Estimation of Nitrogen Load with Multi-pollution Sources Using the SWAT Model: a Case Study in the Cau River Basin in Northern Vietnam

Viet-Bach Tran, Hiroshi Ishidair, Takashi Nakamura, Thu-Nga Do, Kei Nishida

ABSTRACT
Control of non-point source pollution, particularly in terms of nutrients, has advanced to a new phase where the identification of pollution sources and processes is necessary for complex river systems. The Soil and Water Assessment Tool (SWAT) is a process-based model that has been applied to manage aquatic environments in multiple river basins worldwide. In this study, nitrogen (N) loads from point and non-point pollution sources in the Cau River Basin, one of the three most polluted river basins in Vietnam, were simulated. Three scenarios with different combinations of pollution sources were developed to evaluate the major contributions of natural sources, cultivation, industry, households, craft villages and livestock in the study area. A set of hydrological and water quality parameters was successfully calibrated and validated with data observed over multiple years. The model results showed good performance in stream flow simulations at all four hydrological stations. The best performance for the N load simulation was under a scenario representing the dominant contribution of the non-point sources, which caused high amounts of N runoff and was likely triggered by rainfall. The modelling approach presented in this study provides an example for establishing a modelling platform for complex pollution systems.

INTRODUCTION
Aquatic eutrophication is a challenging global environmental issue, primarily caused by the excessive loading of nutrients, such as nitrogen (N) and phosphorus (P) into water bodies [1]. The export of N pollutants to rivers driven by human-related activities is a major problem at the river basin level [2–4]. There are multiple pathways through which N sources contribute to the pollution of stream water; in general, they can be separated into two types: point sources and non-point sources. Point sources include effluent from municipal and industrial areas; therefore, they are relatively simple to monitor and control [5]. Non-point source pollution originates from diffuse sources on land and is carried to water environments by surface runoff [6]. Non-point source pollution cannot be traced back to a single source, which makes it difficult to measure and regulate [5,7]. Diverse influencing factors of N transport and transformation make estimating each pollution source’s N load contribution a challenge, especially in river basins with complex pollution sources but with limited data on the pollution sources and N concentration in the water environment [8].

Since the renovation policy was initiated in 1986, Vietnam has faced aquatic eutrophication problems due to the excessive release of nutrients, including N. Rapid socioeconomic growth has resulted in water pollution in both urban and rural areas across the country, and the quality of water resources in Vietnam appears to be further degrading.
Wastewater from municipal and industrial areas has been discharged directly into rice fields, canals, lakes and rivers without treatment [9]. Many rivers have been contaminated by untreated wastewater from anthropogenic activities such as cultivation, livestock-related activities, industrial production and crafts [10–13].

Belonging to the Thai Binh River system in North Vietnam, the Cau River is one of the three most polluted rivers in the country [14]. Receiving wastewater from the administrative provinces, including a part of the Hanoi Capital area, the water quality of the Cau River Basin has been deteriorated as a result of typical human-related activities. To control the surface water quality, the Vietnamese government has established the Vietnam Surface Water Quality Standards [15]. These standards define the limits of water parameters and the permitted concentration of pollutants existing in the surface water and can be used to assess the level of pollution in a water source. Observed data indicate that the water quality in the midstream and downstream reaches of the Cau River has deteriorated [16]. Previous studies of the Cau River reported that the main sources of excessive nutrient discharge into the upstream areas are from domestic effluent and agricultural production activities. Conversely, in districts lying along the downstream regions of the Cau River, craft villages, animal feedlots and human livelihood wastewater were responsible for the decrease in the surface water quality in the basin [14,16,17].

Obtaining an adequate knowledge of the N sources and their respective contributions to the river basin is needed for policy makers to develop a general framework to manage the aquatic environment. Modelling of the water quality is a strong and reasonable tool to achieve this mission. Indeed, several dynamic process-based models, such as the Soil and Water Assessment Tool (SWAT) [18], the Hydrological Simulation Program-FORTRAN (HSPF) [19], the Integrated Catchment Model-Nitrogen (INCA-N) model [20–22] and HBV-NP [23], have been developed to model N loads in river basins. Of such models, SWAT is applied most widely because of its open source features as well as its capability to simulate pollutant loads from both point and non-point sources to river basins. There are a number of studies that have been conducted to quantify N loads in river catchments using the SWAT model [24–31] all over the world. Many of them have focused on assessing N loads from agricultural production, typically cultivation. Nevertheless, non-point sources such as sources from paddy fields, have never been simple to model. In addition to runoff from agriculture, there are several types of non-point source pollution that impact stream waters, such as urban runoff from areas without sewers, septic leachate or runoff from failed septic systems and activities on land that generate contaminants [5]. In Vietnam, except for large cities, towns and concentrated population areas at the provincial level have poor sewerage and septic systems. Together with domestic effluent, human-related socio-economic activities from such areas are significant pollution sources, of which craft villages are examples. Production activities in craft villages are typical in Vietnamese rural areas with high population densities and poor infrastructure [32]. These types of complex pollutant sources potentially obstruct the development of water quality modelling, especially when quantifying the input of pollution sources.

The application of process-based models, including SWAT, in Vietnam is limited, especially for water quality modelling [33,34]. The outputs of these models were the predicted water quality parameters, such as dissolved oxygen DO, ammonium NH$_4^+$, nitrite NO$_2^−$, nitrate NO$_3^−$ and phosphate PO$_4^{3−}$, in streams, however, simulated outputs from such models are still uncertain without calibration and validation steps. This study focused on the application of the SWAT model to simulate discharge and transport processes of dissolved total nitrogen (DTN), which is the most important N form [35] and available data in this region, from point and non-point sources in a river basin with complex anthropogenic pollution sources. The purpose of this study is to assess the potential of applying the SWAT model to estimate nutrient loads to river basins in Vietnam. The Cau River Basin, a region with very complex pollution sources, was selected as the study region.

**MATERIALS AND METHODS**

**Study area**

Belonging to the Thai Binh River Basin in North Vietnam, the Cau River Basin was selected as the study region. Originating from the northwest of Bac Kan Province and ranging from 21°07’ N to 22°18’ N and from 105°28’ E to 106°08’ E, the Cau River Basin has a drainage area of 6570 km$^2$ and runs approximately 290 km along six administrative provinces in Vietnam, including the Hanoi Capital area in its downstream reaches (Fig. 1a).

The study region is influenced by a tropical monsoon climate. The annual mean air temperature ranges spatially from 18°C to 23°C. The annual mean precipitation in the basin is approximately 1800 mm, of which approximately 80% occurs in May-Oct (wet season) and the rest in Nov-Apr.
(dry season). There is only one hydrological station operating in the region; four previously used stations are no longer operative.

Forests and shrubs are the dominant land use types in the watershed, covering 49% of the total area. Approximately 36% of the basin is used for agriculture, including cultivation (rice, corn, soybeans, peanuts, sweet potatoes and tea) and livestock. The rest of the basin consists of built-up areas (8%), bare soil areas (4%) and water areas (3%). The spatial land use contributions of the Cau River Basin are unbalanced. The majority of the forest areas are in the upstream area of the basin, while agricultural and built-up regions are in the downstream areas. Along the river in the downstream area close to the outlet, there are concentrated anthropogenic activities (Fig. 1b).

**SWAT model**

SWAT is a process-based river basin model that was primarily developed to assess the impact of land management practices on water and sediment as well as agriculture chemical yields in large complex watersheds with various soils, land use and management conditions over long periods of time [18]. The water quality, including total nitrogen (TN), in a stream can be simulated using the SWAT model. In the SWAT model, a watershed is divided into multiple sub-basins, which are then divided into homogeneous spatial units characterized by similar geomorphological and hydrological properties, called hydrological response units (HRUs) [36]. A detailed description of the model can be found in [18]. In this study, the ArcSWAT version of SWAT2012 was used.

**Input data**

**General data**

A summary of the data requirements for the SWAT model and their sources is presented in Table 1.

The 90-m Digital Elevation Model (DEM), extracted from the United States Geological Survey (USGS) [37] was used to delineate the sub-basins. With a threshold area of 10,000 ha, the study area was divided into 35 sub-basins, which were further divided into 429 HRUs.

The land use data in 2007 were obtained from the Ministry of Natural Resources and Environment (MONRE) [38] and were reclassified according to the land use standard of SWAT. The soil properties map was extracted from the Food and Agriculture Organization of the United Nations (FAO) [39]. After reclassifying the soil categories in SWAT, the parameters of the soil characteristics were set, based on the soil properties database of Vietnam by [40].

The meteorological and hydrological data in the study area were collected from the Institute of Meteorology and Hydrology (IMH) [41], which belongs to MONRE. Meteorological data, such as the maximum and minimum temperatures, sunshine hours, relative humidity and wind speed at one station and the daily rainfall at 13 stations, have a long time series from 1960 to 2014. Conversely, the hydrological data are inadequate. The four previously used hydrological stations,

Observations of DTN concentrations (including ammonium, nitrite, nitrate, organic nitrogen) at the Gia Bay and Yen Dung (outlet) stations from 2011 to 2014 were collected from the Vietnam Environment Administration (VEA) [42]. There were five recording times each year in March, May, July, September and November, except 2013, which lacks a record for September.

**Pollution load data**

Inputs of nitrogen loads from various natural sources and anthropogenic activities such as forest, grass land, cultivation, households, industry, craft villages and livestock were estimated as the followings:

**Natural sources**: parameters of nitrogen loads are available in soil chemical option of land uses of forest and grass of SWAT model.

**Cultivation**: information of current crop management practices for the six administrative provinces located in the Cau River Basin were retrieved from Vietnam General Statistical Office [43]. Most of agriculture field in the region were under double paddling crop with spring season (20thJan–15thJun) and summer season (20thJun–15thNov). The average nitrogen fertilizer was applied in a season is 150 kg urea per ha for both paddy field and annual crop land use.

**Households**: pollution from households was set in built-up area via septic systems of the SWAT, the conventional septic tanks are the main facilities. Based on the average water consumption rate in Vietnam, 100 L/(day·cap) [44], the septic tank effluent flow rate was assumed as 30% of average water consumption rate with 30 L/(day·cap). DTN concentration of the septic tank effluent was set to be 60 mg/L as conventional option in the SWAT model. In SWAT, septic tank effluent drain into subsurface soil layer affecting soil moisture content and the percolation of soil water through the unsaturated zone [18].
Industry: annual wastewater discharge without the concentration data from industry was extracted from database of VEA, 2015 [41]. In this study, threshold concentration of ammonium and organic nitrogen in Vietnam standard [45] was used as assumed parameter to estimated input TN load from industry.

Craft villages: information on wastewater discharge and their concentration from craft villages are available in the reports [32,42]. Craft work that contributes most nitrogen pollution is from food and drink productions at household level. Wastewater discharge from food and drink production craft villages in the region is approximately 40,000 m³/day [42] with average of DTN concentration of 121 mg/L [32].

Livestock: input nitrogen load from livestock was calculated by the number of cattle, swine and poultry in the region [42], and the nitrogen ratio that each of them release in a specific time [46].

SWAT model development and evaluation

The overall methodology for this study is shown in Fig. 2. First, the hydrological model of SWAT was set up, calibrated and validated to find the good-fit hydrological parameters. Subsequently, the scenarios of pollution source inputs, including point sources and non-point sources, were developed and entered into the model. After the calibration at Gia Bay station and validation steps at Yen Dung station for the water quality parameterization, SWAT simulated DTN loads from each pollution scenario. By comparing the performances of the simulated DTN loads with the observed data, the input pollution scenarios were finally, evaluated.

The performances of the discharge and DTN load for the SWAT model were evaluated through calibration and validation steps using the Soil and Water Assessment Tool Calibration and Uncertainty Procedure (SWAT-CUP) with SUFI-2 algorithm [47]. The statistical indices, such as the Nash-Sutcliffe efficiency ($E_{NS}$) [48], the percent bias (PBIAS) and the linear regression with the coefficient of determination ($R^2$), were used as objective functions to optimize the model performance (see Eqs. (1)–(3)). In this study, the general model performance rating values for $E_{NS}$ and PBIAS on a monthly scale recommended by [49] were used to evaluate the model performance (Table 2). For $R^2$, values greater than 0.5 were considered to be acceptable [50].

\[
E_{NS} = 1 - \frac{\sum_{i=1}^{n} (Y_{i}^{obs} - Y_{i}^{sim})^2}{\sum_{i=1}^{n} (Y_{i}^{obs} - \bar{Y}^{obs})^2} \tag{1}
\]

\[
PBIAS = 100 \times \frac{\sum_{i=1}^{n} (Y_{i}^{obs} - Y_{i}^{sim})}{\sum_{i=1}^{n} Y_{i}^{obs}} \tag{2}
\]

\[
R^2 = \frac{\left[ \sum_{i=1}^{n} (Y_{i}^{obs} - \bar{Y}^{obs}) \sum_{i=1}^{n} (Y_{i}^{sim} - \bar{Y}^{sim}) \right]^2}{\sum_{i=1}^{n} (Y_{i}^{obs} - \bar{Y}^{obs})^2 \sum_{i=1}^{n} (Y_{i}^{sim} - \bar{Y}^{sim})^2} \tag{3}
\]

In the above equations, $n$ indicates the total number of observations, $Y_{i}^{obs}$ and $Y_{i}^{sim}$ are the values of the observed and simulated variables at the $i$-th time-step, respectively, and $\bar{Y}^{obs}$ and $\bar{Y}^{sim}$ are the averages of the observed and simulated values, respectively.

Developing scenarios for the pollution sources

Wastewater from human-related activities, including industries, cropping, craft villages, households and livestock, are responsible for the deterioration of the water quality in this river basin [16]. Industrial operation scales in the basin vary with both large- and small-scale operations. The large-scale operations are concentrated in an industrial zone with treatment plants, while the small-scale operations are scattered spatially and have no treatment plants. Of these pollutant sources, the Large-scale industries was classified as point sources (PS) and the Natural sources, Cultivation and Household were classified as non-point sources (NPS). Because of the uniqueness in the context of the scattered distribution and a large number of the sources in this region, Small-scale industries, Craft villages and Livestock were tested as either PS or NPS types in this study. There is a fundamental difference between the two calculations for PS and NPS in SWAT model. In the case of PS, the pollution sources are constantly set at a specific point to be directly connected to a stream through adequate sewerage systems then pollutant loads are subjected to biochemical processes and transported downstream. On the other hand, pollutant loads from NPS are applied uniformly to a specific area and episodically mobilized by rainwater runoff and/or soil infiltration to a stream then subjected to the biochemical processes and transported downstream. Default settings were used for the land uses of Natural sources, Cultivation and Households, however, there is no option for setting unit loads of the regionally-unique pollution types, i.e. Small scale industries, Craft villages and Livestock. Those sources
Fig. 2 Framework of SWAT modelling (WQ indicates water quality).

Table 2 General performance rating for selected statistics on a monthly scale [45].

<table>
<thead>
<tr>
<th>Performance rating</th>
<th>$E_{NS}$</th>
<th>Streamflow</th>
<th>PBIAS (%)</th>
<th>N,P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very good</td>
<td>$0.75 &lt; E_{NS} \leq 1.00$</td>
<td>$</td>
<td>PBIAS</td>
<td>&lt; 10$</td>
</tr>
<tr>
<td>Good</td>
<td>$0.65 &lt; E_{NS} \leq 0.75$</td>
<td>$10 \leq</td>
<td>PBIAS</td>
<td>&lt; 15$</td>
</tr>
<tr>
<td>Satisfactory</td>
<td>$0.50 &lt; E_{NS} \leq 0.65$</td>
<td>$15 \leq</td>
<td>PBIAS</td>
<td>&lt; 25$</td>
</tr>
<tr>
<td>Unsatisfactory</td>
<td>$E_{NS} \leq 0.50$</td>
<td>$</td>
<td>PBIAS</td>
<td>\geq 25$</td>
</tr>
</tbody>
</table>
The monthly observed discharge data at the four former hydrological stations were used for the model calibration. Using SWAT-CUP, a sensitivity analysis was conducted. In addition to sensitivity parameters, such as CN2, ALPHA_BF, GW_DELAY, GWQMN and SURLAG, which significantly impact the discharge simulation [51,52], the results of the sensitivity analysis in SWAT-CUP also present the role of other parameters in changing the simulated discharge (Table 4).

Regarding the model evaluation criteria proposed by [49], the simulated performance of the model at the four former stations was very good, except for PBIAS at the Thac Gieng station (14.11%), which was in the range of good performance according to the rating (Table 5). After the calibration steps, the model was then run again for the validation. The observed and simulated discharges at the Gia Bay station (from 2004 to 2014) were compared to check the accuracy of the model performance in a hydrological simulation. The statistical values, $E_{NS}$, $R^2$ and PBIAS, for this station were also very good with values of 0.92, 0.93 and $-1.3$, respectively.

The hydrological graph in Fig. 3 shows a tight correlation between the monthly observed and simulated discharge. In short, the SWAT model performed an acceptable simulation for the hydrology condition. This is a prerequisite for simulating a water quality model with good performance.

Complement of observed data with load-discharge regression

Because the observed N concentration was scattered (four or five times per year), the DTN load–discharge relationship at the Gia Bay and Yen Dung stations were conducted to expand the collected data to a concentrated timescale (monthly). Water flow and nutrient loads needed to be matched to a straight line on a log–log plot to generate a load–discharge relationship [53,54]; the relationship was estimated using the following equation:

$$L = aQ^b$$  \(\text{(4)}\)

where $L$ is the nutrient load (kg/d), $Q$ is the stream discharge (m$^3$/s) and $a$ and $b$ are constants [55]. The DTN load–discharge relationship at the Gia Bay station was developed using the daily observed discharge and the observed DTN load. At the outlet of the river (Yen Dung), there is no hydrological station to observe the stream discharge. The simulated discharge from the calibrated hydrological model from the previous step was, therefore, used to determine the

### Table 3: Scenarios with combination of pollution sources.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Natural sources</th>
<th>Cultivation</th>
<th>Households</th>
<th>Large-scale industry</th>
<th>Small-scale industry</th>
<th>Craft villages</th>
<th>Livestock</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NPS</td>
<td>NPS</td>
<td>NPS</td>
<td>PS</td>
<td>PS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>NPS</td>
<td>NPS</td>
<td>NPS</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>3</td>
<td>NPS</td>
<td>NPS</td>
<td>NPS</td>
<td>PS</td>
<td>NPS</td>
<td>NPS</td>
<td>NPS</td>
</tr>
</tbody>
</table>

PS (kg-N/d) indicates point sources and NPS (kg-N/(ha·d)) indicates non-point sources.
Table 4  Sensitive parameter values for the hydrology and water quality simulations using the SWAT model.

<table>
<thead>
<tr>
<th>Process</th>
<th>Parameter</th>
<th>Descriptions</th>
<th>Unit</th>
<th>Range</th>
<th>Default value</th>
<th>Calibrated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge</td>
<td>a__CN2.mgt</td>
<td>Initial SCS Runoff curve number for moisture condition II</td>
<td></td>
<td>35 – 98</td>
<td>0.50</td>
<td>-5</td>
</tr>
<tr>
<td></td>
<td>v__ALPHA_BF.gw</td>
<td>Baseflow alpha factor</td>
<td></td>
<td>0 – 1</td>
<td>0.048</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td>v__GW_DELAY.gw</td>
<td>Groundwater delay time</td>
<td>d</td>
<td>0 – 500</td>
<td>31</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>v__GWQMN.gw</td>
<td>Threshold depth of water in the shallow aquifer required for return flow to occur</td>
<td>mm</td>
<td>0 – 5000</td>
<td>1000</td>
<td>4850</td>
</tr>
<tr>
<td></td>
<td>v__GW_REVAP.gw</td>
<td>Groundwater revap coefficient</td>
<td></td>
<td>0.02 – 0.2</td>
<td>0.02</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>v__REVAPMN.gw</td>
<td>Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur</td>
<td>mm</td>
<td>0 – 500</td>
<td>750</td>
<td>430</td>
</tr>
<tr>
<td></td>
<td>v__CANMX.hru</td>
<td>Maximum canopy storage</td>
<td>mm</td>
<td>0 – 100</td>
<td>0</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>v__ESCO.bsn</td>
<td>Soil evaporation compensation factor</td>
<td></td>
<td>0 – 1</td>
<td>0.95</td>
<td>0.181</td>
</tr>
<tr>
<td></td>
<td>v__SURLAG.bsn</td>
<td>Surface runoff lag coefficient</td>
<td></td>
<td>0.05 – 24</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>v__CH_N2.rte</td>
<td>Manning value for main channel</td>
<td></td>
<td>0.01 – 0.3</td>
<td>0.014</td>
<td>0.038</td>
</tr>
<tr>
<td></td>
<td>v__CH_K2.rte</td>
<td>Effective hydraulic conductivity in main channel alluvium</td>
<td>mm/hr</td>
<td>0 – 500</td>
<td>0</td>
<td>22.5</td>
</tr>
<tr>
<td></td>
<td>v__SOL_AWC.sol</td>
<td>Available water capacity of soil layer</td>
<td>mm H2O/mm soil</td>
<td>0 – 1</td>
<td>0.315</td>
<td></td>
</tr>
<tr>
<td></td>
<td>v__SOL_ALB.sol</td>
<td>Moist soil albedo</td>
<td></td>
<td>0 – 0.25</td>
<td>0</td>
<td>0.136</td>
</tr>
<tr>
<td>DTN load</td>
<td>v__EROGN</td>
<td>Organic N enrichment ratio</td>
<td></td>
<td>0 – 5</td>
<td>3</td>
<td>0.663</td>
</tr>
<tr>
<td></td>
<td>v__CDN.bsn</td>
<td>Denitrification exponential rate coefficient</td>
<td></td>
<td>0 – 3</td>
<td>1.4</td>
<td>0.379</td>
</tr>
<tr>
<td></td>
<td>v__SDNCO.bsn</td>
<td>Denitrification threshold water content</td>
<td></td>
<td>0 – 1.1</td>
<td>1.1</td>
<td>0.680</td>
</tr>
<tr>
<td></td>
<td>v__RCN.bsn</td>
<td>Concentration of nitrogen in rainfall</td>
<td>mg/L</td>
<td>0 – 15</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>v__NPERCO.bsn</td>
<td>Nitrogen percolation coefficient</td>
<td></td>
<td>0 – 1</td>
<td>0.2</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>v__SHALLST.gw</td>
<td>Initial depth of water in the shallow aquifer</td>
<td>mm</td>
<td>0 – 50,000</td>
<td>1000</td>
<td>1460</td>
</tr>
<tr>
<td></td>
<td>r__RCHRG_DP.gw</td>
<td>Deep aquifer percolation fraction</td>
<td></td>
<td>0 – 1</td>
<td>Varies</td>
<td>-0.261</td>
</tr>
<tr>
<td></td>
<td>v__SOL_NO3.chm</td>
<td>Initial NO3 concentration in the soil layer</td>
<td>mg/kg</td>
<td>0 – 100</td>
<td>0</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>v__BC1.swq</td>
<td>Rate constant for biological oxidation of ammonium-N to nitrite-N in the reach at 20°C</td>
<td>1/d</td>
<td>0.1 – 1</td>
<td>-</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>v__BC2.swq</td>
<td>Rate constant for biological oxidation of nitrite-N to nitrate-N in the reach at 20°C</td>
<td>1/d</td>
<td>0.2 – 2</td>
<td>-</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>v__RS4.swq</td>
<td>Rate coefficient for organic N settling in the reach at 20°C</td>
<td>1/d</td>
<td>0.001 – 0.1</td>
<td>-</td>
<td>0.06</td>
</tr>
</tbody>
</table>

_r_: existing parameter value is multiplied by (1+ a given value)
_a_: existing parameter value is added to a given value
_v_: existing parameter value is to be replaced by a given value
load–discharge relationship. The regression values for both stations with the coefficient of determination $R^2$ were over 0.85, which may be acceptable to estimate the daily DTN loads (Table 6). Subsequently, the DTN loads were converted to a monthly timescale and prepared for calibration for the DTN load simulation.

**Dissolved total nitrogen simulation**

*Calibration and validation of modelling parameters at the Gia Bay station*

Calibration for the DTN loads under Scenario 1 at the Gia Bay station was conducted by comparing the simulated and regressed TN loads for the period from 2011 to 2014. SWAT-CUP was used for the sensitivity analysis to identify the parameters significantly influencing the DTN loads. The model performance for the calibration period was evaluated as being in very good agreement because the $E_{NS}$, $R^2$ and PBIAS values were 0.77, 0.80 and 15.7, respectively. The validation period showed the same performance with very good values of $E_{NS}$, $R^2$ and PBIAS. The graphical evaluation also displays a good match between the observed and simulated DTN loads (Fig. 4) in terms of the timing of peak as well as the level of base flow. The parameter setting was used for simulation at whole basin-scale.

*Estimation of DTN load under different pollution scenarios*

After the calibration and validation steps at the Gia Bay station, the SWAT model was run for estimating DTN loads under the three pollution scenarios at Yen Dung station, outlet of the Cau River Basin. The seasonal and yearly variations of the DTN loads are shown in Fig. 5 under the

**Table 5** Values of the goodness-of-fit statistics for the discharge and DTN load simulations.

<table>
<thead>
<tr>
<th>Process</th>
<th>Station</th>
<th>Period</th>
<th>Procedure</th>
<th>$E_{NS}$</th>
<th>$R^2$</th>
<th>PBIAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge</td>
<td>Thac Gieng</td>
<td>1963–1980</td>
<td>Calibration</td>
<td>0.84</td>
<td>0.87</td>
<td>14.11</td>
</tr>
<tr>
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<td>Thac Buoi</td>
<td>1970–1979</td>
<td>Calibration</td>
<td>0.87</td>
<td>0.92</td>
<td>8.94</td>
</tr>
<tr>
<td></td>
<td>Tan Cuong</td>
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<td>Calibration</td>
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<td>0.91</td>
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<td>Phu Cuong</td>
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<td>Calibration</td>
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<td>0.91</td>
<td>4.21</td>
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<td></td>
<td>Gia Bay</td>
<td>2004–2014</td>
<td>Validation</td>
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<td>0.93</td>
<td>-1.3</td>
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<tr>
<td>DTN Load</td>
<td>Gia Bay</td>
<td>2011–2014</td>
<td>Calibration</td>
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<td>0.8</td>
<td>15.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2007–2010</td>
<td>Validation</td>
<td>0.87</td>
<td>0.91</td>
<td>20.95</td>
</tr>
</tbody>
</table>

**Table 6** Load–discharge relationships for DTN.

<table>
<thead>
<tr>
<th>Station</th>
<th>Load-discharge relationship</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gia Bay</td>
<td>$LOAD_{DTN} = 48.36Q^{1.245}$</td>
<td>0.85</td>
</tr>
<tr>
<td>Yen Dung</td>
<td>$LOAD_{DTN} = 72.091Q^{1.187}$</td>
<td>0.88</td>
</tr>
</tbody>
</table>
different scenarios. Compared with the observed DTN load, Scenario 3 performed best in both the dry and wet seasons. Under Scenario 2, the simulated seasonal DTN load contribution to the river in the dry season was much higher than the observed data. Of the three scenarios, Scenario 3 was the most appropriate for both dry and wet seasons.

In general, the wet season contributed much more to the DTN load than the dry season under all pollution source scenarios. As can be seen in Fig. 5, the Cau River Basin received its highest pollutant load in the wet season of 2013. This was associated with the largest rainfall, over 2,000 mm in the respective season. Figure 6 shows the relationship between simulated monthly DTN loads under the Scenario 3 and monthly rainfalls in both dry and wet season. The simulated DTN loads under the Scenarios 3 were strongly dependent on monthly rainfalls through the years. In this scenario, the contribution rate of DTN load in wet season was higher than that in dry season. From the result of the Scenario 3, Cultivation and Livestock were identified as the two largest sources, followed by Small-scale industries.

Fig. 4 DTN loads calibration (2011-2014) and validation (2007-2010) under Scenario 1 at the Gia Bay station with monthly rainfall.

Fig. 5 Observation-based and simulated DTN loads under each pollution scenario with cumulative seasonal rainfall at Yen Dung.
and Craft villages (Fig. 7). On the other hand, effluents of Household, Large-scale industries and Natural sources were relatively minor and evenly contributed to the overall DTN load in the basin. Although contributions of the Large-scale industries were stable among the four years, those of all other sources increased significantly in the year 2013 with the highest rainfall. The loads from Livestock, Small-scale industries and Craft villages were as sensitive to rainfall as that of Cultivation because of the pathways of nitrogen to soil surface. On the other hand, of the load from Household was less sensitive with rainfall because of the septic tank systems installed in subsurface soil layer. With high contribution to river basin, effluent from Livestock should be considered to reuse effectively. In addition, loads from the Small-scale industries and Craft villages, another locally unique source in developing countries, were non-negligible and should be carefully taken in consideration for the water environment management in such complex pollution system.

**CONCLUSIONS**

This study successfully applied a process-based modelling approach to simulate DTN loads from various pollution sources. The hydrological and water quality simulation results showed a good match between the observation and calculation. Of the three scenarios of pollution sources, the Scenario 3 demonstrated the best performance in DTN load estimation at the outlet of the Cau River Basin. The simulated DTN loads under the Scenario 3 were strongly depended on monthly rainfalls through the years. The approach to pollution scenarios used in this study can be applied to other watershed with complex pollution sources to identify the nutrient pollution systems using the SWAT model.
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