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Simulation of watershed hydrology and stream water quality under land use and climate change scenarios in Teshio River watershed, northern Japan

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ABSTRACT

Quantitative prediction of environmental impacts of land-use and climate change scenarios in a watershed can serve as a basis for developing sound watershed management schemes. Water quantity and quality are key environmental indicators which are sensitive to various external perturbations. The aim of this study is to evaluate the impacts of land-use and climate changes on water quantity and quality at watershed scale and to understand relationships between hydrologic components and water quality at that scale under different climate and land-use scenarios. We developed an approach for modeling and examining impacts of land-use and climate change scenarios on the water and nutrient cycles. We used an empirical land-use change model (Conversion of Land Use and its Effects, CLUE) and a watershed hydrology and nutrient model (Soil and Water Assessment Tool, SWAT) for the Teshio River watershed in northern Hokkaido, Japan. Predicted future land-use change (from paddy field to farmland) under baseline climate conditions reduced loads of sediment, total nitrogen (N) and total phosphorous (P) from the watershed to the river. This was attributable to higher nutrient uptake by crops and less nutrient mineralization by microbes, reduced nutrient leaching from soil, and lower water yields on farmland. The climate changes (precipitation and temperature) were projected to have greater impact in increasing surface runoff, lateral flow, groundwater discharge and water yield than would land-use change. Surface runoff especially decreased in April and May and increased in March and September with rising temperature. Under the climate change scenarios, the sediment and nutrient loads increased during the snowmelt and rainy seasons, while N and P uptakes by crops increased during the period when fertilizer is normally applied (May through August). The sediment and nutrient loads also increased with increasing winter rainfall because of warming in that season. Organic nutrient mineralization and nutrient leaching increased as well under climate change scenarios. Therefore, we predicted annual water yield, sediment and nutrient loads to increase under climate change scenarios. The sediment and nutrient loads were mainly supplied from agricultural land under land use in each climate change scenario, suggesting that riparian zones and adequate fertilizer management would be a potential mitigation strategy for reducing these negative impacts of land-use and climate changes on water quality. The proposed approach provides a useful source of information for assessing the consequences of hydrology processes and water quality in future land-use and climate change scenarios.

1. Introduction

Land-use activities, which include conversion of natural landscapes for human use and changing management practices for human-dominated lands, have transformed a large proportion of the planet's land surface (Turner et al., 2001). Land-use change such as deforestation, increase and intensification of agricultural land, or expansion of urban land in a watershed can influence hydrologic processes, including infiltration, groundwater recharge, baseflow and runoff (Laurance, 2007; Lin et al., 2007; Bradshaw et al., 2007; Hurkmans et al., 2009). Watershed development from dominant natural land cover to more artificial land systems often reduces baseflow by changing groundwater flow pathways to surface water bodies (Lin et al., 2007). Croplands, pastures, plantations, and urban areas have expanded regionally and globally in recent decades, accompanied by large increases in

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fertilizer application (Thampi et al., 2010; Tilman et al., 2001). Anthropogenic nutrient inputs to the biosphere from fertilizers now exceed natural nutrient sources, resulting in significant effects on water quality in streams, rivers, lakes and estuaries (Manson, 2005). Excessive fertilization of farmland often affects in-stream processes, such as biotic and abiotic immobilization and mineralization in river channels (Johnson et al., 1997). The major environmental consequences of excessive phosphorous and nitrogen inputs are water pollution, biodiversity loss, and eutrophication in aquatic ecosystems (Gitau et al., 2010; Chiang et al., 2010). Intensification of agricultural land including intensive cultivation of annual crops, plowing of soil on steep slopes, and poor soil conservation practices also produce serious soil erosion following soil nutrient depletion (Alibuyog et al., 2009). Fan and Shibata (2014a) reported that land use change (changing from paddy field to farmland field) remarkably impacted on hydrological and hydrochemical ecosystem services in the Teshio watershed, especially the nutrient retention was more sensitive to land use changes.

Global climate change, including changes of precipitation and temperature patterns, may significantly alter water quantity and quality in a watershed (USEPA, 2014). Global warming increases the water holding capacity of the atmosphere, resulting in global increases of precipitation and evapotranspiration (Howden et al., 2007). On average, global surface temperatures have increased about 0.74 °C over the past 100 years (Jeppesen et al., 2009). Winter temperature increase will cause more precipitation to fall as rain instead of snow, and snowpack will melt earlier in spring (Chiew and McMahon, 2002). Therefore, basin hydrology will shift from a combined rainfall/snowmelt regime to a more rainfall-dominant one, increasing flood risk in winter and the probability of droughts in summer. Higher temperature also increases potential evapotranspiration, which may lead to decreased runoff and soil moisture (Band et al., 1996; Stone et al., 2001; Jeppesen et al., 2009; Somura et al., 2009). Erosion and sediment transport processes are also influenced by climate change. For example, greater soil loss by erosion often occurs in regions with strong variability of precipitation and runoff (Marshall and Randhir, 2008). Moreover, soil erosion may cause significant offsite effects of river and reservoir sedimentation on hydroelectric power generation and irrigation efficiencies (Nelson et al., 2009). Murdoch et al. (2000) stated that a potential impact of climate change is increased diffusive sources of pollutant loads from agricultural land to river systems (Bouraoui et al., 2002). Increases of air and water temperature have been shown to increase biological productivity and decomposition, leading to an altered nutrient cycle, enhanced eutrophication, and degradation of water quality in a watershed (Chiew and McMahon, 2002; Jha et al., 2004; Bouraoui et al., 2004).

Fresh water is one of the most important resources for humans, flora and fauna (Bu et al., 2014). Terrestrial watershed and aquatic ecosystem provide bundles of ecosystem services such as water purification, provisioning of habitat for the aquatic organisms, flood control, water supply and food provision. As land use and climate changes and their effects become a pressing issue, it is important to understand the consequences it will have on water quantity and quality issues (Mander and Meyer, 2012). Human life and well-being depends on having clean water to use for drinking, food production, industrial uses, transportation and recreation, while ecosystems rely on clean water to provide life and habit. Rivers are open ecosystems which depend on their surrounding terrestrial landscape. The quantity and quality of river water could be dramatically affected by land use and climate changes and their negative consequence leads to decline in the services it provides. Nutrient export to running waters is conditional on landscape features like hydrology, climate, topography and soil types. The sediment and water quality are the critical environmental indicators to assess the water pollution degree and environmental health. The catchment-scale hydrochemical models could simulate the water quantity and quality under different land use and climate changes, which are useful for functional water management and land use planning to further sustain human benefits and the health of nature system (Pärn et al., 2012). Earlier studies have quantitatively assessed water quantity and quality under land-use or climate changes separately (e.g., Ferrier et al., 1995; Chang et al., 2001; Howden et al., 2007; Bradshaw et al., 2007; Metzger et al., 2008; Alibuyog et al., 2009; Fan and Shibata, 2014a). Few studies have analyzed and compared the impact of both land-use and climate changes on water quantity and quality, even though those changes are simultaneously occurred in the same period (Lin et al., 2007; Chiang et al., 2012). Therefore, modeling and understanding the responses of water quantity and quality to both land-use and climate changes in the future are very useful and valuable toward optimizing land-use planning, management and policy in a watershed, particularly one with expanding agriculture. Given this backdrop, this study uses model to assess the impacts of multiple land-use and climate change scenarios on hydrologic components and water quality at watershed scale. Specific objectives are: (1) to evaluate impacts of land-use and climate changes on water quantity and quality at watershed scale; (2) to analyze relationships between hydrologic components and water quality under different land-use and climate change scenarios at watershed scale. Our hypotheses were: (1) there are significant impacts of land-use and climate changes on water quantity and quality; (2) there are close relationships between hydrologic components and water quality under land-use and climate changes.

2. Methods

2.1. Overview of study approach

The overall analytical framework consists of land-use change modeling, development of climate change scenarios, and modeling of water, nutrient and sediment dynamics in a watershed. We simulated future land-use patterns using the Conversion of Land Use and its Effects (CLUE) model, which is based on logistic regression models and has driving factors including spatial policies and land-use demand. We developed the multiple climate change scenarios generated by a general circulation model (GCM) for the study watershed. Following the development of change scenarios for land use and climate, we applied the Soil Water and assessment Tool (SWAT) to simulate water, nitrogen, phosphorus, and sediment dynamics under multiple land-use and climate change scenarios at the watershed scale. We then analyzed relationships between hydrologic and water quality components to test the hypothesis that future land-use and climate changes will impact yields of water, sediment, nitrogen, and phosphorus in the watershed.

2.2. Study site

The study site is in the Teshio River catchment in northern Hokkaido of North Japan. The Teshio is the fourth longest river in Japan; it originates from the foot of Mt. Teshio and flows into the Sea of Japan (Ileva et al., 2009,b; Fan and Shibata, 2014a,b). The Teshio is a representative watershed of northern Japan. It consists of forest, agricultural land and human settlements, with average population ~90,000 concentrated in the middle and upper parts of watershed, which are dominated by agriculture (Fan and Shibata, 2014a). Ileva et al. (2009) stated that excess fertilizer application on agricultural land in the middle Teshio watershed increased