Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/watres

Modeling *Escherichia coli* removal in constructed wetlands under pulse loading

Yaseen A. Hamaamin [a,b], *Umesh Adhikari* [a], *A. Pouyan Nejadhashemi* [a,c,*], *Timothy Harrigan* [a], *Dawn M. Reinhold* [a]

[a] *Department of Biosystems and Agricultural Engineering, Michigan State University, 524 S. Shaw Lane, Room 216, East Lansing, MI 48824, USA*

[b] *Department of Civil Engineering, University of Sulaimani, Sulaimani, KRG, Iraq*

[c] *Department of Plant, Soil and Microbial Sciences, Michigan State University, 1066 Bogue Street, Room A286, East Lansing, MI 48824, USA*

ARTICLE INFO

Article history:
Received 30 April 2013
Received in revised form
17 October 2013
Accepted 22 October 2013
Available online 31 October 2013

Keywords:
Wetland
Duckweed pond
ANFIS
Escherichia coli
Pulse loading
Tile drain

ABSTRACT

Manure-borne pathogens are a threat to water quality and have resulted in disease outbreaks globally. Land application of livestock manure to croplands may result in pathogen transport through surface runoff and tile drains, eventually entering water bodies such as rivers and wetlands. The goal of this study was to develop a robust model for estimating the pathogen removal in surface flow wetlands under pulse loading conditions. A new modeling approach was used to describe *Escherichia coli* removal in pulse-loaded constructed wetlands using adaptive neuro-fuzzy inference systems (ANFIS). Several ANFIS models were developed and validated using experimental data under pulse loading over two seasons (winter and summer). In addition to ANFIS, a mechanistic fecal coliform removal model was validated using the same sets of experimental data. The results showed that the ANFIS model significantly improved the ability to describe the dynamics of *E. coli* removal under pulse loading. The mechanistic model performed poorly as demonstrated by lower coefficient of determination and higher root mean squared error compared to the ANFIS models. The *E. coli* concentrations corresponding to the inflection points on the tracer study were keys to improving the predictability of the *E. coli* removal model.

1. Introduction

Several major disease outbreaks related to agricultural pathogens have resulted in human infection and death, economic loss and beach closures (Hrudey and Hrudey, 2004; Kanter, 2011; MIDEQ, 2011). In the United States, total coliform, fecal coliform, *Escherichia coli* (*E. coli*) and *Enterococci* are the major waterborne pathogen indicators. In general, most non-native waterborne pathogens originate either from point sources (e.g., sewage discharge) or nonpoint sources (e.g., agricultural practices) (National Research Council, 2004).

On many North American farm operations liquid manure is applied to fields for nutrient recovery and disposal (Joy et al., 1998), where a large portion of the agricultural land receiving manure has been tile drained (Jamieson et al., 2002). Bacteria can pass through the soil to sub-surface tile drains and contaminate

---

[*] *Corresponding author*. Department of Biosystems and Agricultural Engineering, Michigan State University, 524 S. Shaw Lane, Room 225, East Lansing, MI 48824, USA. Tel.: +1 517 432 7653; fax: +1 517 432 2892.
E-mail address: pouyan@msu.edu (A.P. Nejadhashemi).

0043-1354/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.watres.2013.10.052

Nomenclature

ANFIS	Adaptive neuro-fuzzy inference systems
A_s	Parameter accounting for the effect on adjacent media grains on the flow about a collector
C	Tracer concentration, mg/l
C_e	Effluent fecal coliform concentration, CFU/100 ml
CFU	Colony forming unit
C_o	Influent fecal coliform concentration, CFU/100 ml
d	Dispersion number
D	Dispersion coefficient, m^2/day
d_c	Collector diameter, m
d_p	Particle diameter, m
DTD	Detention time distribution
$Ecoli_p$	Measured influent *E. coli* concentrations at time *t*, CFU/ml
$Ecoli_t$	Expected effluent *E. coli* concentrations with no wetland degradation impact at time *t*, CFU/ml
$Ecoli_{t\text{-}42}$	Expected effluent *E. coli* concentrations with no wetland degradation impact at time *t*-42, CFU/ml
$Ecol_{t\text{-}190}$	Expected effluent *E. coli* concentrations with no wetland degradation impact at time *t*-190, CFU/ml
$Ecol_{t\text{-}96}$	Expected effluent *E. coli* concentrations with no wetland degradation impact at time *t*-96, CFU/ml
ϕ	Temperature coefficient
g	Gravitational constant, m/s^2)
h	Depth of wetland bed, m)
I_0	Incident solar radiation received at the wetland surface, cal/(m^2.day)
I_{avg}	Average solar radiation, cal/(m^2.day)
k	Overall removal rate coefficient, 1/day
K_B	Boltzmann constant, J/K
k_f	Removal rate coefficient due to adsorption, filtration and sedimentation, 1/day
k_i	Removal rate coefficient due to solar radiation, 1/day
k_t	Removal rate coefficient due to temperature at t °C, 1/day
$k_{t,20}$	Removal rate coefficient at 20 °C, 1/day
L	Length of the wetland, m
μ	Fluid viscosity, N.s/m^2
R^2	Coefficient of determination
RMSE	Root mean squared error
Solar	Solar radiation below the wetland–air interface, w/m^2
T	Hydraulic retention time, days
t	Water temperature, °C
T	Hydraulic residence time, days
T_a	Absolute temperature, K
Temp	Water temperature below the wetland–air interface, °C
t_t	Time, days
u	Velocity of flow, m/day
u	Pore water velocity, m/day
VFS	Vegetative filter strip
WASP	Water Quality Analysis and Simulation Program
x	Distance from inlet, m
α	Sticking efficiency
η	Single collector removal efficiency
θ	Porosity of the wetland bed
ρ	Fluid density, kg/m^3
ρ_p	Particle density, kg/m^3
τ	Vertical light extinction coefficient, 1/m
φ	Light mortality constant, m^2/cal

surface waters (Joy et al., 1998). Evans and Owens (1972) reported a 30- to 900-fold increase in bacteria concentration in tile drain effluent within 2 h of liquid swine manure application. Regardless of the application method, high concentrations of bacteria have been found in tile drains after heavy rainfall that occurred soon after manure application (Samarajeewa, 2010).

Several studies have attempted to model fecal coliform or *E. coli* transport in various best management practices such as vegetated filter strips (Parajuli et al., 2008; Guber et al., 2009) and waste stabilization ponds (Polprasert et al., 1983; Mayo, 1995; Bahlaoui et al., 1998; Von Sperling, 1999; Von Sperling, 2005; Parajuli et al., 2008). However, few studies have addressed the fate of fecal coliforms, including *E. coli*, in constructed wetlands. In general, coliform removal has been modeled using first-order area-based or volume-based models that describe effluent in terms of influent concentration, retention time and the first-order removal rate constant, with or without background concentrations (Kadlec and Wallace, 2009). Khatiwada and Polprasert (1999) used a dispersed flow equation to model *E. coli* removal in surface flow wetlands by dividing the first-order rate coefficient into temperature, solar radiation, sedimentation, adsorption and filtration coefficients for a cattail-based surface flow wetland. Boutilier et al. (2011) used the Water Quality Analysis and Simulation Program (WASP) to mimic *E. coli* transport in surface flow wetlands and reported that the model was good for predicting average effluent *E. coli* concentration but did not adequately forecast extreme (minimum and maximum) values. Carleton (2002) proposed the Damkohler number (*Da*) distribution model (DND) for predicting contaminant transport in treatment wetlands, but its application was limited because it required several sets of inlet-outlet concentration data at different hydraulic loading rates before the model could be applied.

Fuzzy logic is a useful modeling technique for assessing ambiguous complex natural processes such as pollution dynamics and thus may be applicable for modeling pollution removal in wetlands which are affected by different physical, chemical and biological factors (Karim et al., 2008; Lohani et al., 2012; Qasaimeh et al., 2012). However, its applicability requires further evaluation with experimental data. Fuzzy logic is a modeling approach that incorporates a human “rule of thumb” approximate reasoning method in decision-making. It uses graded fuzzy values between 0 and 1 rather than crisp values. Fuzzy logic is an effective approximate method for complex biological systems that cannot be easily described mathematically (Jain and Martin, 1998; Tay and Zhang, 1999; Stottmeister et al., 2003). Only knowledge of factors that influence a process and a qualitative relationship between the cause and effect are required with the fuzzy logic approach. This makes the technique useful for representing