

APPLICATION OF A 2-D NUMERICAL MODEL FOR COMPUTING SUSPENDED SEDIMENT AND NUTRIENTS TRANSPORTS TO NHUE RIVER (HANOI, VIETNAM)

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Since suspended sediment and organic matter loads were extremely high in Nhue River (Hanoi, Vietnam), a 2-D depth-average model was constructed to simulate hydrodynamic state, suspended sediment transport and environmental change around the confluence between Nhue River and its tributary, To Lich River. The biochemical conversions were constructed based on the QUAL2E conceptual scheme¹. The model is capable of backwater simulation that was frequently seen there. The simulation results indicated a strong suspended sediment deposition. A clear deterioration of environment was simulated. Within few hundred meters from the confluence two water masses were incompletely mixed in normal discharge condition.

Key words: Nhue River, Hanoi, 2-D model, QUAL2E, suspended sediment, wastewater pollution

1. INTRODUCTION

Fast urbanization and rapid economic development in Vietnam without efficient collection and treatment of wastewaters lead to a dramatic degradation of environment. In Hanoi capital city of Vietnam, the wastewater is not directly discharged to the Red River, but largely flows through Nhue River, a tributary of the Red River (**Fig. 1**). With a population of more than 3 millions and no wastewater treatment facility², the city's wastewater characterized by extremely high BOD and containing fully suspended organic particulate provokes a severe problem to the environment of Nhue River from the confluence of the city main sewer line, To Lich River. Based on the fact that suspended loads in both rivers, Nhue and To Lich, are high, in this work, we applied a 2-D numerical model for studying the hydrodynamic state, suspended sediment (SS) transport and nutrient changes around the confluence between two rivers.

2. DESCRIPTION OF THE STUDIED SITE

The calculation area is junction of Nhue and To Lich Rivers which consists of about 1600 m of Nhue River and nearly 800 m of To Lich River (**Fig. 1**). Briefly, To Lich River stems from the West Lake located in the northern part of Hanoi, flows across the city to the south before joining Nhue River in a

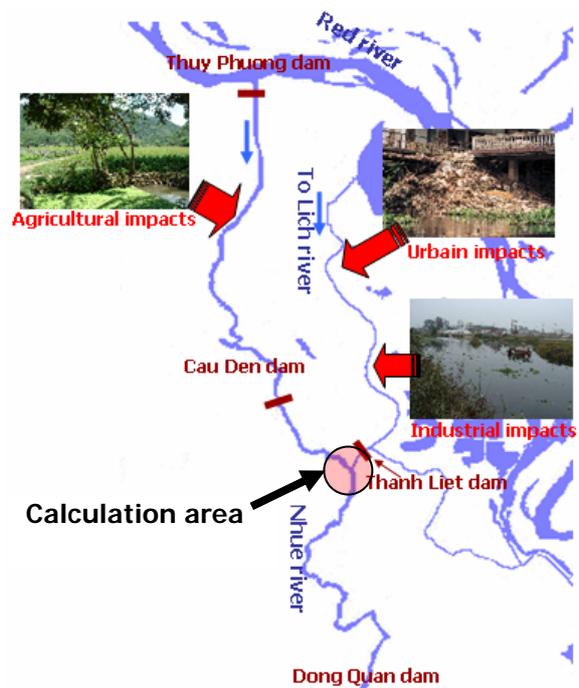


Fig. 1 Map of Nhue River

total of 14 km length. The wastewaters of the city were directly discharged into To Lich River without any treatment and turned this river into a main open-air sewer of the city. The Nhue River takes its source from the Red River in the north west of Hanoi city, collects the To Lich's water at 20.2 km, and joins the Chau Giang River at 72 km (not in the map). The mean water depths in normal discharge of

the Nhue and To Lich Rivers are about 2.5 and 1.5 m, respectively.

The Nhue River's water was characterized by high SS content because its water source stems from the Red River where water was famous of high SS load³⁾. Our monthly surveys during the years 2002 and 2003 gave an average 265 mg/l of SS. Particularly, during rainy season the Red River water usually contained more than 1000 mg SS/l (**Fig. 2**). Different from the Red River water where inorganic solid accounted for large proportion of SS, SS in To Lich water was characterized mostly by organic detritus. The surveys during 2002-2003 have shown average 75 mg SS/l in To Lich River. In dry time, when only domestic wastewater presented in the river, the SS content could increase up to 160 mg SS/l. The BOD value showed clearly the pollution condition of To Lich River where monthly BOD in dry time reached as high as 70 mg O₂/l (**Fig. 3**). The high loads of SS and BOD of two main water sources resulted in water pollution and many other severe problems to aquatic species as well as local inhabitants²⁾.

3. MODEL SETUP

The biochemical conversion module was set up based on the conceptual scheme of the Enhanced Stream Water Quality Model (QUAL2E or Q2E) constructed by EPA⁴⁾. The biological conversion of environmental variables integrated with the transport equations of 2-D depth average concentration of material provides insight of the environmental variation of the studied river section.

The considered state variables extracted from QUAL2E conceptual scheme¹⁾ are listed in **Table 1**. This selected variable set gives advantage in modeling pH, an essential parameter governing the partition of various species in aquatic environment.

Bottom attaching algae were not considered in this conceptual scheme since water in this studied system was turbid and irradiation was completely attenuated before reaching to the river bottom.

Governing equations for surface flow are

$$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial(uh)}{\partial t} + \frac{\partial(u^2h)}{\partial x} + \frac{\partial(uvh)}{\partial y} = & -gh \frac{\partial z_s}{\partial x} - \frac{\tau_b^x}{\rho} - \frac{\tau_v^x}{\rho} \quad (2) \\ & + \frac{\partial}{\partial x}(-\overline{u^2}h) + \frac{\partial}{\partial y}(-\overline{u^1v^1}h) \end{aligned}$$

$$\begin{aligned} \frac{\partial(uh)}{\partial t} + \frac{\partial(uvh)}{\partial x} + \frac{\partial(v^2h)}{\partial y} = & -gh \frac{\partial z_s}{\partial y} - \frac{\tau_b^y}{\rho} - \frac{\tau_v^y}{\rho} \quad (3) \\ & + \frac{\partial}{\partial x}(-\overline{u^1v^1}h) + \frac{\partial}{\partial y}(-\overline{v^2}h) \end{aligned}$$

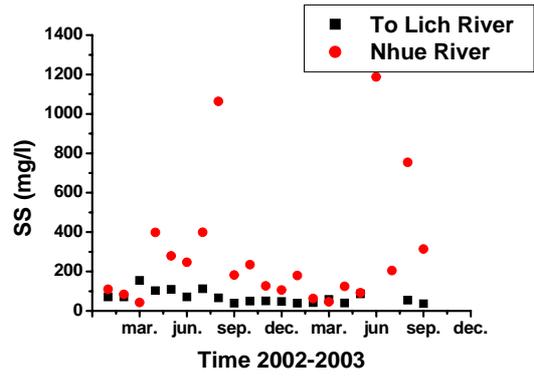


Fig. 2 Suspended solid downstream To Lich River, and upstream Nhue River monthly 2002 and 2003

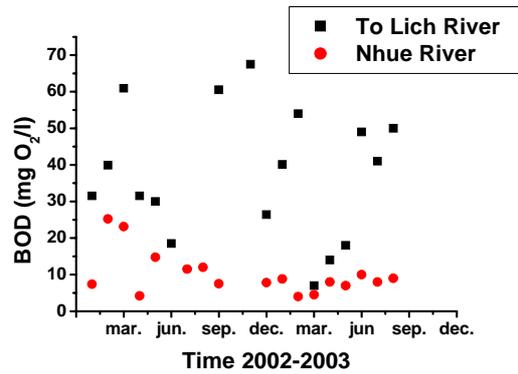


Fig. 3 BOD downstream To Lich River, and 5 km upstream the confluence in Nhue River monthly 2002 and 2003

where h is local depth of flow, u and v are depth-average velocity components in x and y directions, respectively, g is gravitational acceleration, τ_b^x and τ_b^y are bottom shear stresses, τ_v^x and τ_v^y are additional bottom shear stresses due to vegetation, z_s is water height from reference level, and $\overline{u^2}$, $\overline{u^1v^1}$, and $\overline{v^2}$ are depth-average Reynolds stresses.

The governing equations for transport and conversion of state variables listed in **Table 1** consist of the transport and conversion terms. The transport term including advection and dispersion is identical for every variable. The conversion term differs from variable to variable to characterize the bio-physicochemical processes that variables experience in aquatic media. Thus the mathematical expression of the temporal change of variable is:

$$\begin{aligned} h \frac{\partial C_i}{\partial t} = & -h \left(u \frac{\partial C_i}{\partial x} + v \frac{\partial C_i}{\partial y} \right) \\ & + h \left[\frac{\partial}{\partial x} \left(\varepsilon_{sh} \frac{\partial C_i}{\partial x} \right) + \frac{\partial}{\partial y} \left(\varepsilon_{sh} \frac{\partial C_i}{\partial y} \right) \right] + \text{Conver.}(C_i) \quad (4) \end{aligned}$$

in which C_i indicates concentration of considered state variable, ε_{sh} is lateral diffusivity and assumed equal to horizontal eddy viscosity, and $\text{Conver.}(C_i)$ represents the conversion term of variable (**Table 2**).

Table 1 Model state variables

Variable	Symbol	Unit
Inorganic suspended solid	SS	mg SS/l
Dissolved oxygen	DO	mg O ₂ /l
Biological oxygen demand	BOD	mg O ₂ /l
Ammonia nitrogen	NH ₄	mg N/l
Nitrate nitrogen	NO ₃	mg N/l
Phytoplankton	CHL	mg C/l
Total dissolved inorganic carbon	C _T	mg C/l
Alkalinity	ALK	mmol H/l
pH/H ⁺	[H ⁺]	mg H/l

Table 2 Bio-physicochemical processes present in conversion terms of variables

Variable	Conversion term
SS	$Er - De$
BOD	$Hyd + FastCOxid - R_{ON_{Denitri}} Denitri + Sed_{BOD} - Sett_{BOD}$
CHL	$Growth_{CHL} - Death_{CHL} - Resp_{CHL} - Sett_{CHL}$
DO	$R_{OC_{CHL}} Growth_{CHL} - R_{OC_{CHL}} Death_{CHL} - SOD - FastCOxid - R_{ON_{Nitri}} Nitri + Re aeO_2$
NH ₄	$R_{NO_{Hyd}} Hyd - R_{NC_{CHL}} P_{ap} Growth_{CHL} + R_{NC_{CHL}} Resp_{CHL} - Nitri + Sed_{NH_4}$
NO ₃	$Nitri - Denitri - R_{NO_3_{CHL}} (1 - P_{ap}) Growth_{CHL} - Sed_{NO_3}$
C _T	$R_{CC_{FastCOxid}} FastCOxid + R_{CC_{Resp}} Resp_{CHL} - R_{CC_{Growth}} Growth_{CHL} + Re aeCO_2 + Sed_{CO_2} - Prep_{CO_3}$
ALK	$R_{ALK,CHL} Resp_{CHL} - (R_{ALK,CHL} P_{ap} - R_{ALK,N} (1 - P_{ap})) Growth_{CHL} - R_{ALK,Nitr} Nitri + R_{ALK,Deni} Denitri$
pH/[H ⁺]	$f([H^+])$

Detail description of processes and their parameters is given by Chapra et al¹⁾ and Trinh et al⁵⁾

4. SIMULATION AND DISCUSSION

Previously, a 1-D numerical model was applied for calculation of longitudinal variation of water

quality to the whole Nhue River⁵⁾. However, attempts in calculation precisely water state around the confluence, such as back water effect in To Lich River or lateral stratification of water quality after mixing of two water masses was unsatisfactory because of limits of 1-D model. Thus, 2-D approach was expected to resolve those tasks. Moreover, bed deformation and flooding calculations, the ultimate calculations should be taken into account in such high suspended load and easily flooding river, could be further made with the 2-D model.

(1) Backwater and lateral stratification

In term of hydrodynamic simulation, a two upstream inflow system was set up. It should be mentioned that in this river system whenever discharge in the Nhue increased (water level increased as well), Thanh Liet dam was partly or completely close to prevent backwater to Hanoi city (**Fig. 1**). Therefore, the common tendency is that discharge of the To Lich River decreased when discharge of the Nhue increased. Based on these observations, a one day hydrodynamic boundary conditions was set up.

As mentioned early, the environmental data that we have were applied for large scale area and no data were collected exactly at the same positions of boundaries of the selected area for this 2-D model. Thus, the data collected at nearest positions of this studied site were applied for simulation. It was expected that this application would provide typical environmental change of the studied river (**Table 3**).

a) Transport of suspended sediment

As introduced above, SS in the studied system consists of very different types: the alluvial inorganic SS and particulate organic detritus. These two SS types have different settling rates and when two water masses mixed together after the confluence, they tended to flocculate to form larger size particles. However, due to data deficiency, only one settling rate was selected for calculation. A value of 3.9 m/d was extracted from the work of Trinh et al⁵⁾ and applied for this model as settling rate of inorganic SS. The particulate organic detritus was formulated as a part of BOD. The simulated transport of inorganic SS at different discharge conditions is shown in **Fig. 4**.

As seen from **Fig. 4**, inorganic SS abundant in mainstream intruded into To Lich River when the Thanh Liet dam was close. In this simulation, after 3.8 hours, discharge in To Lich River was zero and the inorganic SS intruded more than 200 m into the To Lich at 4.21 hours (**Fig. 4b**).

Table 3 Boundary conditions; taken averagely from the 2002-2003 monthly samplings at 5 km upstream the confluence in Nhue River (mainstream) and at 800 m upstream the confluence in To Lich River (tributary)

Variable	Mainstream	Tributary
SS (mg/l)	72.00	3.00
DO (mg/l)	6.00	1.00
BOD (mg C/l)	11.80	58.70
NO ₃ (mg N/l)	0.53	0.31
NH ₄ (mg N/l)	0.65	12.62
CHL (mg C/l)	0.319	0.781
pH	7.39	7.46

Alkalinity and C_T were calculated from equilibria between H⁺ and other major ions in water

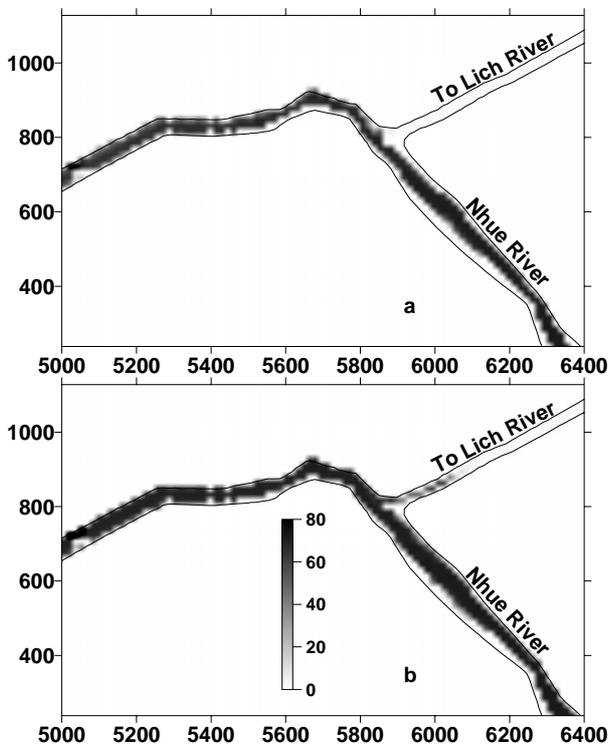


Fig. 4 Visualization the inorganic SS at different discharges; mainstream and tributary inflows in (a)= 27.8 m³/s and 1.8 m³/s, respectively, in (b)= 44.6 m³/s and 0.005, respectively

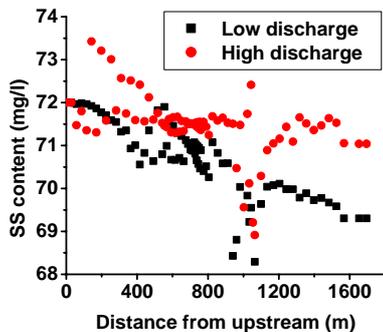


Fig. 5 Longitudinal SS profiles at the stream center in low (35 m³/s) and high (82 m³/s) discharges

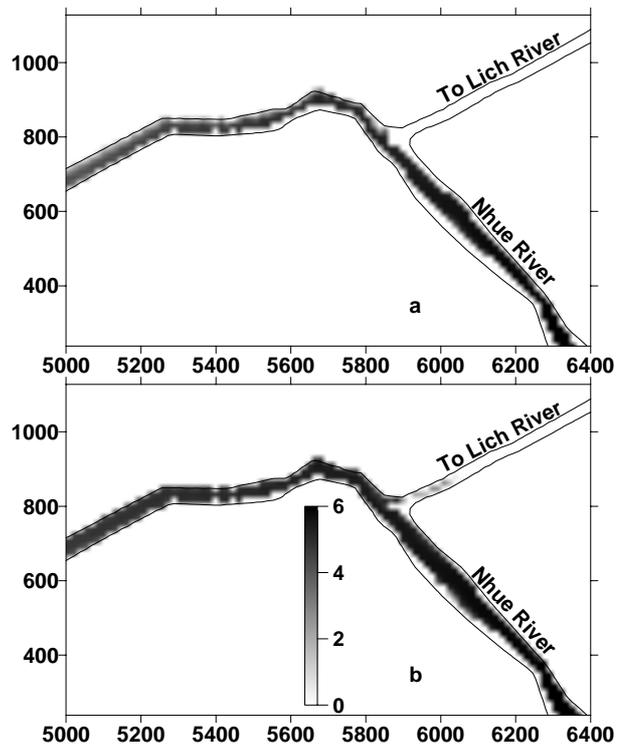


Fig. 6 Transport of dissolved oxygen (mainstream inflow and tributary inflow in [a] = 27.8 m³/s and 1.8 m³/s, respectively; in [b] = 44.6 m³/s and 0.005 m³/s, respectively)

Since settling rate applied for this simulation was calibrated from monthly data throughout 2 consecutive years 2002-2003 usually showed gradual decrease of SS content downstream, it was expected that the simulation would show similar result.

In order to examine this expectation, longitudinal variations of SS at different discharge conditions were taken into account (Fig. 5). Clearly, the applied settling rate produced deposition, even at extremely high discharge (SS content reduced downstream). Thus it is concluded that this 2-D model applied for SS simulation is rational.

b) Variation of nutrients

The simulation of nutrients and biological organism transport and conversion is centerpiece of ecological modeling. The success of ecological model application relies on this simulation.

Fig. 6 represents the profiles of simulated DO at different discharges. In all profiles, especially Fig. 6a when the To Lich River's discharge was significant the simulated DO decreased downstream. This decreasing tendency is seen at every discharge level, since downstream DO was always lower than upstream boundary (Fig. 8). That was similar to the fieldwork since benthic activity was strong and the DO hardly rose up to be equal its upstream level.

Other notice from the simulation of DO is that when discharge of the To Lich was insignificant

(Fig. 6b), DO level in the To Lich River, close to the confluence, was also raised. It is similar to the simulation of SS and field observation (results not shown). This notice was applied not only for DO and SS but also for other variables. To make it clear, the computations of phytoplankton and NH_4 at 100 m upstream the confluence in the To Lich River are shown in Fig. 7. As expected, when Thanh Liet dam was close in high discharge, water from Nhue River had flown in and changed water quality there. So, at high discharge of the Nhue, one can find water in To Lich River as fresh as in Nhue River.

c) Lateral stratification

One question could be answered in application of 2-D depth average model is how water changes laterally. In application to the confluence between Nhue and To Lich Rivers, this question becomes strategic since downstream water is result from mixing of two different water masses. In some field observations water quality was seen laterally stratified few hundreds meter downstream the confluence. Sediment samples collected in two river banks about 100 m downstream the confluence contained different amount of particulate organic matters (sediment in left bank where To Lich River joins Nhue River had higher organic matter content than sediment in the right bank had (results not shown)). The 2-D depth average model could help to identify the spatial and temporal scale of this stratification.

Apparently, the simulated river reach was not sufficiently long enough to observe a complete mixing of two water masses (Fig. 8). At 2.92 hours and 24 hours when the To Lich's inflow was set as 1.8 and 3.2 m^3/s , respectively, the DO level downstream the simulation area was significantly different from left bank to right bank. So when the To Lich's inflow was substantial, one could observe a lateral stratification about 800 m downstream the confluence. However, it should be noted that water transport in this model was purely governed by hydraulic force and rather simple hydrodynamic resistance. The calculation did not take into account human activities (mussel harvesting, duck culturing, boating) or complexity of the river bed where submerged artificial objects and tree-type vegetation have sometimes altered the regularity of hydraulic flow.

(2) Diurnal variation of water quality in April 23-24 2003

In previous subsection, the 2-D model was tested at different discharges to perceive typical change of water quality in extreme conditions. In this subsection the model was employed to simulate

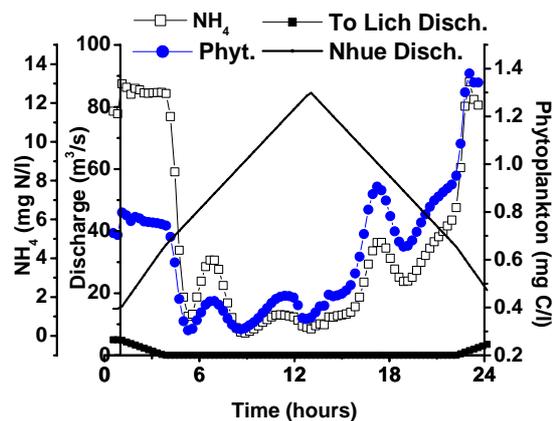


Fig. 7 Variations of water quality downstream To Lich River

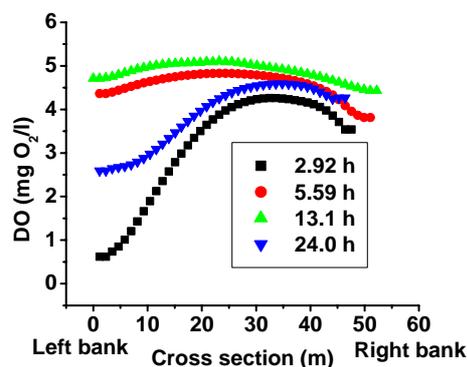


Fig. 8 Cross sectional profiles of downstream DO

the observation obtained in April 23-24 2003 when water quality varied considerably between day and night. It was observed that in April 23-24, downstream discharge was nearly constant at 20 m^3/s . Thanh Liet Dam was open to maintain a discharge of 5 m^3/s . Boundary conditions of state variables were taken as in Table 3. The simulation results of DO and NH_4 together with measured data collected at monitoring station 5 km downstream the confluence are shown in Fig. 9-10. Because the downstream of the simulated area was still 4 km upstream the monitoring station, we could only have a qualitative comparison of the measured and simulation results. The high BOD loading from To Lich River was main reason for very low DO at 5 km downstream the confluence (Fig. 9).

Although, the simulated DO level was not as low as the observation (around 3 mg/l) but this level tended to decrease and could reach the same low level after 5 km. The magnitude of simulated DO level change was about 0.15 mg/l and could be as high as 1 mg/l after 5 km to be similar with the observation (Fig. 9). Diurnal change of NH_4 was observed though not so clear and coincident with our experiment data (Fig. 10). The small diurnal variation of NH_4 indicated that NH_4 in water was extensive to phytoplankton uptake.

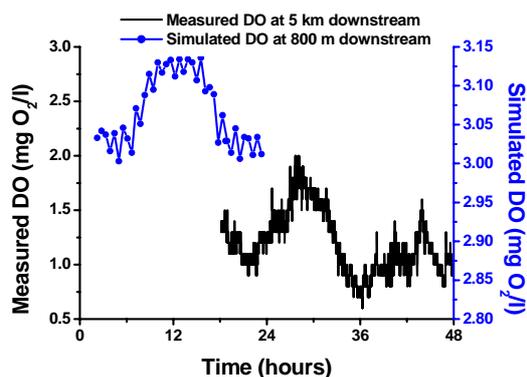


Fig. 9 Diurnal variation of DO downstream the confluence

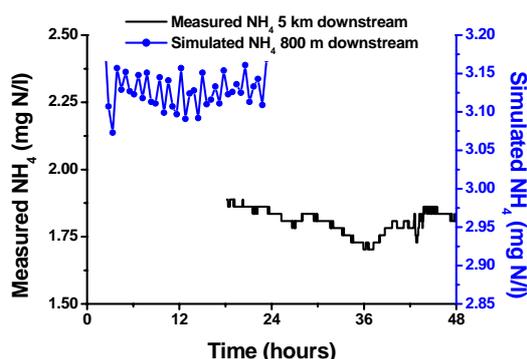


Fig. 10 Diurnal variation of NH_4 downstream the confluence

5. CONCLUSION

It is the first time that a 2-D hydrodynamic+ biochemical model was successfully applied for the junction between Nhue River and To Lich River. The advantage of application of 2-D numerical model compared with 1-D model is that it could simulate smoothly transport of state variables at junction between river reaches. With 2-D model, one could simulate back water effect observed frequently in To Lich River when Nhue River's discharge was high. Simulation showed that within the calculation area and in low discharge condition, water was not completely mixed. Lateral stratification of different water quality still can be seen few hundred meters downstream. With more study on sediment contribution, vegetation coverage, SS flocculation and roughness coefficient, more precise simulation could be obtained.

In future, bed deformation due to high SS load and flooding can be simulated based on the current study. Based on this conceptual scheme, a more

universal and complete biochemical model can be setup. The complete model can simulate separately biomasses of bacteria, zooplankton, dissolved organics and particulate organics.

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