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Heat as a hydraulic tracer for horizontal subsurface flow constructed wetlands

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ABSTRACT

Hydraulic tracer studies for horizontal subsurface flow constructed wetlands require addition of a conservative chemical tracer to track the flow path of wastewater inside subsurface media. However since one would wish to use fully conservative tracers disposal problems of the wetland effluent are created. In this study the use of heat as a hydraulic tracer was explored. Heat is considered an environmentally friendly alternative to chemical tracers as the post-study wetland and effluent temperature equilibrates to ambient conditions. Nevertheless the non-conservative behaviour of heat creates a distorted response curve at the outlet from which the hydraulic performance indices cannot be easily computed. In this paper we were able to develop a mapping methodology accepting a heat tracer response curve as an input and is converted to a conservative chemical tracer response curve by establishing a mathematical relationship between heat and conservative solute hydrodynamic dispersion. The methodology was tested by conducting a dual heat-chemical tracer study on a laboratory-scale unplanted subsurface flow constructed wetland and the predicted chemical tracer response was compared with the actual experimental chemical tracer response data. The predicted response curve adequately matched the experimental response curve supported by the fact that there was a 5% and 6% relative difference in Peclet number and mean of the RTD respectively. The outcome of this study is that it is possible to use the proposed mapping methodology in conjunction with a heat tracer to quantify hydraulic behaviour of subsurface flow constructed wetlands without having to use a conservative chemical tracer.

1. Introduction

Residence time distribution (RTD) studies are used to assess the hydraulic performance of horizontal subsurface flow constructed wetlands (HSSF CWs) [1]. These studies entail addition of a tracer into the CW feed and continuous monitoring of the concentration at the outlet, after which suitable numerical methods are applied to the response curve to quantify a set of performance indices [2,3]. Accurate characterisation of hydraulic behaviour requires the tracer to be conservative [4]. In essence the tracer should be highly soluble in the feed water to prevent sorption onto the wetland sediments [5] as well as being resistant to biological, chemical and photochemical decay [6,7]. Examples of conservative tracers include fluorescent dyes such as fluorescein [8] and Rhodamine WT [9], the chloride ion [10] and the bromide ion [11]. These tracers potentially pose downstream environmental risks since they show a high persistence. Dedicated disposal infrastructure for the reactor effluent is required as a result and this ultimately increases the cost of performing the study.

Heat has frequently been used in hydrogeology as a tracer for groundwater movement [12,13]. Applications include quantifying hydrodynamic exchanges at the streambed-aquifer interface in the hyporheic zone [14] as well as for the identification and characterization of fractures in aquifers [15–17]. The drawback of using heat is its non-conservative behaviour [18]. A temperature gradient across the fluid-solid interface causes heat to be easily absorbed by the packed media [19], effectively retarding the velocity of the tracer with the consequence being an altered response curve and distorted description of the hydraulic behaviour of the system. Nevertheless, it is preferred over conventional chemical tracers due to the availability of cheap and simple to operate temperature measurement devices [20] and the effluent from the study need not

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Nomenclature

α_1	Longitudinal solute dispersivity
α_t	Transverse solute dispersivity
$\alpha_{f/s}$	Interfacial mass transfer coefficient
a_v	Interfacial surface area
β_l	Longitudinal thermal dispersivity
β_t	Transverse thermal dispersivity
$C(t)$	Concentration of dye at time t
$C_{initial}$	Initial wetland tracer concentration
C_{inlet}	Wetland inlet tracer concentration
C_{max}	Concentration of chemical dye as $t \to \infty$
C_{out}	Outlet concentration
C_{pf}	Fluid specific heat capacity
C_{ps}	Solid specific heat capacity
$C_{p,gravel}$	Specific heat capacity of gravel
$C_{p,water}$	Specific heat capacity of water
$\delta_{pinewood}$	Thickness of pinewood
$\delta_{polystyrene}$	Thickness of polystyrene
$\delta_{pond\ liner}$	Thickness of pond liner
D	Chemical dispersion coefficient
$D_{heat,f}$	Heat dispersion in fluid phase
D_m	Molecular diffusion coefficient
ε	Packed bed porosity
e	Effective volume utilization
$E(t)$	Residence time distribution function
erfc	Complementary error function
$F(t)$	Cumulative distribution function
γ	Zero order production coefficient
$h_{f/s}$	Interfacial heat transfer coefficient
H	Packed bed depth
h_{air}	Convective heat transfer coefficient of air
h_{water}	Convective heat transfer coefficient of water
K_d	Distribution coefficient
k_{gravel}	Thermal conductivity of gravel
k_s	Solid thermal conductivity
k_{water}	Thermal conductivity of water
k_0	System thermal conductivity
$k_{pinewood}$	Thermal conductivity of pinewood
$k_{polystyrene}$	Thermal conductivity of polystyrene
$k_{pondliner}$	Thermal conductivity of pond liner
λ_T	Heat dispersion coefficient
L	Packed bed length
μ	First order decay coefficient
N	Number of equally sized CSTRs placed in series
Pe	Peclet number
ρf	Fluid density
ρ_s	Solid density
ρ_b	Bulk density
ρ_{gravel}	Gravel density
ρ_{water}	Water density
R	Chemical retardation factor
R_T	Thermal retardation factor
σ^2	Variance
S	Adsorbed solid concentration
τ	Nominal residence time
t	Time
$\bar{t}_m$	Mean of residence time distribution
T	Temperature
T_a	Ambient temperature
T_f	Fluid temperature
$T_{initial}$	Initial wetland temperature
T_{inlet}	Wetland inlet temperature
T_s	Solid temperature
U	Pore water velocity
U_{wall}	Wall heat transfer coefficient
$\dot{\nu}$	Volumetric flow rate
V_{total}	Total volume of reactor
W	Packed bed width
x	Distance

be disposed; rather it can be temporarily stored allowing it to equilibrate with ambient conditions and then be re-used.

To date, little has been published regarding the use of heat as a tracer for RTD studies on HSSF CWs and is most likely due to its non-conservative behaviour. In this study we sought to develop a mathematical model, based on transport phenomena theory, which maps an input of response data obtained from a non-invasive tracer in the form of heat to the response curve which would be obtained from a conservative chemical tracer. This approach would allow for accurate hydraulic behaviour of the wetland to be ascertained without having to tackle the environmental hazards posed by conservative tracers. The model was then tested by conducting a combined conservative solute and heat tracer RTD study on a laboratory-scale HSSF CW. The shape of the predicted conservative tracer response curve was compared with the actual experimental response curve as well as their corresponding hydraulic performance indices.

The overall aim of developing a methodology to obtain accurate hydraulic information of an HSSF CW using a heat tracer could be achieved by fulfilling the following research objectives:

1. To develop the heat tracer transport equation with a similar form or functionality to the chemical tracer transport equation.
2. To solve the chemical and heat tracer transport equations subject to initial and boundary conditions applicable to a step change RTD study.
3. To establish a mathematical relationship between the heat and chemical tracer hence allowing transferral of data from the heat space to chemical space.
4. To test the methodology by conducting a dual heat and chemical tracer study on a laboratory scale unplanted HSSF CW.

2. Theory

2.1. Hydraulic modelling using an RTD study

An RTD study is used to quantify the extent of mixing inside an HSSF CW [21]. In the step change response experiment, a tracer is introduced as a step in concentration in the feed pipe and its concentration monitored at the outlet [22] so that the cumulative distribution curve can be determined according to (1). The response curve can then be used to quantify hydraulic behaviour using the method of moments as well as a variety of reactor models including the tanks in series (TIS) and advective-dispersive transport models [23].

$$F(t) = \frac{C(t)}{C_{max}} \tag{1}$$

2.1.1. Method of moments analysis

Hydraulic behaviour is described by determining the first and second temporal moments of the response curve in (1) [24]. The first moment is the centroid of the response curve [25], representing the mean of the RTD of fluid inside the system and is calculated using (2). $\bar{t}_m$ is compared to the nominal residence time τ, shown in (3), to provide the effective volume utilization in (4) [26]. Effec-