EM-13-03

Impact Analysis of Population Growth and Fertilizer Use on Nitrogen Runoff in Nam Ngum Basin, Laos

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Abstract

Human population growth has led to increased energy and food production, fertilizer usage and wastewater flows. Increased nitrogen availability is a worldwide cause of eutrophication of rivers, lakes and estuaries, however, quantitative evaluation the impacts of nitrogen loads has been insufficient in developing countries because of poor data availability. The Nam Ngum River basin, Laos, which supplies quality water for domestic use in the Vientiane Metropolis, was selected as the target area for this study. A conceptual nitrogen balance model with three nitrogen pools was developed and combined with a rainfall runoff model. Simulated river discharge and nitrogen loads agreed with the observed data. Then, we investigated future nitrogen load variations in the basin under different population growth and agricultural modernization scenarios. As a result, even when population in the basin increased 2.1 times, nitrogen load did not change significantly (11,676 tons/year in 2000 and 11,822 tons/year in 2050). However, the fertilizer increase scenario, from 25 kg/ha/season to 50 kg/ha/season, showed significant increase in nitrogen loading, from 11,676 ton/year to 17,010 ton/year. Our results provide initial insight into the magnitude and spatial distribution of nitrogen loading in Nam Ngum River Basin.

Introduction

The water quality problem is particularly serious in the rapidly developing tropical Asian monsoon region, where more than 30% of the world's chemical fertilizers are applied. Because the population is still increasing, and it is necessary to develop infrastructure to achieve stable food production and water environmental conservation (Tanaka et al., 2013). Normally, water quality is observed at the mainstream only, limiting understanding of the spatial distribution of nutrient runoff from monitoring surveys alone. Additionally, it is difficult to understand the spatial and temporal distribution of water resources and nutrient loading in developing countries due to low observation density and lack of observation data at the tributary level. Conceptual and physically based models (Lee et al. 2006) describe the processes responsible for nitrogen wash-off into surface water and leaching to groundwater in large heterogeneous basins. Such models allow forecasting and a better understanding of processes. However, even if these facts are well known, few scientific works on water quality in developing countries have been published until recently, because available data are quite limited in such regions. In this study, a water cycle and nitrogen dynamics model, which considered the local cultivation and water treatment system, was developed and applied to a tropical Asian monsoon basin with a paddy rice culture similar to that of Japan.

Methodology

Study Area

The Nam Ngum River basin in Laos is a tributary of the Mekong River. The river is about 415 km long with a catchment area of about 17,000 km^2. The Nam Ngum 1 dam has an effective storage capacity of 4.7 billion m^3, located in the middle stream of the basin (Fig. 1). The Nam Ngum 1 dam is dedicated to power generation, and supplies electricity to the Laos capital, Vientiane, as well as exporting it to Thailand.

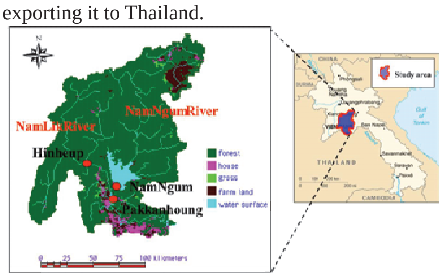

Fig 1. Nam Ngum basin

Rainfall-Runoff model

TOPMODEL is widely used for hydrological characteristic analysis, water management, water quality analysis, and future forecasting. TOPMODEL was proposed by Beven and Kirkby (1979) based on the contributing area concept in hill slope hydrology. This model is based on the exponential transmissivity assumption, which leads to a topographic index ln(a/To/tan$b$), where a is the upstream catchment area draining across a unit length, To is the lateral transmissivity under saturated conditions, and tan$b$ is the local gradient of the ground surface. Fig. 2 illustrates the conceptual structure of the water cycle as estimated by TOPMODEL. Additionally, a dam operation model was combined with TOPMODEL to calculate water storage in the reservoirs (Hanasaki et al. 2007).

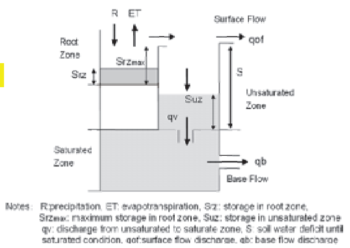

Fig 2. TOPMODEL

Nitrogen balance model

A conceptual nitrogen balance model considering three pools in soil such as organic N, Ammonium N and Nitrate N was developed for this study, as shown in Fig. 3. Soil N, mainly present in organic form, is almost unavailable to plants. The vegetation uses inorganic forms of N, which are made available by organic matter decomposition. Soil microorganisms convert the N contained in organic matter in a process called mineralization. For details on the calculation methods for each nitrogen flux and denitrification process, please see Yoshida et al., 2017.

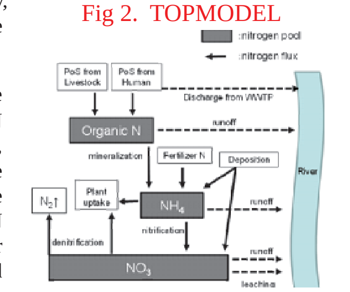

Fig 3. Nitrogen balance model

Result and Discussion

Model Verification

Using the proposed model, water and nitrogen balances from 1995 to 2004 in the Nam Ngum Basin were calculated at a 1 km × 1 km resolution. The first 5 years of data were used for parameter calibration and the latter 5 years of data were used for validation. Parameters were calibrated by trial and error method to maximize the Nash-Sutcliffe efficiency (NSE) at Pakkanhoung (catchment area: 14,300 km^2) station. Fig. 4 shows the observed and calculated river discharge at Pakkanhoung station. The estimated NSE in the calibration and validation periods were 0.54 and 0.50, respectively. Fig. 5 shows a comparison of the calculated and measured Total Nitrogen (TN) concentrations at Pakkanhoung station. The correlation coefficient between the calculated and observed values was R = 0.75. Fig. 6 shows the spatial distribution of the annual mean TN concentration (1995–2004). In the Nam Ngum River basin, the TN concentration was almost less than 1 mg/L because of low population density and low fertilizer use in the farmland. This analysis found that the TN concentration was not affected by the spatial distribution of population density but was calculated to be relatively high in the farmland.

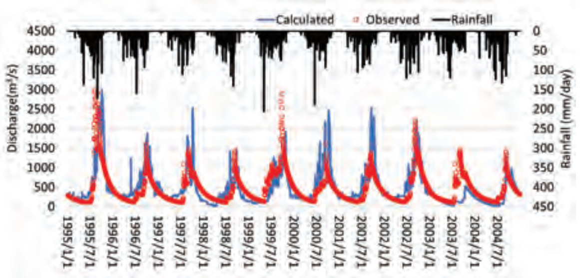

Fig.4 Calculated and observed river discharge at Pakkanhoung station(1995-2004)

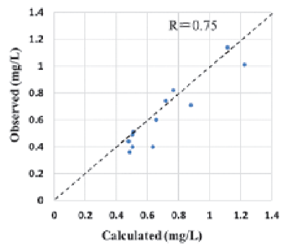

Fig.5 Calculated and observed TN concentration

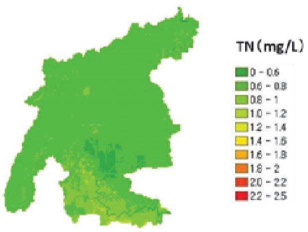

Fig.6 Spatial distribution of annual mean TN concentration

Scenario Analysis

Fig. 7 shows the change in total nitrogen concentration under the population growth and fertilizer increase scenarios. The population of the Nam Ngum River basin was 420 thousand in 2000 and will increase 2.1 times to 860 thousand in 2050. The nitrogen load did not change significantly (11,676 t/year in 2000 and 11,822 t/year in 2050) as a result of population increase. The maximum population density in the Nam Ngum River basin in 2000 was about 2,000 people/km^2 in urban areas, with most people living in rural areas. Even if the population were to increase by 2.1 times, the population density would remain low. The fertilizer increase scenario, however, from 25 kg/ha/season to 50 kg/ha/season, showed a significant increase in nitrogen loading, from 11,676 t/year to 17,010 t/year. To increase food production in response to future population growth, it is necessary to increase production per unit area. Doubling the fertilizer application rate to 50 kg/ha resulted in a 46% increase in the annual nitrogen load at Pakkanhoung station.

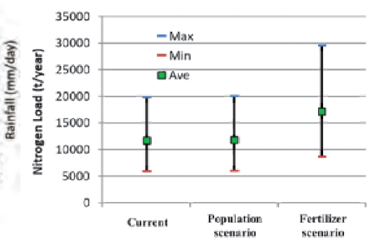

Fig.7 Change in annual mean nitrogen load under the future scenarios

Conclusion

The Nam Ngum River basin, Laos, which supplies high quality domestic water to Vientiane Metropolis, was selected as the target. Simulated river discharge and nitrogen loading agreed with the observed data. Next, we investigated future variations of nitrogen loading in the basin under the population growth and agricultural modernization scenarios. As a result, even when population in the basin increased by 2.1 times, the nitrogen load did not change significantly. However, the fertilizer increase scenario, from 25 kg/ha/season to 50 kg/ha/season, showed a significant increase in nitrogen load. Our results provide a first insight into the magnitude and spatial distribution of nitrogen loading in Nam Ngum River Basin. This type of model may be useful for future impact assessments.