*Research article*

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

**KOSHI YOSHIDA***
*Graduate School of Frontier Sciences, The University of Tokyo, Chiba, Japan*
*Email: kyoshida@edu.k.u-tokyo.ac.jp*

**ISSAKU AZECHI**
*Graduate School of Bioresources, Mie University, Mie, Japan*

**TOSHIAKI IIDA**
*Faculty of Agriculture, Iwate University, Iwate, Japan*

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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. The Nam Ngum River basin is 415 km long with a 17,000 km$^2$ catchment area, and the main land uses in 2000 were paddy (15.6%), forest (32.3%), shrub (40.3%) and urban (0.2%). By UN estimation, population in Laos is expected to increase 2.1 times from 2000 to 2050, and fertilizer use also will increase to produce sufficient food. Therefore, future water quality is a main concern in this river basin. Meteorological and hydrological data from 1995 to 2004, and spatial data such as topography, land use, and soil properties were collected for model simulation. 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, showing that this type of model may be useful for future impact assessments.

**Keywords** nitrogen load, point sources, diffuse pollution, agricultural modernization

## INTRODUCTION

As the population increases, especially in developing countries, there is a need to increase food production. This can be achieved in two ways: by expanding farmland and by increasing the yield per unit area. The area of agricultural land in the world has already begun to decrease due to soil degradation and other reasons, thus it is difficult to expect a significant increase in the area of agricultural land. Therefore, the most realistic approach is to increase the yield per unit area (i.e. increase the number of crops planted per year by switching to high-yielding varieties and introducing irrigation systems). The introduction of high-yielding varieties, known as the Green Revolution, has increased agricultural productivity, but chemical fertilizer inputs and advanced management of agricultural water (irrigation and drainage) have become prerequisites for cultivation of such crops. As a result, pollution in closed water bodies in Asia has become a problem due to excessive nutrient runoff caused by rapid population increase and the massive

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application of chemical fertilizers. 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. A variety of methods have been used to model nitrogen transfer in river basins. Conceptual and physically based models (Lee et al., 2006; Conan et al., 2003; Whitehead 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).

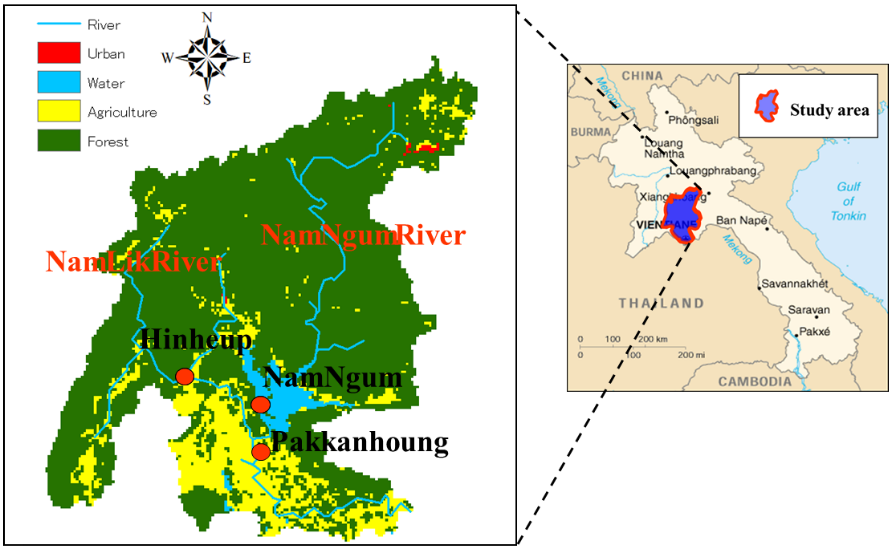


**Fig. 1 Nam Ngum River basin**

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. The estimated basin population is 420 thousand persons and the average population density of the basin is about 25 people/km$^2$. The basin area accounts for 7% of the total land area and the basin population accounted for 9% of the total population of Laos in 2000. The sewerage penetration rate in Laos is estimated to be 19.2%, but this is mainly in urban areas.

Modernization in the agricultural sector is also lagging, with an irrigation rate of only 11%. According to interviews in farming villages near Vientiane, the amount of fertilizer applied is still

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low, averaging 25 kgN/ha/season, and some farmers do not apply any fertilizer in rainfed paddy fields. The land use in the basin is paddy fields (16%), forests and bushes (72%), and residential land (only 0.2%). The Nam Ngum 2 dam (effective storage capacity: 2.6 billion tons, completed in 2011) and the Nam Ngum 5 dam (effective storage capacity: 250 million tons, completed in 2012) are already in operation in the basin (Kudo et al., 2013), but this study considered only the Nam Ngum 1 dam, because the meteorological, hydrological data required for the model simulation, and collected from the hydro yearbook published by the Mekong River Commission, were only available from 1995-2004. Water samples were collected monthly at Pakkanhoung station and the total nitrogen concentration was measured at the National University of Laos in 2003-2004. Additionally, a field survey on water use, water treatment, irrigation, and cultivation methods were conducted in the KM6 irrigation area in Nam Ngum basin. The factors affecting the water environment can be broadly classified into point source loadings from people and livestock and non-point source loadings from forest, farmland and urban areas. For the point source load, statistical data, such as those on population and number of livestock, were collected from the Bureau of Statistics, and the units of nitrogen loading in the Mekong River basin were used (Tanaka et al., 2013). In Laos, households use septic tanks, is the simplest facility in sewage treatment. The tanks receive domestic wastewater, which is treated by sedimentation and anaerobic decomposition before the supernatant liquid is discharged into the drainage river. In Laos, the temperature is high all year round, and the active decomposition of microorganisms is expected to rapidly decompose excreta, but the treatment efficiency is extremely low due to lack of proper maintenance. Livestock excrement is directly disposed in farmland and grassland, then discharged into the ground water system after decomposition and absorption processes in the surface soil.

**Rainfall-Runoff Model**

To evaluate nitrogen transportation according to the river water flow, a distributed water cycling model was developed and applied to analyze the water balance in the basin. TOPMODEL was employed for the rainfall-runoff analysis. Such a distributed model can include the spatial distributions of topography, land use, and soil characteristics. Therefore, 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). For details, please see Yoshida et al., 2017.

**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 mainly 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. Although plants can use both forms of inorganic N, Nitrate is preferred because of its greater solubility in water. In other words, nitrates quickly dissolve in the pore solution, which is taken up by plants. On the other hand, this also means that nitrate is easily leached to groundwater. Ammonium N is less mobile because it strongly adsorbs on clay minerals due to its positive charge. Denitrification is the anaerobic microbial reduction of N, and is used as an electron acceptor, resulting in the transfer of soil nitrogen to the atmosphere.

The budget of each pool is expressed in the following equations.

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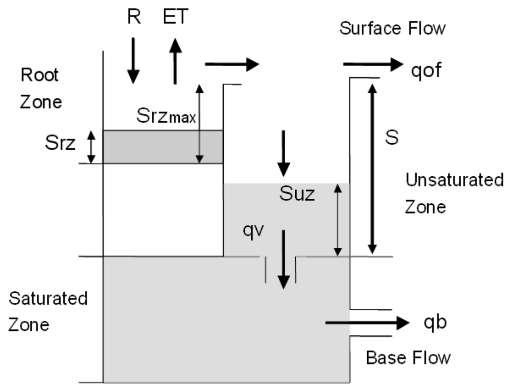
$$\frac{dN_{org}}{dt} = PSNL - MinerN - RunoffN_{org} \quad (1)$$

$$\frac{dN_{ammo}}{dt} = DepoN_{ammo} + FertiN + MinerN - PupN_{ammo} - NitriN - RunoffN_{ammo} \quad (2)$$

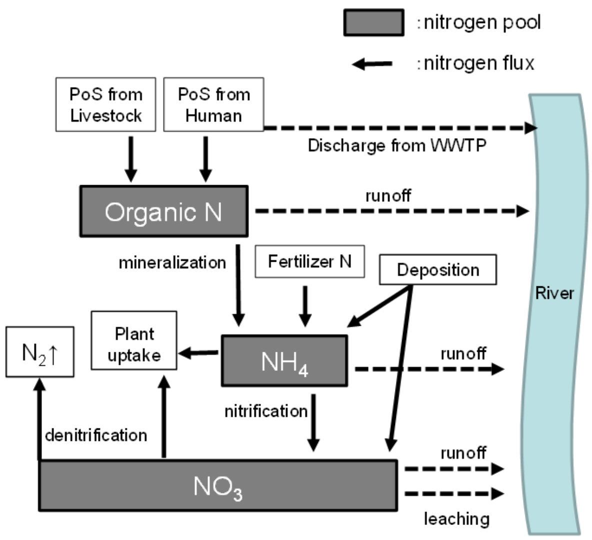
$$\frac{dN_{nitra}}{dt} = DepoN_{nitra} + NitriN - PupN_{nitra} - DenitN - LeachN_{nitra} - RunoffN_{nitra} \quad (3)$$

where $N_{org}$ is organic nitrogen (kg/ha), *PSNL* is input N from point-sources (kg/ha/day), *MinerN* is the mineralization rate (kg/ha/day), *RunoffN* is the nitrogen loss by surface runoff (kg/ha/day), *Nammo* is ammonium nitrogen (kg/ha), *DepoN* is nitrogen deposition (kg/ha/day), *FertiN* is fertilized nitrogen (kg/ha/day), *NitriN* is the nitrification rate (kg/ha/day), *Nnitra* is nitrate nitrogen (kg/ha), *PupN* is the plant uptake rate (kg/ha/day), *DenitN* is nitrate nitrogen loss by denitrification (kg/ha/day), and *LeachN* is nitrate nitrogen loss by leaching (kg/ha/day). For details on the calculation methods for each nitrogen flux and denitrification process, please see Yoshida et al., 2017.




Notes: R:precipitation, ET: evapotranspiration, Srz: storage in root zone, Srzmax: maximum storage in root zone, Suz: storage in unsaturated zone qv: discharge from unsaturated to saturate zone, S: soil water deficit until saturated condition, qof:surface flow discharge, qb: base flow discharge

**Fig. 2 TOPMODEL structure**




Note) PoS : Point Source
WWTP: Waste Water Treatment Plant

**Fig. 3 Structure of the nitrogen balance model in soil**

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## Future Population Growth and Fertilizer Increase Scenarios

According to the United Nations prediction of 2000, the Laos population will increase 2.1 times by 2050. At the same time, chemical fertilizer use will also increase to produce sufficient food by agricultural modernization. This study evaluated the impacts of such population and fertilizer increases on nitrogen loading in the Nam Ngum River basin. In 2000, the total population of Nam Ngum basin was 420 thousand. Therefore, a population increase of 460 thousand people by 2050 was assumed and used for impact analysis. Additionally, we assumed that fertilizer use would increase from 25 kgN/ha/season to 50 kg/ha/season to check the sensitivity of the model.

## RESULTS AND DISCUSSION

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) of discharge and total nitrogen (TN) concentration 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.

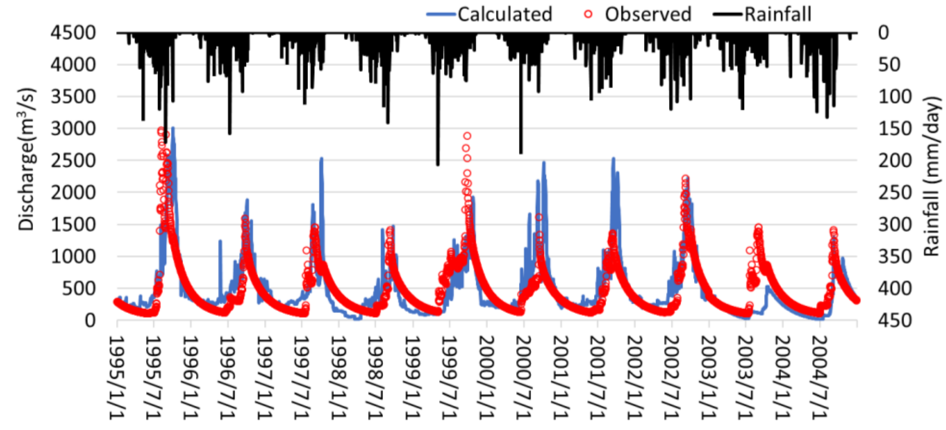


**Fig. 4 Calculated and observed river discharge at Pakkanhoung station**

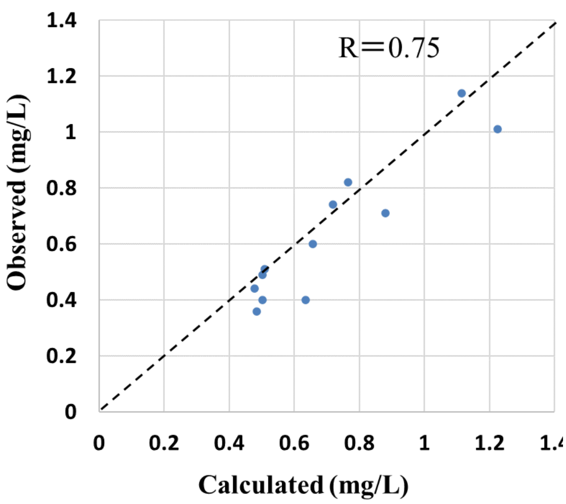


**Fig. 5 Calculated and observed TN concentration at Pakkanhoung station**

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Model performance can be evaluated as "satisfactory", if NSE > 0.50 (Moriasi et al., 2007). The reason for the relatively low accuracy is that the input rainfall was only one point at Pakkanhoung station. Fig. 5 shows a comparison of the calculated and measured TN concentrations at Pakkanhoung station. The data used in this study were TN concentrations that were measured by the authors from 2003-2004; the observed and calculated TN concentrations are compared here. The correlation coefficient between the calculated and observed values was R = 0.75, indicating that the calculated values were slightly overestimated compared to the observed values. The estimated average annual nitrogen load at Pakkanhoung station was 11,676 t/year and 8.1 kg/ha/year per unit area. Fig. 6 shows the spatial distribution of the annual mean TN concentration (1995-2004) and population density (persons/$km^2$) map in 2000. In the Nam Ngum River basin, the total nitrogen 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 total nitrogen concentration was not affected by the spatial distribution of population density but was calculated to be relatively high in the farmland during simulation periods.

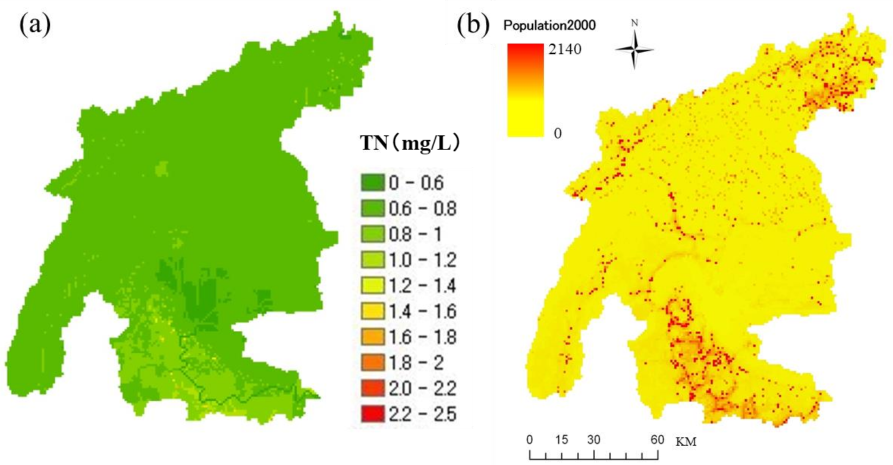


**Fig. 6 Spatial distribution of (a)annual mean total nitrogen concentration and (b) population density (persons/$km^2$)**

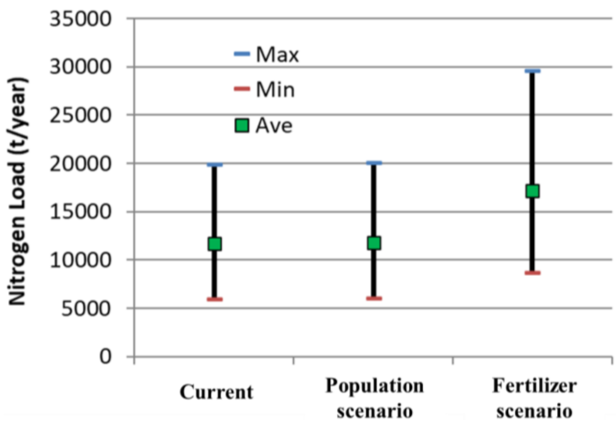


**Fig. 7 Change in annual mean nitrogen load under the future scenarios**

Fig. 7 shows the change in annual mean nitrogen load 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 in the basin. The maximum population density in the Nam Ngum River basin in 2000 was about 2,140 persons/$km^2$, with most people living in rural areas. Even if the population were to increase by 2.1 times, the population density would remain low; thus, there would be no significant impact on the

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water quality environment of the basin. 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. The current fertilizer application rate is 25 kgN/ha, which is extremely low. To increase food production in response to future population growth, it is necessary to increase production per unit area. Therefore, we assumed a scenario of increasing the amount of applied fertilizer and evaluated the impact on the water quality environment of the watershed. Doubling the fertilizer application rate to 50 kg/ha resulted in a 46% increase in the annual nitrogen load at Pakkanhoung station. The nitrogen discharge load per unit area increased from 8.1 kg/ha/year (equivalent of 0.66 mg/L) to 11.8 kg/ha/year (equivalent of 0.95mg/L) under this scenario, however, the water quality environment was still favorable.

## CONCLUSION

The Nam Ngum River basin, Laos, which supplies high quality domestic water to Vientiane Metropolis, was selected as the target area for this study. The UN has estimated that the population in Laos will increase by 2.1 times between 2000 and 2050, and producing sufficient food for the higher population will require increased fertilizer use. Therefore, changes in future water quality is the main concern for this river basin. Meteorological and hydrological data from 1995 to 2004, and spatial data such as topography, land use, and soil properties were collected for model simulation. A conceptual nitrogen balance model with three nitrogen pools was developed and combined with the rainfall runoff model. 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 (11,676 t/year in 2000 and 11,822 t/year in 2050). However, the fertilizer increase scenario, from 25 kg/ha/season to 50 kg/ha/season, showed a significant increase in nitrogen load from 11,676 t/year to 17,010 t/year. 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.

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