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Hydrological modeling of Fecal Indicator Bacteria in a tropical mountain catchment

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ABSTRACT

The occurrence of pathogen bacteria in surface waters is a threat to public health worldwide. In particular, inadequate sanitation resulting in high contamination of surface water with pathogens of fecal origin is a serious issue in developing countries such as Lao P.D.R. Despite the health implications of the consumption of contaminated surface water, the environmental fate and transport of pathogens of fecal origin and their indicators (Fecal Indicator Bacteria or FIB) are still poorly known in tropical areas. In this study, we used measurements of flow rates, suspended sediments and of the FIB *Escherichia coli* (*E. coli*) in a 60-ha catchment in Northern Laos to explore the ability of the Soil and Water Assessment Tool (SWAT) to simulate watershed-scale FIB fate and transport. We assessed the influences of 3 in-stream processes, namely bacteria deposition and resuspension, bacterial regrowth, and hyporheic exchange (i.e. transient storage) on predicted FIB numbers. We showed that the SWAT model in its original version does not correctly simulate small *E. coli* numbers during the dry season. We showed that model's performance could be improved when considering the release of *E. coli* together with sediment resuspension. We demonstrated that the hyporheic exchange of bacteria across the Sediment-Water Interface (SWI) should be considered when simulating FIB concentration not only during wet weather, but also during the dry season, or baseflow period. In contrast, the implementation of the regrowth process did not improve the model during the dry season without inducing an overestimation during the wet season. This work thus underlines the importance of taking into account in-stream processes, such as deposition and resuspension, regrowth and hyporheic exchange, when using SWAT to simulate FIB dynamics in surface waters.

1. Introduction

The occurrence of bacterial pathogens in surface waters threatens human health, especially in developing countries. About 1.5 M people, mainly children, die annually from water-borne diseases, mainly as a consequence of the consumption of water contaminated by bacterial pathogens (WHO, 2015). These bacterial pathogens can be of fecal origin, e.g. from cattle or from human feces when open defecation is practiced or when sanitation systems are lacking or faulty. Proxies such as *Escherichia coli* (*E. coli*) are used as Fecal Indicator Bacteria (FIB) to detect the occurrence of fecal bacteria in a sample as they present a relatively cheap, easy and low risk way to detect the potential presence of pathogens of fecal origin (Rochelle-Newall et al., 2015). In wealthier countries, legislation has set thresholds of *E. coli* for both drinking and bathing water, e.g. in Europe 0 Most Probable Number (MPN) per 100 mL

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(Directive 80/778/EEC) and 1000 MPN 100 mL^{-1} (2006/7/EC), respectively. In developing countries, however, contaminated surface water is often used for drinking, cooking, bathing and washing (Ribolzi et al., 2011a; Saqalli et al., 2015).

In rural areas such as the uplands of Northern Laos, open defecation is widespread as a consequence of the lack of adequate sanitation systems. This has resulted in high levels of fecal contamination in surface waters (Boithias et al., 2016; Causse et al., 2015; Ribolzi et al., 2016; Rochelle-Newall et al., 2016). Steep slopes and high runoff, soil erosion and subsequent soil particle transfer to river networks exacerbates the microbial contamination of rivers (Patin et al., 2012; Ziegler et al., 2009). All this is further aggravated by the recent rapid changes in land use in the area (Lacombe et al., 2010; Turkelboom et al., 2008; Valentin et al., 2008a). Cultivation has evolved from a system with 10–15 years fallow periods to one where only 1–4 years fallow periods are used (Huon et al., 2013). That, combined with a progressive replacement of annual crops by tree plantations (e.g. teak) has led to increased runoff and erosion and hence, increased transport of soil surface particles into downstream aquatic systems (Lestrelin et al., 2012; Roder et al., 1997; Valentin et al., 2008a; Vigiak et al., 2008b).

The environmental fate and transport of FIB are still poorly understood in tropical rivers and wetlands (Rochelle-Newall et al., 2015; Nguyen et al., 2016). Unlike temperate regions, tropical ecosystems are generally characterized by higher and more stable temperatures, higher light intensities, and lower variability in day length and, in the case of humid tropical regions, higher relative humidity. In addition, surface water in tropical areas is often more turbid as compared to temperate rivers (Milliman and Syvitski, 1992), which reduces sunlight penetration and decreases fecal bacteria die-off rates (Chan et al., 2015).

Modeling is commonly used for the prediction and management of water quality for irrigation, recreation, aquaculture, and other purposes. Spatially distributed dynamic models provide a way to quantify large-scale fluxes of water, suspended matter, nutrients and pathogens in both soil and river compartments as a function of climate and land use. Modeling can also be an interesting tool for assessing the long term impact of global change, including the impact of land use change, on the services provided by ecosystems such as the retention of pathogen bacteria (de Groot et al., 2010). To date, few studies have modeled the fate of bacteria of fecal origin at the catchment scale, especially in tropical areas (Causse et al., 2015; Hofstra, 2011). This is mainly due to the paucity of data needed to adequately parameterize models and describe the processes involved (Cho et al., 2016a). The mechanistic semi-distributed model Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012) has previously been used in a range of environments (Baffaut and Sadeghi, 2010; Bougeard et al., 2011; Chin, 2011; Cho et al., 2012; Coffey et al., 2010; Iudicello and Chin, 2013; Kim et al., 2010; Niazi et al., 2015) and has been shown to be a promising tool for assessing the fate of fecal bacteria in temperate river basins. However, the applicability of this model for tropical regions remains to be evaluated.

The bacteria module of SWAT includes simulation of several probable mechanisms. For example, the amount of bacteria being transferred across the Sediment-Water Interface (SWI) has been previously investigated (Kim et al., 2010; Collins and Rutherford, 2004; Jamieson et al., 2005; Wu et al., 2009). Kim et al. (2010) have focused on bacterial resuspension initiated by high flow-induced shear stress on stream beds. However, for the moment, the importance of hyporheic exchange or groundwater influence on bacterial fate and transport during baseflow remains to be explored. The objectives of this study were (1) to simulate observed patterns of *E. coli* contamination in a tropical mountain headwater catchment with the current version of the SWAT model, and (2) to develop the new SWAT bacteria module and to test it using observations from a mountainous catchment in Northern Laos.

2. Materials and methods

2.1. Study design

In this paper we explore the ability of the SWAT model to simulate accurate *E. coli* numbers in a tropical montane catchment. To do so, we first calibrated the model for daily discharge and suspended sediment loads. We evaluated the ability of the current version of the SWAT model to simulate *E. coli* numbers. We then tested 4 methods to improve *E. coli* numbers simulation with SWAT combining in-stream processes, namely resuspension and deposition, bacterial regrowth, and hyporheic exchange.

2.2. Study area: the Houay Pano catchment

The study site is located in a headwater catchment, 10 km south of Luang Prabang city in Northern Lao P.D.R. (Fig. 1(a)). The 0.6 km^2 (60 ha) Houay Pano catchment is part of the 800,000 km^2 Mekong basin. This catchment can be considered as being representative of the montane agro-ecosystems of South-East Asia. It is the experimental site of the Multi-Scale Environmental Changes (MSEC, http://msec.obs-mip.fr/) program in Lao P.D.R. (Valentin et al., 2008a) and it belongs to the French network of critical zone observatories (RBV, *Réseau des Bassins Versants*, http://rnbv.ipgp.fr/).

The climate is sub-tropical humid and is characterized by a monsoon regime with a dry season from October to April, and a wet season from May to September. The mean annual temperature is 25.3 °C. Mean annual rainfall recorded at Luang Prabang from 1960 to 2006 is 1268 mm, about 76% of which falls during the wet season. Inter-year variability is high (standard deviation SD = 349 mm, i.e. coefficient of variation CV = 28%) with a minimum of 444 mm and a maximum of 2100 mm. Altitude within the catchment ranges from 435 to 716 m (Fig. 1(b)). The mean slope gradient is 52% with a maximum of 135% and a minimum of 1% (SD = 21%, CV = 41%).

Annual crops are mostly grown as a "slash and burn" agricultural system, with no chemical inputs and long fallow periods. However, over the last 20 years, the area has experienced a reduction in the fallow period from 10–15 years to 1–4 years (Valentin et al., 2008a), partly because of teak tree plantations. Land use in the Houay Pano catchment (2012) thus includes plots of shifting agriculture (19%), fallow (39%), teak (33%) and secondary forest (9%) (Fig. 1(c)). The geological substrate is mainly constituted of argilites, siltstones and fine-grained sandstone from Permian to Upper Carboniferous (Department of Geology and Mines, 1990). Soils are classified in three major orders (US Taxonomy soil classification system): Entisol, Ultisol and Alfisol (Fig. 1(d)) which cover about 20%, 30% and 50% of the catchment area, respectively (Chaplot et al., 2005; Ribolzi et al., 2011b). The Laksip village, located downstream the S4 station (Fig. 1(b)), has 442 inhabitants (data from 2007). Details on the numbers of roaming animals and field workers in the catchment during the wet and dry seasons are given in Section 2.5. A more detailed description of the Houay Pano catchment, including soil and land use can be found in Ribolzi et al. (2011a) and Huon et al. (2013).

2.3. Climate data

Daily climate data (rainfall, temperature, relative humidity, wind speed and solar radiation) in the Houay Pano catchment was collected by an automatic climate station (Campbell BWS200 equipped with ARG100, 0.2 mm capacity tipping-buckets). In