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Assessing potassium environmental losses from a dairy farming watershed with the modified SWAT model

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ABSTRACT

Potassium (K) was intensively used to optimize agricultural crop yield. Potassium losses should be accurately quantified for efficient nutrient management. However, no hydrologic model had been developed yet to quantify daily K losses at watershed scale. The Soil and Water Assessment Tool (SWAT) model was modified (named SWAT-K) by including the main K dynamic processes (solid–liquid distribution in soil and stream, plant uptake, and transportation with water flow and soil erosion) to simulate stream K load and K budget at the watershed scale. The SWAT-K was tested on the dairy farming Shibetsu River Watershed (672 km^2), Eastern Hokkaido, Japan. The solid–liquid distribution coefficient for K in suspended sediment was 10 ml g^{-1}. Langmuir equation was fitted to describe the solid–liquid distribution of K in soil, which derived an affinity constant of 0.046 L mg K^{-1} and was used directly in SWAT-K. The fitted Langmuir equation also derived an adsorption maximum for K in soil. The adsorption maximum for K in soil normalized for clay content ranged from 4 to 20 g K kg^{-1}, and the fitted value of 15.5 g K kg^{-1} was used in SWAT-K. The SWAT-K satisfactorily predicted the daily dissolved K load at watershed outlet, and estimated an annual dissolved K load of 27.3 kg K ha^{-1} $year^{-1}$. The simulated pasture K yield of 36.1 (±2.5) kg K ha^{-1} $year^{-1}$ was close to the observed data of 38.0 (±3.1) kg K ha^{-1} $year^{-1}$. Then the model was used to quantify K budget at watershed scale. The simulated dissolved K leaching was 15.1 kg K ha^{-1} $year^{-1}$, and simulated soil K surplus of 75.1 kg K ha^{-1} $year^{-1}$ was much higher than plant uptake of 28.4 kg K ha^{-1} $year^{-1}$. The large amount of leaching and soil storage indicated that agricultural K input might be excessive and reducing the K application was recommended.

1. Introduction

Potassium (K) is an essential and major nutrient for plant growth (Sparks and Huang, 1985). Potassium stimulates early growth, increases protein production, improves the efficiency of water use, and improves plant resistance to diseases and insects (Kayser and Isselstein, 2005). Soil exchangeable K is held on the cation exchange sites of soil particles. However, exchangeable K usually accounts for only a small fraction of the soil total K. The large amount of unavailable K is principally locked up in the structural framework of soil minerals (Barré et al., 2008). The exchangeable K is readily released to the soil solution and thus can be easily absorbed by plant. The exchangeable K can be distributed in liquid (dissolved form) as well as be sorbed on solid (sorbed form) in land and stream. The unavailable K only becomes exchangeable K upon long-term weathering. Intensive crop production continually needs K fertilizers in large amounts to increase plant available K and to optimize crop growth (FAO, 2011). Dairy farming leads to K losses from the manure of the grazing cattle of which diet can be supplemented with K to enhance milk production. Agricultural practices, e.g., overuse of fertilizing nutrients and dairy farming, can degrade the environment and water quality in particular (Gourley et al., 2007; Silanikove et al., 1997). In fact, the K ion is mobile in soils, especially in sandy soils which have a low clay content and a low CEC

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(Pal et al., 1999; Dassannayake, 1990), and consequently significant portion of the soil K can be lost from agricultural land and enter into receiving waters by being transported in the soil solution and water (Alfaro et al., 2004; Kayser and Isselstein, 2005). Potassium leaching from soil to groundwater increases the K concentration in groundwater. When groundwater discharges into stream, K concentration in stream is further increased. The experiments conducted by Owens et al. (2003) found that the major transport pathway of K was via subsurface flow, and there could also be considerable K losses through surface runoff, i.e., K was either dissolved in water, sorbed on eroded soil particles or unavailable K in the material lost during erosive rainfall events, thus increasing K losses from land to streams. Unlike nitrogen (N) and phosphorus (P), high K concentration in groundwater and surface water is not a major environmental concern (Withers and Haygarth, 2007). However, a permissible limit of 12 mg K L^{-1} for drinking water was recommended by the European Directive 80/778/EEC. Potassium concentration higher than this permissible limit may pose a risk to human health. In order to avoid the unnecessary K waste in agriculture and deterioration of drinking water, the accurate determination of K losses to receiving waters is necessary (Askegaard et al., 2004; Kayser et al., 2012). However, to date little attention was paid to K losses to streams in complex watersheds.

Understanding the K losses at large watershed scale by field experiment for a long period requires tremendous investment of time and/or money. Modeling can be used as a critical tool to support the work and enables its users to study long-term assessment of K losses. Geochemical models have previously been developed to specifically look at the transport of solutes including K in the soil, plant, groundwater, and/or surface water. For example, solutes transport in variably saturated soil can be simulated by LEACHM (Hutson and Wagenet, 1992), PHREEQC (Parkhurst and Appelo, 1999), HP1 (Jacques and Šimůnek, 2005), HYDRUS (Šimůnek et al., 2005, 2006), or CAEDYM (Hipsey and Hamilton, 2008). Solutes transport in the groundwater can be simulated by MT3DMS (Zheng and Wang, 1999) or SEAWAT (Langevin et al., 2003). Solutes transport among surface water, variably saturated soil, and groundwater can be simulated by MIKE SHE (DHI, 2003). Solutes transport in lake can be simulated by coupling surface water hydrodynamic-biogeochemical model ELCOM-CAEDYM with a model of soil physical and geochemical processes (Hipsey et al., 2014). These geochemical models can partition the K between the dissolved and sorbed forms in soil and/or groundwater. Plant nutrients (N, P and K) uptake from soil can be simulated by LUCIA (Marohn and Cadisch, 2011; Marohn et al., 2013). However, those above mentioned models had never been applied to simulate K dynamics in soil, plant, groundwater, and surface water simultaneously. In order to assess K dynamics across large complex watersheds, all components of soil, plant, groundwater, and surface water should be included. Watershed-scale hydrological models, such as AnnAGNPS (Bingner and Theurer, 2001), HSPF (Donigian et al., 1993) and SWAT (Arnold et al., 1998) were found to have all the four major components (soil, plant, groundwater and surface water). These models have been widely used by researchers and decision makers to understand hydrologic, ecological and biogeochemical processes as well as to examine the effects of human activities and climate change or variability on water quantity and quality (sediment, N, P, pesticide, bacteria) at watershed scale (Srivastava et al., 2007). As far as we know, these models had not yet implemented the geochemistry to partition K between the dissolved and sorbed forms and the aforementioned K transfer and transport processes. Therefore, none of these models could be used to assess K dynamics at watershed scale. Among the watershed-scale models, the model we selected to be upgraded with the K dynamic processes in land and stream was the SWAT because of its suitability for larger catchments, its freely available open source code, the existence of an extensive user manual, its user-friendly GIS interface and its worldwide community of users (Arnold et al., 2012; Gassman et al., 2014). The SWAT incorporates spatially distributed watershed inputs and simulates a number of processes, such as hydrology, for sediments and nutrients (N and P) in large complex watersheds with varying soils, land uses and management conditions over long periods of time (Arnold et al., 2012). The SWAT has been widely applied to quantify and manage soil and in-stream contaminants fate such as sediment (e.g., Wang et al., 2015; Zhou et al., 2015), N (e.g., Boithias et al., 2014a,b; Ferrant et al., 2013), P (e.g., Winchell et al., 2014; Ullrich and Volk, 2009) and pesticides (e.g., Boithias et al., 2011; Fohrer et al., 2014) at watershed scale.

In this study, only the quantity of exchangeable K (in dissolved form or/and sorbed form) was counted in total K in land and stream. The objectives of this study were to: (1) modify SWAT (named SWAT-K) to simulate the K losses from land to stream and in-stream K cycling, (2) evaluate the performances of the SWAT-K based on the case study in Shibetsu River Watershed (eastern Hokkaido, Japan), where 41% of the land surface is covered by pastures for dairy farming (Hayakawa et al., 2009; Jiang et al., 2011, 2014; Wang et al., 2015), and (3) compute the K budget in this watershed considering the agriculture management operations (harvest and applications of fertilizers and manure) in the pastures.

2. Materials and methods

2.1. Study site description

The study site was the Shibetsu River Watershed (SRW). It covers an area of 672 km^2 and is located in eastern Hokkaido, Japan (outlet location is shown in Fig. 1a; 43.634N, 145.085E). About 29% of the watershed was the mountainous area where elevations range from 295 m to 1059 m and slopes were greater than 10%, as shown in Fig. 1b and c (Jiang et al., 2011). This region had a hemi-boreal climate, characterized by warm summers and cold winters. Precipitation averaged 1128 mm $year^{-1}$ and the annual mean temperature was 5.0 °C (1980–2008 average, Japan Meteorological Agency, http://www.jma.go.jp). The snow period persisted from early December to late April. Average streamflow at the outlet of SRW is 22 $m^3 s^{-1}$ (1980–2008) and streamflow varied with seasons (up to 350 $m^3 s^{-1}$ during high flow periods) (Ministry of Land, Infrastructure and Transport, Japan, http://www1.river.go.jp). The annual water yield was usually larger than annual precipitation as the watershed receives external groundwater contribution (EXT) from other areas (Hayakawa et al., 2009). The average value of EXT calculated from annual water budget from 1980 to 2008 was 504 mm $year^{-1}$ (1.38 mm day^{-1}) (Jiang et al., 2011). The mountainous areas might be where EXT joined SRW.

The major soil types in the watershed included Histosols (3.3%), Vitric Andosols (13.9%), Cambisols (20.6%), Silandic Andosols (46.1%), Haplic Fluvisols (9.1%), Regosols (4.5%) and Gleyic Fluvisols (2.6%) (IUSS, 2006), which corresponds to Peat soils (PS), Regosolic Kuroboku soils (RKS), Brown Forest soils (BFS), Kuroboku soils (KS), Brown Lowland soils (BLS) and Gray Lowland soils (GLS), respectively, in Japanese soil classification (Cultivated Soil Classification committee, Japan, 1995) (Fig. 1d). The principal characteristics of the soils were presented by Jiang et al. (2011). All the soils in this watershed were formed from volcanic ashes.

The watershed consisted of forest (53.7%), agriculture (40.8%), urban area (4.5%), and water (1.0%) (Fig. 1e). The dominant vegetation in forests was the Japanese larch (*Larix kaempfer* L.). Pasture (mainly *Phleum pratense* L.) covered 95% of the agricultural land, which was mainly used for dairy farming. The livestock mainly consisted of beef cattle, dairy cattle and horses, and there was about 2.07 livestock units per hectare (one livestock unit is equivalent to 1