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The modified SWAT model for predicting fecal coliforms in the Wachusett Reservoir Watershed, USA

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ABSTRACT

This study assessed fecal coliform contamination in the Wachusett Reservoir Watershed in Massachusetts, USA using Soil and Water Assessment Tool (SWAT) because bacteria are one of the major water quality parameters of concern. The bacteria subroutine in SWAT, considering in-stream bacteria die-off only, was modified in this study to include solar radiation-associated die-off and the contribution of wildlife. The result of sensitivity analysis demonstrates that solar radiation is one of the most significant fate factors of fecal coliform. A water temperature-associated function to represent the contribution of beaver activity in the watershed to fecal contamination improved prediction accuracy. The modified SWAT model provides an improved estimate of bacteria from the watershed. Our approach will be useful for simulating bacterial concentrations to provide predictive and reliable information of fecal contamination thus facilitating the implementation of effective watershed management.

1. Introduction

Freshwater resources are susceptible to various fecal contaminations. Fecal coliform, also known as thermotolerant coliforms (Ashbolt et al., 2001), are a subgroup of total coliforms associated with fecal contamination. Most fecal coliform bacteria are not pathogenic, but they indicate the possibility of the presence of microbial pathogens, which are detrimental to public health (Noble et al., 2003). Fecal coliform sources include: agricultural runoff, sewage, and wild and domestic animal feces (Howell et al., 1995; Alderisio and DeLuca, 1999; Gerba, 2000; Guber et al., 2006; Servais et al., 2007; Cho et al., 2010a). Another potential source of fecal contamination is the release of fecal coliform from streambeds. Previous studies have demonstrated that sediments can contain one to three orders of magnitude more fecal coliform than the overlying water column (Goyal et al., 1977; Doyle et al., 1992; Buckley et al., 1998; Crabill et al., 1999; Smith et al., 2008; Rehmann and Soupir, 2009; Cho et al., 2010a; Pachepsky and Shelton, in press).

Several studies found that the levels of fecal coliform are substantially affected by meteorological conditions (Gannon

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and Busse, 1989; Marsalek and Rochfort, 2004; Paul et al., 2004; Petersen et al., 2005; Tani et al., 1995; Kim et al., 2007, 2010; Cho et al., 2010b). Previous studies demonstrated that solar radiation has a substantial influence on the survival of fecal coliform in natural waters (Bellair et al., 1977; Mancini, 1978; Fujioka et al., 1981; McCambridge and McMeekin, 1981; Auer and Niehaus, 1993; Sinton et al., 1999, 2007; Cho et al., 2010b). Mancini (1978) found a strong relationship between die-off rates and solar radiation from *in-situ* studies. Solic and Krstulovic (1992) observed an increase in die-off rate in response to high intensity of solar radiation in laboratory experiments. Cho et al. (2010b) reported that in-stream levels of fecal coliform are sensitive to solar radiation and therefore the solar radiation intensity is one of control factors to model fecal coliform in surface waters.

Modeling, in conjunction with laboratory experiments and field observations, can help improve the understanding of the fate of fecal coliform in water. In addition, this approach can be used to provide predictive decision-support information for effective public health management. The Soil and Water Assessment Tool (SWAT), a widely used watershed model that operates on a continuous daily time-step, was further expanded by adding a bacteria module (Sadeghi and Arnold, 2002). Baffaut and Benson (2003) used the bacteria module to predict flow rates and fecal coliform concentration. Parajuli (2007) and Parajuli et al. (2009) applied this module to modeling nutrient and fecal coliform in two different sub-basins in Kansas. Coffey et al. (2010) used the original version of the SWAT to predict fecal coliform in Irish catchments, showing satisfactory prediction accuracies in the calibration step. In addition, the SWAT bacteria module was modified to consider streambed fecal coliform release and deposition (Kim et al., 2010). The effect of solar radiation on bacterial die-off, however, has not been considered in simulations of fecal coliform concentration in a water body.

The objectives of this study are (a) to develop and evaluate a solar radiation-associated bacteria module in the SWAT model and (b) to calibrate and validate the model to predict fecal coliform concentrations. This will provide an understanding of the fate of bacteria, which may lead to the implementation of more effective management decisions.

2. Materials and methods

2.1. Study area

The Wachusett Reservoir is one of the primary drinking water sources to the residents of the Greater Boston area in Massachusetts. The Stillwater River is one of the two largest tributaries of the Wachusett Reservoir and drains approximately 30% of the watershed (Fig. 1). The basin has a very low percentage of impervious cover (<10%) and high percentage of protected land with active watershed protection program in place.

2.2. Bacteria module in SWAT model

In this study, the upgraded SWAT bacterial module (Kim et al., 2010) was modified by adding the solar radiation-associated die-off. Fig. 2 shows the proposed in-stream bacteria algorithm in the SWAT model, including resuspension of fecal coliform and die-off by solar intensity. When current sediment concentration is less than the maximum sediment concentration, resuspension of sediment will occur. Otherwise, sediment deposition will occur. Total die-off is calculated by summing the base mortality, removal by deposition, and die-off due to solar radiation.

Previous studies had used solar intensity and temperature to estimate bacterial die-off (Mancini, 1978; Chapra, 2007; Cho et al., 2010b). The current version of SWAT does not include the effect of solar intensity on die-off rate. The bacteria in-stream module (rtbact.f) was modified by adding a new parameter (SOLLPCH) to observe the effect of solar intensity, and also to improve prediction accuracy. This parameter has been widely used to estimate the bacteria die-off by solar intensity (Mancini, 1978; Mayo, 1995; Canale et al., 1993; Xu et al., 2002; Cho et al., 2010b). The natural die-off rate is needed to calculate the total die-off rate. The natural, the die-off rate at 20 °C can be calculated by using Equation (1) below:

$$K = K + I(t)\cdot K_s. \tag{1}$$

where K_n is the natural die-off rate [d^{-1}], which indicates NATDIELP parameter in the model; $I(t)$ is the solar radiation [MJ m^{-2} d^{-1}]; and K_s is the solar radiation coefficient [m^2 MJ^{-1}], which represents SOLLPCH parameter in the model.

A first-order decay equation (Chick's law) is used to determine the amount of bacteria removed by die-off and regrowth as described by Sadeghi and Arnold (2002). The total die-off rate is estimated assuming that temperature is constantly 20 °C. Therefore, the total die-off rate is recalculated by using a temperature adjustment factor as follows:

$$C_t = C_0 e^{-KtA(T-20)} \tag{2}$$

where C_t is concentration at time t; C_0 is initial concentration; K is decay rate [d^{-1}]; t is time [days]; A is temperature adjustment factor [THBACT]; and T is temperature [°C].

When streambed sediments are resuspended, the amount of the released bacteria ($M_{B,res}$, CFU) is determined as follows:

$$M_{B,res} = M_{S,res}\cdot C_{B,B}. \tag{3}$$

where $M_{S,res}$ is the mass of resuspended sediment (ton); and $C_{B,B}$ is the fecal coliform concentration in streambed sediments (CFU/g sediment). Here, sediment bacteria concentration ($C_{B,B}$) has not been monitored in this watershed, but it was estimated by calibration process within a range of reported concentrations (Pachepsky and Shelton, 2011). The fecal coliform suspended in stream water ($M_{B,W}$) are divided into free-floating ($M_{B,free}$) and sediment-associated bacteria (Bai and Lung, 2005). The sediment associated fecal coliform are further divided into bacteria attached to the suspended sediments ($M_{B,sus}$) and fecal coliform attached to the deposited sediments ($M_{B,dep}$), as follows:

$$\frac{M_{B,free} + M_{B,sus} + M_{B,dep}}{M_{B,W}} = \frac{1 + K_p\cdot conc_{sed,sus} + K_p\cdot conc_{sed,dep}}{1 + K_p\cdot conc_{sed,i}}. \tag{4}$$

where $conc_{sed,sus}$ is the concentration of the suspended sediments; $conc_{sed,dep}$ is the concentration of the deposited