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Pesticide transport simulation in a tropical catchment by SWAT

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ABSTRACT

The application of agrochemicals in Southeast Asia is increasing in rate, variety and toxicity with alarming speed. Understanding the behavior of these different contaminants within the environment require comprehensive monitoring programs as well as accurate simulations with hydrological models. We used the SWAT hydrological model to simulate the fate of three different pesticides, one of each usage type (herbicide, fungicide and insecticide) in a mountainous catchment in Northern Thailand. Three key parameters were identified: the sorption coefficient, the decay coefficient and the coefficient controlling pesticide percolation. We yielded satisfactory results simulating pesticide load dynamics during the calibration period (NSE: 0.92–0.67); the results during the validation period were also acceptable (NSE: 0.61–0.28). The results of this study are an important step in understanding the modeling behavior of these pesticides in SWAT and will help to identify thresholds of worst-case scenarios in order to assess the risk for the environment.

1. Introduction

The mountainous regions of Southeast Asia are undergoing drastic changes in land-use and land-management strategies, including changes in farming practices (Fox and Vogler, 2005; Ziegler et al., 2009). In northern Thailand, for example, market demands have driven intensification in crop production, including the introduction of new, high-value crops (Schipmann and Qaim, 2011; Schreinemachers et al., 2011). As many of these crops are targeted for sale in large, competitive local and regional markets, great efforts are afforded to limit damage from insects, disease, and climatic elements. It is estimated that crop damage/loss by pests and disease would be 50% if agrochemicals were not applied (Oerke and Dehne, 2004). Currently, Thailand ranks third out of 15 Asian countries in mass of pesticides per unit area applied each year (Walter-Echols and Yongfan, 2005). As pesticides pose a risk to human health, it is important to understand how they move through the environment via surface runoff, preferential transport, or vertical leaching (Kruawal et al., 2005; Panuwet et al., 2012).

Losses of pesticides to the environment depend greatly on transport pathways and the physico-chemical properties of the compounds (Duffner et al., 2012; Sangchan et al., 2012). Many hydrological models have been developed that facilitate modeling pesticide movement from sources into catchment surface and groundwater systems (Gevaert et al., 2008). Hydrological models are usually applied to predict runoff within a catchment and to assess water resources management practices (Singh and Frevert, 2006). Not all models used for these assessments were developed specifically for simulating agrochemical transport at all appropriate scales of interest. For example, some models simulate pesticide fate only at the scale of individual fields, while others allow basin-wide simulations. Common field-scale models are the Pesticide Root Zone Model (PRZM, Carsel et al., 1985) or GLEAMS (Groundwater Loading Effects of Agricultural Management Systems, Leonard et al., 1987).

Borah and Bera (2004) presented a summary of several hydrological models at the watershed scale with regard to their strengths and restrictions in terms of pesticide transport modeling. AnnAGNPS (Annualized Agricultural Nonpoint Source Model, Bingner et al., 1997), the Hydrology Simulation Program-FORTRAN (HSPF, Johanson and Kliewer, 1982), and the Soil and Water Assessment Tool (SWAT, Arnold et al., 2011) have been successfully applied to simulate pesticide transport at the catchment scale. Of these models, AnnAGNPS is believed to be a good predictor of

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effects of management practices on watershed scales. HSPF was highlighted for its strength in studying the impact of urbanization, whereas SWAT has been recommended for predominantly agricultural watersheds (Borah and Bera, 2004).

Our study focuses on improving the implementation of the popular SWAT model for studying pesticide fate in agricultural catchments in northern Thailand. Use of the SWAT model is well documented and it is increasingly being used to simulate pesticide transport (Gassman et al., 2007; Holvoet et al., 2008). The processes implemented in SWAT to simulate pesticide transport are largely controlled by specific physicochemical parameters such as sorption coefficient, half-life time, or percolation coefficients (Neitsch et al., 2011). A large physico-chemical parameter database, incorporated in the recent SWAT version, enables the user to simulate the movement of many common compounds at the catchment scale (Arnold et al., 1998). A further advantage of SWAT is the opportunity to include specific land-management operations and crop rotations.

SWAT has been successfully applied for pesticide simulations in temperate regions. For example, Larose et al. (2007) effectively used SWAT to study atrazine in the Cedar Creek Watershed within the St. Joseph River Basin in northeastern Indiana (USA). Catchment-scale simulations reached Nash-Sutcliffe efficiency (NSE) values of 0.43–0.59, and the model satisfactorily captured the dynamics of stream flow and atrazine concentrations in the relatively large (707 km^2) agricultural catchment. Simulations on the transport pattern of isoxaflutole became acceptable after careful model parameterization (Ramanarayanan et al., 2005).

In contrast, Boithias et al. (2011) did not reach the same conclusions for the Save river in south-western France. Trifluralin loads were underestimated or overestimated during a flood, and the coefficient of determination (R^2) between monitored and simulated loads was only 0.38. Similarly, unsatisfactory results were obtained by Parker et al. (2007) in simulations of metolachlor, atrazine, and trifluralin in the Sugar Creek Watershed, Indiana. Trifluralin concentrations were predicted with R^2 values between 0.02 and 0.51. For atrazine, R^2 values ranged between 0.21 and 0.41. metolachlor simulations had R^2 ranging from 0.28 to 0.41.

Luo and Zhang (2009) presented results of a SWAT simulation of the transport of chlorpyrifos and diazinon in a watershed in California. They reached NSEs around 0.55, with variability existing for rainfall periods versus irrigation periods. Ficklin et al. (2012), simulating the transport of chlorpyrifos and diazinon in another large Californian agricultural watershed (Sacramento River watershed 23,300 km^2), reported that the loads of both compounds were only moderately determined by streamflow (chlorpyrifos: $R^2 = 0.44$; diazinon: $R^2 = 0.23$). In recent times, Ahmadi et al. (2013) simulated atrazine loads of Eagle Creek in Indiana, USA, with NSEs between 0.14 and 0.52.

In the past, the SWAT model has been calibrated mostly using the Parasol calibration tool (van Griensven and Meixner, 2007), which is a built-in routine of SWAT. In the Parasol tool within SWAT, most parameters directly related to the fate and transport of pesticides are not selectable and therefore not part of the autocalibration. The same is true for the built-in sensitivity analysis tool of SWAT. Thus, calibration of these parameters in prior studies has been performed almost exclusively manually (Ahmadi et al., 2013; Ramanarayanan et al., 2005; Boithias et al., 2011). Alternatively, default values have often been used (e.g. Luo and Zhang, 2009; Zhang and Zhang, 2011). Only recently, Ficklin et al. (2012) presented an automatic calibration of some of the pesticide-related parameters in SWAT using the SUFI-2 method (Abbaspour et al., 2004).

In this study, we apply a new Monte-Carlo-based calibration method, ANSELM, with SWAT to study the transport of three pesticides in a tropical catchment in northern Thailand. We compare modeled daily stream concentrations, loads and applications with measured data. In the modeling process, we perform a Latin-hypercube (LH) sensitivity analysis of all pesticide-related parameters. All these parameters are integrated in the calibration, together with the time of pesticide application as an additional parameter. After model testing, we perform an uncertainty analysis. In addition to the goal of understanding the dynamics of pesticide movement in the catchment, which is rapidly undergoing agricultural changes, we also sought to develop improved methods for such simulations using SWAT, particularly for tropical environments.

2. Material &methods

2.1. Study site

The Mae Sa catchment (18° 54″ N, 98° 54″ E), located 35 km northwest of Chiang Mai in northern Thailand, has a total area of about 77 km^2. In 2006, about 24% of the catchment area was under agricultural use, whereas much of the remaining area was covered by deciduous and evergreen forest characterized by various degrees of disturbance. The catchment spreads over elevations ranging from 325 to 1540 m a.s.l. Many hillslopes are steeper than 100%. The main soil types are Acrisols and Cambisols (FAO, 1998; Schuler, 2008). The underlying geology includes granite and gneiss along with pockets of freshwater limestone and marble. Tropical climatic conditions are dominant, with a mean air temperature of 21 °C and a total annual rainfall of 1250 mm. The rainy season typically begins in May and ends in late October, with the dry season extending from November to April. Typical crops now grown in the Mae Sa catchment are bell pepper, litchi, chayote, cabbage and flowers (Schreinemachers et al., 2011). Most crops are grown in the rainy season. Those grown in the dry season are irrigated. Many farmers in the study area frequently shift from one crop to another between different years (Schreinemachers and Sirijinda, 2008). Among the different categories of pesticides, insecticides were used most frequently (87%), followed by fungicides (68%) and herbicides (29%) (Schreinemachers et al., 2011). Pesticides are applied manually with hand-spraying devices.

2.2. Stream flow and pesticide monitoring

From January 2008 to December 2010 we operated two weather stations (Thies GmbH, Germany; UIT GmbH, Germany) equipped with sensors for monitoring air temperature, solar radiation, relative humidity, wind speed and rainfall. Rainfall data were recorded by 12 automatic tipping bucket gauges (Fischer GmbH, Germany), which were evenly distributed throughout the watershed (Fig. 1). At the main catchment outlet, an automatic water sampler (6712 Portable sampler) coupled with an ultrasonic water level sensor (710 Ultrasonic module, Teledyne ISCO Inc., USA) was installed to collect water samples and to measure stream flow at 10-min intervals. A stage–discharge relation curve was derived by a series of calibration measurements using an acoustic digital current meter (OTT ADC GmbH, Germany) across a wide range of discharges. Water samples were taken discharge-proportionally on a daily basis. In total, 82 and 89 samples were collected in 2008 and 2009, respectively.

Water samples were analyzed for one herbicide, one fungicide and five insecticides (reported by Sangchan et al., 2012). For our modeling study, we selected one pesticide of each usage group: Atrazine (herbicide), chlorothalonil (fungicide) and endosulfan (insecticide). Key physico-chemical properties of these pesticides are presented in Table 1. Water samples were filtered through glass fiber filters (GF/F, 0.7 μm, Whatman Inc., USA). Pesticides were extracted from water samples by solid phase extraction (SPE) (Supelclean™ Envi-carb, Supelco, Germany). Chlorothalonil and endosulfan were analyzed by a gas chromatograph-micro electron capture detector (GC-μECD). Atrazine was analyzed by a gas chromatograph-nitrogen phosphorus detector (GC-NPD). The selected samples with outstanding high peak concentrations were confirmed by a gas chromatograph–mass spectrometer (GC–MS). Limit of detection, recoveries and relative standard deviation (RSD) of the monitored pesticides are shown in Table 2. Pesticide loads in the river were calculated by multiplying measured average daily pesticide concentrations by the corresponding mean daily discharge. Additional information on the sampling and analyzing procedure is reported in Sangchan et al. (2013).

2.3. Modeling

SWAT is a semi-distributed, watershed-scale model that operates at a daily time step. The model requires input data on climate, topography, soil and land use. The basic entities of SWAT are hydrological response units (HRUs). Apart from simulating surface and subsurface hydrological processes, SWAT provides sub-models to simulate different management operations and pesticide fate and transport (Neitsch et al., 2011). SWAT, however, does not simulate stress on plants due to pests or stress relief following pesticide application. Thus, the effect of pesticides on plants is not