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Research article

Coupling HYDRUS-1D with ArcGIS to estimate pesticide accumulation and leaching risk on a regional basis

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ABSTRACT

HYDRUS-1D is a well-established reliable instrument to simulate water and pesticide transport in soils. It is, however, a point-specific model which is usually used for site-specific simulations. Aim of the investigation was the development of pesticide accumulation and leaching risk maps for regions combining HYDRUS-1D as a model for pesticide fate with regional data in a geographical information system (GIS). It was realized in form of a python tool in ArcGIS. Necessary high resolution local soil information, however, is very often not available. Therefore, worldwide interpolated 250-m-grid soil data (SoilGrids.org) were successfully incorporated to the system. The functionality of the system is shown by examples from Thailand, where example regions that differ in soil properties and climatic conditions were exposed in the model system to pesticides with different properties. A practical application of the system will be the identification of areas where measures to optimize pesticide use should be implemented with priority.

1. Introduction

Land use intensification is usually accompanied by a reduction in the use of traditional methods of pest management and an increase in the use of synthetic insecticides, fungicides and herbicides (Riwthong et al., 2015). As a consequence, pesticide poisoning is an important health problem in Thailand as a result of the intensive use of hazardous pesticides (Tawatsin et al., 2015). Similar problems exist in several low and middle-income countries, such as Mexico, Brazil, Uruguay, Cameroon or Malaysia (Schreinemachers et al., 2011). Fast agricultural development results in an increase in agricultural productivity and inevitably in a shift from extensive to more intensive types of land use (Riwthong et al., 2015). Traditional methods of pest management are replaced by agrochemicals and the intensity and amount of pesticide use grows rapidly (Schreinemachers et al., 2011; Riwthong et al., 2015). In Brazil, for example, the pesticide market experienced a rapid expansion of 190% over the last decade while pesticides are a major public health problem (Rigotto et al., 2014). According to Riwthong et al. (2015), farmers in the upland areas of northern Thailand spray pesticides up to 16 times a year and use about 22 kg of active ingredients per hectare. Inappropriate pesticide handling, improper use of personal protective equipment as well as inadequate understanding of the toxicity of the chemicals (Panuwet et al., 2008) put farmers in Thailand at high risk of pesticide poisoning. Panuwet et al. (2008) used urinary concentrations of pesticide metabolites to assess the farmers' exposure to pesticides. Each year, thousands of cases of pesticide intoxication are reported with morbidity rates between 76.4 and 96.6 per 100000 inhabitants (Tawatsin et al., 2015).

Apart from the significant human health risk, there are adverse consequences also for the environment. Pimentel (1995) estimated that less than 0.1% of the pesticide applied to the crop actually reaches the target pest. The rest enters the environment and adversely affects beneficial biota, contaminates soil, water and the atmosphere and, eventually, ends up again in contaminating the human population. The costs in Thailand of externalities like health hazards, residues in food and water or resistance build-up are high, but since pesticides still have a high reputation in their relevance for securing sufficient agricultural production, Thailand's crop protection policy has been and is still rather supportive for pesticide use (Jungbluth, 1996; Tirado et al., 2008; Schreinemachers et al., 2011). Thus, several studies conclude with the urgent

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necessity of an integrated pest management in Thailand, the promotion of good agricultural practice and of raising awareness among farmers regarding the risk they are exposing themselves to (Riwthong et al., 2015), and, furthermore, the promotion and development of non-synthetic methods of pest control and the restriction of highly hazardous pesticides (Schreinemachers et al., 2011; Tawatsin et al., 2015). A system to estimate pesticide accumulation and leaching risk which can be used to identify highly endangered areas in a region, could supply predictable data of the pesticide's risk potential and thus play an important role in developing an integrated pest management. The results can be used as a decision support for a sustainable pest management.

HYDRUS-1D has established itself as a reliable instrument for simulating pesticide transport in soils (Ladu and Zhang, 2011; Šimůnek et al., 2013; Leiva et al., 2017; Márquez et al., 2017). HYDRUS-1D is public domain and, thus, freely available. Also, the FORTRAN source code is freely available (PC-Progress, 2017). HYDRUS-1D is a point specific model generally used to describe processes in soil columns or at homogeneous sites. However, because HYDRUS-1D is a site-specific model, there are very few examples where HYDRUS-1D was used to simulate the variability of regions (Assefa and Woodbury, 2013). The effect of the variability of regions with respect to pesticide leaching and accumulation risk is important to find out priority areas for water and soil protection.

In the risk assessment system developed in this investigation, HYDRUS-1D was coupled with ArcGIS to make it applicable to larger regions. This combined system unites the advantageous properties of HYDRUS-1D, as a proper model for pesticide fate, and the possibility of using a geographic information system (GIS). The system has a user-friendly user interface which consists of parameter inputs for soil, land management information, climate information and pesticide application amounts. It offers the possibility to select between different pesticides, climatic regions, and irrigation options. Results of the system are maps showing the accumulation and leaching risk of selected pesticides. As particularly soil information is sometimes very difficult to obtain, the system uses easily available soil data.

Paraquat and atrazine were used as examples to show the applicability of the tool to estimate accumulation and leaching risk based on the simulation of a 10-year period with long-term average climate data. The results are presented as maps with accumulation or leaching risk classes aiming to show differences between different map units. No effort was taken to compare the simulated concentrations with measured concentrations to show actual contaminations. Such site-specific simulations are a completely different approach where much more information is needed, such as time and site-specific pesticide application amounts. This data is simply not available for regions. Due to the same reason, no calibration or validation of the model results was performed. This was not possible, and not necessary, to estimate differences in potential contamination risk.

Thus, the objectives of the investigation were i) to technically achieve a coupling of HYDRUS-1D and ArcGIS with the help of a python script, ii) to test the applicability of the system with available data from different regions in Thailand, and iii) to test whether worldwide available SoilGrids soil data are useable in the system.

2. Materials and methods

2.1. HYDRUS-1D

Numerical models simulating and predicting contaminant transport processes in soils and groundwater are increasingly used in research and engineering projects addressing subsurface pollution problems (Šimůnek et al., 2012, 2013; Giannouli and Antonopoulos, 2015; Shrestha and Datta, 2015; Bernard et al., 2016). There are several models available ranging from relatively simple analytical and semi-analytical solutions, to more complex numerical approaches. Most models famous for predicting the fate and transport of agrochemicals are based on the convection-dispersion equation, such as HYDRUS-1D, which considers convection, dispersion, adsorption and degradation (Ladu and Zhang, 2011; Šimůnek et al., 2012). HYDRUS-1D is a finite element model for simulating water, heat and solute movement in one-dimensional variably saturated media (Šimůnek et al., 2012). It numerically solves the convection-dispersion equation for solute transport and the Richards equation for variably-saturated water flow and can consider processes such as root water uptake, infiltration, evaporation, soil water storage, capillary rise, deep drainage, groundwater recharge and surface runoff (Šimůnek et al., 2012). The solute transport equation accounts for advection and dispersion in the liquid phase and diffusion in the gaseous phase and considers linear equilibrium reactions between the liquid and the gaseous phase, zero-order production, and first-order degradation reactions (Šimůnek et al., 2012). HYDRUS-1D may also consider different physical and chemical non-equilibrium transport situations to account for e.g. preferential flow situations. Although non-equilibrium situations are particularly interesting in case of heterogeneous soils, the governing parameters are difficult to obtain on a regional basis. Therefore, in this investigation only equilibrium conditions were considered.

HYDRUS-1D is widely used to evaluate the fate and transport of chemicals in the unsaturated zone between the soil surface and the groundwater table (Šimůnek et al., 2013). Several authors used HYDRUS-1D to successfully simulate pesticide transport in soils (e.g. Pang et al., 1999; Köhne et al., 2006; Dousset et al., 2007; Papiernik et al., 2007; Abdel-Nasser et al., 2011; Ladu and Zhang, 2011; Giannouli and Antonopoulos, 2015; Shrestha and Datta, 2015; Bernard et al., 2016; Noshadi et al., 2017). Köhne et al. (2009) concluded that HYDRUS-1D is one of the leading model systems for simulating pesticide transport in agricultural structured field soils.

2.2. Soil information

HYDRUS-1D needs soil information to simulate transport of pesticides in soils. Necessary soil information is needed for the layers or horizons at each site to be calculated, or at least values for the topsoil (0–30 cm) and subsoil (30–200 cm) as there are usually big differences, mainly with respect to organic carbon content. In addition, the soil texture is needed (or the clay, silt, and sand content), the bulk density and the soil organic carbon content (C_{org}). The rooting depth defines the lower boundary of the soil; pesticide leaching was assumed to take place once pesticides leave the rooting depth. Important soil physical parameters can be calculated with soil transfer functions from other parameters, such as available water capacity and hydraulic conductivity (estimated from texture), or linear adsorption coefficient K_d (estimated from C_{org}) (reviewed e.g. by Guber and Pachepsky, 2010).

Detailed soil information at larger scales (at least 1:25.000, depending on the size of the region under consideration and the necessary accuracy of the simulation) is difficult to obtain at many places. The reason is either simple non-existence of large scale soil data, or formal and administrative problems making soil data not available to researchers. Therefore, online available soil data on a 250-m grid (SoilsGrids) were used (Hengl et al., 2014, 2017; Shangguan et al., 2017; SoilGrids, 2017). SoilGrids is an automated soil mapping system based on global soil profile and environmental