadlec and Wallace [18]. However, little work has been published to estimate the parameter number of TIS in subsurface upflow wetland (SUW), especially from a "global" versus "local" perspective. The objectives of this study are thus to (a) conduct a tracer study to identify the actual HRT and the flow patterns based on the retention time distribution (RTD) function in an SUW for treating on-site wastewater, and (b) understand the interactive relationships of flow patterns and transport processes between sub-cells due to the varying effect of the media permeability. The results will generate advanced insights into hydraulic dispersion in relation to biogeochemical processes to bridge the gap between hydraulic design and biogeochemical science in the knowledge base of constructed wetlands.

Materials and methods

Site description and experimental design

A performance-based and passive constructed wetland system (i.e., an SUW) following a septic tank was created at University of Central Florida for nutrient removal in 2008. Four parallel 1.52 m wide × 3.05 m long × 0.91 m deep cells were constructed in the test bed, three with different plant species and one with no species to serve as the control case (Fig. 1) [19]. For the purpose of groundwater protection, each cell was encased from surrounding soil by a wooden frame containing an impermeable liner at bottom, a gravel substrate (30.48 cm thick), fabric

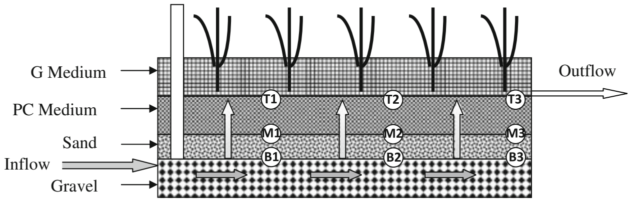


Fig. 1 Profile view of wetlands [19]

interlayer (DuPont^{TM} Weed Control Fabrics), a 15.24 cm sand layer, a 30.48-cm thick pollution control media (50% Citrus grove sand, 15% tire crumbs, 15% sawdust and 20% lime stone; PC media hereafter) layer, growth media (75% expanded clay, 10% vermiculite and 15% peat moss; G media hereafter), and selected plants (Fig. 1). The tracer experiment was conducted in one of the four wetland cells with Canna planted for the enhancement of nutrient removal because Canna outperformed the other two cells planted with blue flag and bulrush [19]. All three planted cells exhibited better removal efficiencies than the control cell with no plant species [19]. The upstream septic effluent was the inflow for final treatment at the selected wetland cell, and the nutrient removal efficiencies were measured based solely on the inflow and outflow at the wetland cell. After completion of nutrient removal testing, the same cell was used to support a tracer test for approximately 2 more weeks. The hypothesis of wetland hydraulics in this study is that the gravel layer will be fully saturated first due to its larger pore space. The water level will then rise gradually and flow out of the cell after passing through the sand and PC media layers. Two customized oxygenators (PVC pipe wrapped with fabric at bottom) introduced oxygen into the gravel layer to enhance the nitrification at the bottom of the wetland cell [19]. The samplers in each wetland cell were installed at 33, 67, and 100% along the longitudinal direction of the wetland. Vertically, the samplers were located at the interface between the different layers (Fig. 1).

Nutrient analysis

Water quality in the wetland system was monitored on a weekly basis from September 2 to 30, 2009. A 24-h composite sample (a representative sample obtained by combining multiple samples at regular intervals) was taken at every sampling port in proportion to the actual flow load during the 24-h period [19]. Dissolved oxygen (DO), pH, and temperature were measured on site by HACH HQd field case [19]. In addition to parameters requiring a grab sample analysis, ammonia-nitrogen (NH_3-N), nitrite-nitrogen (NO_2-N), nitrate-nitrogen (NO_3-N), organic nitrogen–nitrogen (ON-N), total nitrogen (TN), soluble reactive phosphorus–phosphorus (SRP-P), and total phosphorus (TP) were measured by an external certified laboratory [19]. The containers used for nutrient sampling were immediately sealed, labeled, and measured by the external certified laboratory within the same day.

Tracer study

Due to the advantages of low detection limits, zero natural background, low cost, and easy operation, RWT was selected as the water tracing dye to determine the hydraulic patterns and HRT of the SUW system. RWT, a synthetic red to pink dye having brilliant fluorescent qualities, a molecular formula of $C_{29}H_{29}N_2O_5ClNa_2$, and a CAS Number of 37299-86-8, is also known as Acid Red #388. It is often used as a tracer in water to determine the rate and direction of flow and transport. In our study, the RWT liquid (20% solution) was purchased from Keystone Aniline Corporation. An RWT solution with 0.04 g active ingredient was injected into the pipe before the inlet of the SUW. The tracer HRT was then calculated following Headley and Kadlec's practical guide [23]. Ten sets of water samples collected from nine sampling ports were measured in July 2010. Water samples of 50 mL were collected from each sampling port by using a peristaltic pump. The grab samples with the Rhodamine dye were measured by Aquafluor^{TM} (Turner Designs 998-0851) handheld fluorometer. The linear detection range for both dyes is 0.4–300 PPB (active ingredient). Because RWT fluorescence is susceptible to photolysis and sensitive to temperature, samples should be collected in glass bottles and kept in the dark prior to analysis. In addition, the solution with known concentration was analyzed on site for calibration prior to the sample measurement. The minimal root mean square error divided by the peak height of the distribution was evaluated to determine the goodness of fit for the tracer study. Eventually, the RWT distribution was demonstrated by the 3-dimensional (3D) data visualization software package, Voxler® (Golden software, Inc.).

Dispersion model

For an SSF wetland, the nominal HRT can be obtained using Eq. 1:

$$\tau_n = \frac{V_n}{Q} = \frac{\phi(l \times w \times h)_n}{Q}, \tag{1}$$

where τ_n = nominal HRT (days), l = wetland length (m), w = wetland width (m), h = wetland depth (m), V_n = nominal wetland volume (m^3), Q = flow rate (m^3/d), and ϕ = porosity (unitless).

Danckwerts [20] first extensively analyzed RTD, which is generally determined by introducing an impulse of tracer and measuring the time that the tracer spends at the wetland interior. For an impulse tracer addition into a steadily flowing system, the tracer HRT (often referred to as the "tracer HRT" or "mean HRT" (τ), can be achieved by the Eq. 2. A detention time distribution (DTD) is commonly used to represent the time that various fractions of water spend in the wetlands (Eq. 3) [18]. The variance (σ^2) is the square of the spread of the distribution, expressed in units of (time)^2 (Eq. 4):

$$\tau = \frac{\int_0^\infty tC(t)\,\mathrm{d}t}{\int_0^\infty C(t)\,\mathrm{d}t}, \tag{2}$$

$$f(t) = \frac{C}{\int_0^\infty C\mathrm{d}t}, \text{ and} \tag{3}$$

$$\sigma^2 = \frac{\int_0^\infty (t-\tau)^2 C(t)\mathrm{d}t}{\int_0^\infty C(t)\mathrm{d}t}. \tag{4}$$

As presented above, an SUW wetland system is regarded as a process between PFR and CSTR, which are deemed as two extremes of the hydraulic patterns in unit operation. Therefore, many wetland systems were modeled as a number, N, of stirred tank reactors in series. In fitting experimental data, the form for the TIS, shown in Eq. 5 [21], becomes the exponential distribution, which can be considered as single CSTR when $N = 1$ and the PFR when $N = \infty$. As a "shape factor", the shape of the response curve is quite sensitive to change the value of N. The gamma distribution, working as a robust tool, allows modelers to change the N value from a discrete integer to a continuous variable [18]. Thus, in our curve-fitting process, a gamma distribution term took the place of the term $(N - 1)!$ in Eq. 5 (see Eq. 6). The GAMMADIST and SOLVER are available in Microsoft Excel™ to help perform a trade-off in order to obtain the best fit by changing the variables N and τ:

$$g(t) = \frac{N^N}{\tau^N (N-1)!} t^{N-1} \exp\left(-N\frac{t}{\tau}\right). \tag{5}$$

where N = number of tanks (unitless), t = detention time (d), τ = HRT (d); and

$$g(t) = \frac{N^N}{\tau^N \Gamma(N)} t^{N-1} \exp\left(-N\frac{t}{\tau}\right), \tag{6}$$

where $\Gamma(N)$ = gamma function of $N = \int_0^\infty \exp(-x)\, x^{N-1}\mathrm{d}x$.

Permeability of substrate

Two general types of permeability test methods are commonly performed in the laboratory: the constant head method and the falling head method [22]. In this study, the constant head method [22] was used to determine the permeability of sand and PC media. The permeability was converted based on water at a test temperature of 20 °C.

Results and discussions

Tracer HRT

Computational procedure for calculating the tracer HRT may be carried out based on the record in Table 1. The measured RTD curve (Fig. 2) results from an impulse addition of 0.04 g RWT relative to the effluent concentrations of RWT at the wetland cell outlet. The recovery of RWT was calculated as 91.4%, with a main peak on the third day. The tracer HRT (τ) (Table 1) can be calculated by taking 4,376.1 and dividing it by 618.6. Hence, the tracer HRT (τ) is equal to 7.1 days, much less than the nominal HRT of 12.5 days.

Curve fitting

By using GAMMADIST and SOLVER, the value of N (=1.25) may be obtained (Fig. 3). Because the tracer HRT mentioned previously is much less than the expected nominal HRT, fewer samples were collected in the peak period. The low sampling frequency during the peak period reduced the corresponding weight of evaluation indexes in the model fitting process, which eventually led to a mathematical trade-off with a better fit in the tail rather than the peak area.

Distribution of tracer in the wetland

The distribution of tracer in the SUW was plotted by Voxler® (Golden software). This robust program can display the data in a variety of formats: 3D volrender, isosurfaces, contours, 3D slices, orthographic and oblique images, scatter plots, stream lines, and vector plots. A profile view of the tracer distribution in wetland during an 18-day period (Fig. 4) shows ten small images representing a series of detailed flow sequences of water with dye illumination. On each small image, the inlet is on the bottom left and the outlet is on the upper right. The second-day small image indicates that the tracer flowed with water throughout the bottom layer and moved upward along two vertical edges of the wetland (i.e., front and back edge) within 2 days. The blue color in the middle shows that the tracer had not yet become homogenous in that region, which means there might be some "hydraulic retardation" with time in the middle of the wetland. Because most of the tracer at the top layer came from bottom rather than horizontal movement, the overall observation confirmed our concept of the hydrolic "upflow" design. In the third day, the tracer gradually faded away at the inlet side and continued to rise at the outlet side. From day 4 to day 8, there was a rising progress of tracer in the middle and then the peak of the tracer moved out of the outlet from day 9 to day 11. Finally, the remaining tracer flowed gently out of the wetland from day 11 to day 18. Globally, the spatiotemporal tracer distribution provides strong support for the upflow hypothesis in biosystem engineering design.

Table 1 Computational procedure for calculating the tracer HRT

t(d)	*C*(*t*) (ppb)	*C*(*t*) d*t*	*tC*(*t*) d*t*
0.0	0.0	–	–
2.0	73.1	146.2	292.4
3.0	105.1	105.1	315.3
4.0	39.3	39.3	157.3
6.0	32.4	64.8	388.8
8.0	30.0	60.1	480.5
9.0	30.0	30.0	270.1
11.0	24.2	48.3	531.5
13.0	18.5	37.1	481.8
16.0	20.1	60.4	966.7
18.0	13.7	27.3	491.8
	Summation	618.6	4,376.1

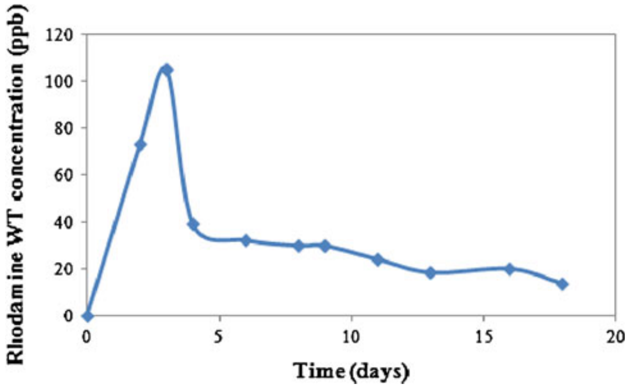


Fig. 2 Measured RTD curve entailing relationship between RWT concentration and time at the outlet

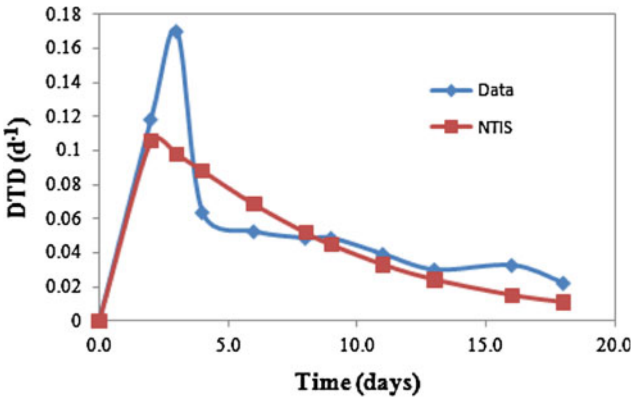


Fig. 3 Model fitting between DTD function and NTIS

Response curve in a local view

The response curves at different sampling ports (Fig. 5) illustrate that permeability decreases from the gravel layer to the sand layer but increases from the sand layer to the PC layer, which coordinates, unifies, and harmonizes the flow patterns and reduces the turbulent flow impact. The higher the permeability value, the more stable the response curve, implying that biofilm can grow better in the PC layer after receiving nutrients carried over from the sand layer. After passing through the PC media, the disorderly flow pattern reverted to normal (same as that of the bottom samples). Nearly the same parameter number (*N*) and HRT values were obtained from these top sampling ports. The response curve in bottom samples presented a similar trend: a peak at the second day with a long tail. The middle three samples displayed three totally different patterns, however, probably caused by the interaction between the low permeability of the sand layer and the irregular pore size of the fabric beneath it. Overall, our innovative PC media demonstrates not only a powerful media for nutrient removal, but also a modulator in terms of hydraulic performance due to the appropriate size distribution among the media components [19] (US Patents 78745591, 7824551 B2, and 7897047).

The original purpose of the fabric liner at the bottom of the sand layer was to separate the gravel layer from the sand layer above. The sand is added beneath the PC medium to better remove pathogens and total suspended solids (TSS). The turbulent flow caused by the fabric layer occasionally increases the HRT in the middle layer (a delayed peak or multi-peak) and the level of contact between water and sand layer, which is the main reason why the *E. coli* removal efficiency reached as high as 99.92% in our previous study [19]. Further, the addition of a fabric layer also provides a secondary effect of horizontal water distribution, which works as a "semi-permeable membrane" allowing upflow paths as uniformly distributed as possible. Although the patterns were totally different across those ports, the values of τ at the same elevation were quite close except at the middle port at bottom, which is partially due to the hydraulic retardation effect.

From a design perspective, the results demonstrate that the middle column of the wetland did not effectively provide homogeneous upflow. In our case, the height to length (*h*:*l*) ratio might be more important than the length to width (*l*:*w*) ratio, which should be highlighted as a new considerable parameter for future SUW design. A shorter length (i.e., a smaller *l*:*w* ratio) can be applied for the future design, which also supports the conclusion in our previous modeling work [24]. Thus, we suggest that a shorter length and a larger depth of the SUW system can be the next-generation SUW for both fixed and mobilized modules in real-world applications.

Nutrient removal

In our study, composite samples were collected across ports M and B (Fig. 1) assuming that water quality would

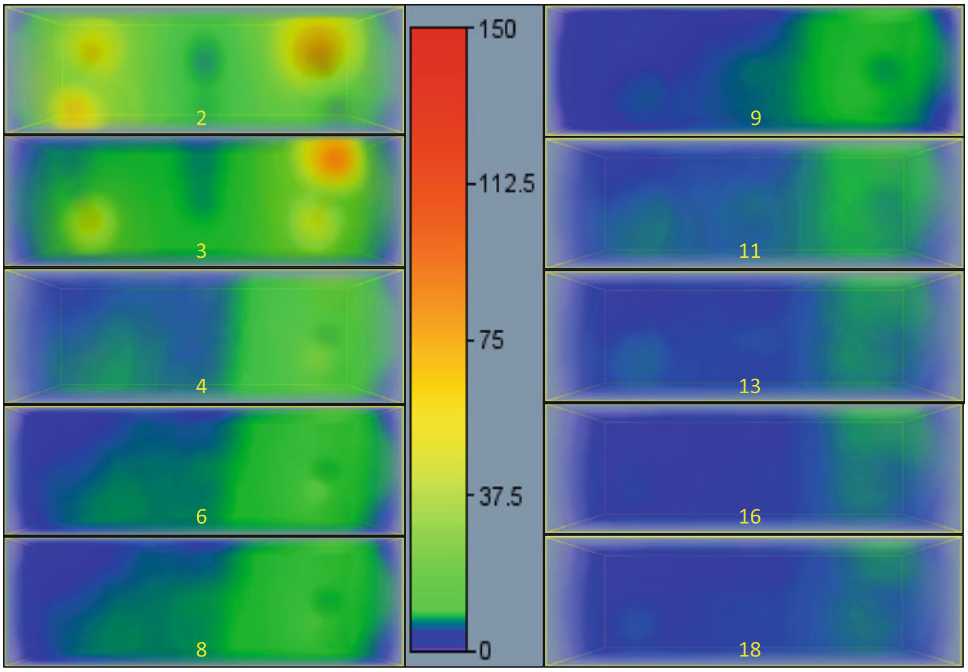


Fig. 4 Profile view of the tracer distribution in wetland (*left five small images* 2, 3, 4, 6, and 8 days; *right five* 9, 11 13, 16, and 18 days). *Vertical scale* is concentration (ppb)

not vary too much in these two layers. Because of the root zone heterogeneity, sampling across three ports at the top layer between the growth and PC media was carried out separately. Water quality analysis spatially across these three layers and ports (Table 2) shows a systematic trend of nitrification and denitrification layer by layer from the bottom to the top layers.

The nutrient removal in SUW reveals the affinity between transport observations and fate phenomena (Table 2). In concert with the upflow pattern, the concentration of TN, ON-N, and NH_3-N decreased layer by layer. In particular, ON-N and TN were lower in the middle top ports (i.e., T2) due to the delayed flow, evidenced by the hydraulic retardation effect in the tracer study (Fig. 4). Therefore, a deeper SUW is recommended in the future to reach a longer HRT and achieve a higher ON-N removal efficiency. A more sufficient aeration via the use of more oxygenators could enhance nitrification and improve NH_3-N removal, however. Such a synergistic modification could further promote overall performance.

Final remarks

The Buckingham Pi theorem in the area of dimensional analysis may be further applied to draw on a relationship between the nominal HRT and real HRT that is a function in terms of several key parameters such as wetland geometry, flowrate, and gravitational acceleration, theoretically. By using a dimensional analysis, we may thus derive an expression based on the following assumed conditions: the variables that affect real HRT (denoted as $\mathrm{HRT_r}$ hereafter), which may or may not be exactly the same as tracer HRT, would be the l, h, V_n, Q, and g. Note that $\tau_n = V_n/Q$ *and* $V_n = l \times w \times h$. Porosity is not considered in this dimensional analysis due to its heterogenous nature across the multi-layered media in an SUW system. With this setting, we have

$$\mathrm{f}(\mathrm{HRT_r}, l, h, V, Q, g) = 0 \tag{7}$$

In this case, there are $n = 4$ variables and $m = 2$ dimensions. We can easily find four variables that we cannot form into a dimensionless group; therefore,

$$\Psi(\pi_1, \pi_2, \pi_3, \pi_4) = 0 \tag{8}$$

Using V_n and Q as the primary variable to retrieve the information of τ_n (nominal HRT) in relation to the $\mathrm{HRT_r}$, we have

$$\pi_1 = V_n^{a_1} Q^{b_1} \mathrm{HRT_r} \tag{9}$$

$$\pi_2 = V_n^{a_2} Q^{b_2} l \tag{10}$$

$$\pi_3 = V_n^{a_3} Q^{b_3} h \tag{11}$$

$$\pi_4 = V_n^{a_4} Q^{b_4} g \tag{12}$$

Working with π_1, π_2, π_3, and π_4, we have all the coefficients of a_i and b_i to be identified sequentially as below:

$$\pi_1 : L^0 T^0 = (L^3)^{a_1} \left(\frac{L^3}{T}\right)^{b_1} T \quad a_1 = -1 \text{ and } b_1 = 1$$

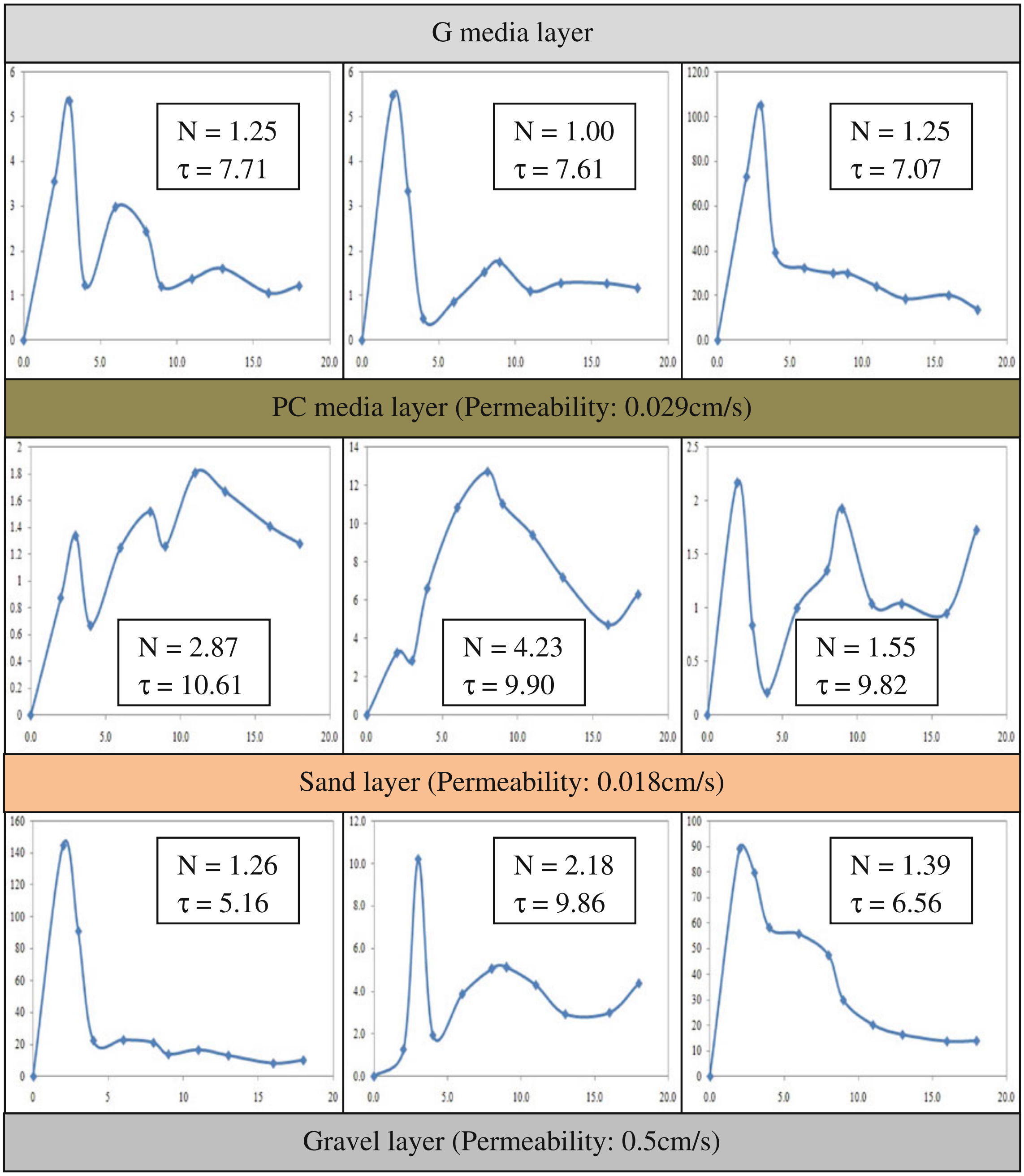


Fig. 5 Comparative analysis of response curves at different sampling ports for reasoning the interfaces between the global and local hydraulic patterns

$$\pi_2 : L^0T^0 = (L^3)^{a_2}\left(\frac{L^3}{T}\right)^{b_2} L \quad a_2 = -1/3 \text{ and } b_2 = 0$$

π

$$\pi_3 : L^0T^0 = (L^3)^{a_3}\left(\frac{L^3}{T}\right)^{b_3} L \quad a_3 = -1/3 \text{ and } b_3 = 0$$

$$L^0T^0 = (L^3)^{a_4}\left(\frac{L^3}{T}\right)^{b_4}\left(\frac{L}{T^2}\right) \quad a_4 = 5/3 \text{ and } b_4 = -2$$

Hence, $\pi_1 = \frac{\mathrm{HRT}_r}{V_n/Q}$, $\pi_2 = \frac{l}{\sqrt[1/3]{V_n}}$, $\pi_3 = \frac{h}{\sqrt[1/3]{V_\eta}}$, and $\pi_4 = \frac{V_n^{5/3}g}{Q^2}$,
Given that $V_n/Q = \tau_n$, we end up having

$$HRT_r = \tau_n\varphi(\pi_2, \pi_3, \pi_4) = \tau_n\varphi\left(\frac{l}{\sqrt[1/3]{V_n}}, \frac{h}{\sqrt[1/3]{V_n}}, \frac{V_n^{5/3}g}{Q^2}\right)$$
$$= \tau_n\varphi\left(\frac{l}{\sqrt[1/3]{V_n}}, \frac{h}{\sqrt[1/3]{V_n}}, \frac{V_n^{5/3}g}{Q^2}\right) = C\tau_n,$$

in which C is a coefficient that bridges the nominal HRT and real HRT. When the real HRT can be investigated by a

Table 2 Spatial distribution of nitrogen concentration, μg/L [19]

	NH_3-N	NO_2-N + NO_3-N	ON-N	TN
Septic effluent	56,061.8	7.5	13,670.3	69,739.5
Port B	27,159.0	7.0	5,325.3	32,489.0
Port M	16,653.3	8.5	5,069.8	21,730.0
Port T1	839.8	5.0	3,684.8	4,526.8
Port T2	1,169.8	16.8	1,497.0	2,681.3
Port T3	1,185.0	8.8	3,607.0	4,799.3

TN total nitrogen, *ON-N* organic nitrogen, *NH_3-N* ammonia nitrogen, *port B* the composite of three bottom samples, *port M* the composite of three middle samples

tracer study, C may be identified numerically in a laboratory as $\mathrm{HRT_r}$ is assumed to be measurable by using the tracer. Obviously, π_2 and π_3 are dimensionless groups associated with the geometry of a wetland and π is a dimensionless group associated with the Froude number $(= v/\sqrt{gl} = (Q/(l \times w))/\sqrt{gl})$.

Conclusions

A tracer study was carried out to confirm upflow hydraulic patterns in concert with a transport model to assess the nutrient removal efficiencies across different locations of the SUW system. Linking HRT with the N value associated with the TIS model collectively provides insightful observations on maintaining nitrification and denitrification mechanisms over different parts of the SUW system. We concluded that the tracer HRT was 7.1 days of the entire SUW, whereas the average N value is 1.25 days within the SUW system. The distribution of tracer in the SUW system was plotted by Voxler® to provide typical visualized evidence of the upflow patterns over space and time. A series of local tracer response curves help demonstrate that permeability of media is a major factor affecting local patterns in a layered structure. Although each layer has its own hydraulic and environmental function, the PC media layer packed on the top of the sand layer demonstrates a smooth hydraulic performance due to the appropriate size distribution among the sorption media components. With regard to the dimensions of the SUW system, in our study the h:l ratio might be more important than the l:w ratio, which should be highlighted as a new considerable parameter for future SUW design. Thus, we suggest a shorter length and larger depth SUW system should be the next-generation design.

References

1. Kadlec RH, Tanner CC, Hally VM, Gibbs MM (2005) Nitrogen spiraling in subsurface-flow constructed wetlands: implications for treatment response. Ecol Eng 25:365–381
2. Ronkanen AK, Kløve B (2007) Use of stabile isotopes and tracers to detect preferential flow patterns in a peatland treating municipal wastewater. J Hydrol 347:418–429
3. Ronkanen AK, Kløve B (2008) Hydraulics and flow modelling of water treatment wetlands constructed on peatlands in Northern Finland. Water Res 42:3826–3836
4. Harman J, Robertson WD, Cherry JA, Zanini L (1996) Impacts on a sand aquifer from an old septic system: nitrate and phosphate. Ground Water 34:1105–1114
5. Wang B, Jin M, Nimmo JR, Yang L, Wang W (2008) Estimating groundwater recharge in Hebei Plain, China under varying land use practices using tritium and bromide tracers. J Hydrol 356:209–222
6. Małoszewski P, Wachniew P, Czupryński P (2006) Hydraulic characteristics of a wastewater treatment pond evaluated through tracer test and multi-flow mathematical approach. Pol J Environ Stud 15(1):105–110
7. Dierberg FE, DeBusk TA (2005) An evaluation of two tracers in surface-flow wetlands: rhodamine-WT and lithium. Wetlands 25(1):8–25
8. Lin AY-C, Debroux J-F, Cunningham JA, Reinhard M (2003) Comparison of rhodamine WT and bromide in the determination of hydraulic characteristics of constructed wetlands. Ecol Eng 20:75–88
9. Giraldi D, De'Michieli Vitturi M, Zaramella M, Marion A, Iannelli R (2009) Hydrodynamics of vertical subsurface flow constructed wetlands: tracer tests with rhodamine WT and numerical modeling. Ecol Eng 35:265–273
10. Kadlec RH, Knight RL (1996) Treatment wetlands. CRC Press, Boca Raton
11. Wang HG, Jawitz JW (2006) Hydraulic analysis of cell-network treatment wetlands. J Hydrol 330:721–734
12. Fogler HS (1992) Elements of chemical reaction engineering, 2nd edn. Prentice Hall, Englewood Cliffs
13. Valocchi AJ (1985) Validity of the local equilibrium assumption for modeling sorbing solute transport through homogeneous soils. Water Resour Res 21:808–820
14. Martinez CJ, Wise WR (2003) Analysis of constructed treatment wetland hydraulics with the transient storage model OTIS. Ecol Eng 20(3):211–222
15. Fan L, Reti H, Wang W (2008) Application of computational fluid dynamic to model the hydraulic performance of subsurface flow wetlands. J Environ Sci 20(12):1415–1422
16. Persson J (2000) The hydraulic performance of ponds of various layouts. Urban Water 2:243–250
17. Worman A, Kronnas V (2005) Effect of pond shape and vegetation heterogeneity on flow and treatment performance of constructed wetlands. J Hydrol 301:123–138
18. Kadlec RH, Wallace SD (2009) Treatment wetlands, 2nd edn. Taylor and Francis Group, Boca Raton
19. Chang NB, Xuan Z, Daranpob A, Wanielista M (2011) A subsurface upflow wetland system for removal of nutrients and pathogens in on-site sewage treatment and disposal systems. Environ Eng Sci 28(1):11–24
20. Danckwerts PV (1953) Continuous flow systems: distribution of residence times. Chem Eng Sci 2:1–13
21. Levenspiel O (1972) Chemical reaction engineering, 1st edn. Wiley, New York
22. ASTM (D2434-68) Standard test method for permeability of granular soils (constant head), ASTM international
23. Headley TR, Kadlec RH (2007) Conducting hydraulic tracer studies of constructed wetlands: a practical guide. Ecohydrol Hydrobiol 7:269–282
24. Xuan Z, Chang NB, Daranpob A, Wanielista M (2010) Modeling the subsurface upflow wetland (SUW) system for wastewater effluent treatment. Environ Eng Sci 27(10):879–888