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MODELLING THE EFFECT OF HUMAN ACTIVITIES ON THE NUTRIENT TRANSFER IN THE RED RIVER BASIN (VIETNAM): PRESENT SITUATION AND PROSPECTIVE SCENARIOS FOR THE NEXT 50 YEARS

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ABSTRACT: The Red River (Vietnam and China), which covers a watershed area of 156451 km^2 with a total population near 30 million inhabitants, is one of the two largest rivers in Vietnam. The backbone of this work consisted in implementing the Seneque/Riverstrahler software which was successfully applied for the first time to a tropical river system as the Red River for assessing the link between human activity in the watershed and water quality of this river system. The first application of this model to the Red River system is described and validated with the data acquired by the monthly surveys of water quality at the outlet of the 3 sub-basins and in the main branch of the Red River during the years 2003 and 2004. After being validated, the model is used to explore a variety of scenarios describing possible future changes, concerning the hydrological management, population increase and land use and agricultural practices in the Red River basin in the next 50 years. The results show a clear increase of the N/P ratios is predicted for the 2050 scenario with respect to the 2003 situation, along with a clear decrease of the Si/N ratios at the outlet of the Red River.

Key words: Seneque/Riverstrahler Model, nutrients, eutrophication, Red river, Vietnam

INTRODUCTION

The Red River originates in Yunnan province (South China) with its names of Yuan River. When entering into the Vietnamese territory in Lao Cai province, it calls Thao (or Cai or Red) river. The Thao river receives the Da River in the right side and the Lo river in the left side at Viet Tri city, and forms a large Delta before flowing into the Chinese sea through 4 estuaries called Ba Lat, Lach Gia, Tra Ly, and Day (Le et al., 2005). The river covers a watershed of 156 451 km^2 (figure 1). A subsequent analysis based on the treatment of the digital elevation model of the NASA (global SRTM 3” resolution) leads to a slightly different watershed area of 142 950 km^2.

The Red River has been strongly influenced by human activities in Vietnam. In the upstream of the Red River basin, deforestation (clear cutting or other harvesting techniques) and land use changes are considered to cause a variety of environmental impacts such as increased flooding and dramatically increased soil erosion from denuded watershed exposed to high intensity tropical rainfall. In its downstream sector, the high intensive farming areas attached to the use of nitrogen and phosphorus fertilizers, the increase of population, the

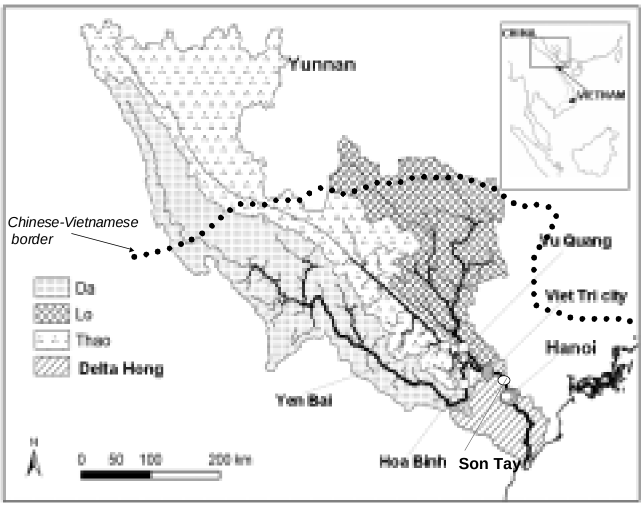

Fig. 1 The Red River basin and hydrological stations

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Note: Discussion on this paper is open until June 2010 economic industrial development and urbanization as well as the increased transportation network have strongly affected the water quality of the Red River system and also influenced the coastal zone ecosystem (MOSTE, 2003; MONRE, 2003).

The first objective of this work was to develop a comprehensive understanding of the linkage between land use and human activities in the watershed in order to quantify the water quality and the transfer of nutrients (N, P and Si) in the Red River drainage network. A second objective is to demonstrate that the tools can be utilisable in Vietnam to test scenarios for management purposes of human impacts in the watershed in the years 2050s. In this paper, we will discuss about the implementation of the Seneque/Riverstrahler software on the Red River basin to predict the results of possible future changes in three aspects on the overall water quality and nutrient delivery of the river system. Explorations by the model such as new reservoir construction in the upstream basins of the Da and the Lo Rivers, rapid increase in population and its degree of urbanization, changes in land use and the intensification of agricultural practices are all subjects that are discussed in this paper.

THE SENEQUE / RIVERSTRAHLER SOFTWARE

The approach used in this study is based on the adaptation of the RIVERSTRAHLER model which has been firstly developed for the Seine River (Billen et al., 1994; Billen and Garnier, 1999), and then for several large European rivers (the Danube (Garnier et al., 2002); the Mose (Garnier et al., 1999); the Scheldt (Billen et al., 2005); the Rhine and the Loire (Garnier et al., 1997)) to address the questions of organic pollution and oxygen balance, nutrient contamination and related eutrophication, transfer and retention in the whole basin. This model combines a simplified hydrological model (HYDROSTRAHLER), relating meteorological constraints to hydrology, to an ecological model (RIVE) and describing in-stream ecological processes (Fig. 2).

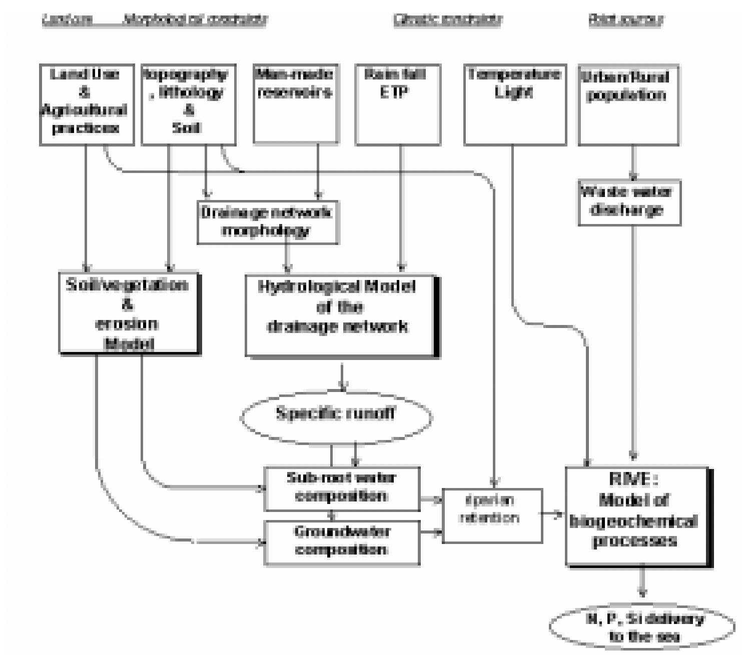

Fig. 2 The structure of the RIVERSTRAHLER model (Billen et al., 1994)

Recently, a new version of the model(Seneque/Riverstrahler software) has been develop

Table 1 Some characteristics of the whole Red River and its main tributaries

	Thao (Yen Bai)	Da (Hoa Binh)	Lo (Viet Tri)	Hong Delta total	Red River (total)
Topography					
Basin area, km²	57 150	51 285	34 559	9435	156 451
Length main branch, km	902	1010	470	236.5	1138.5
Land use (in 1997)					
Rice, %	18.7	12.5	8.1	63	17
Industrial and other cultures, %	14.4	3.0	58.6	3.9	19.8
Grassland, %	7.2	3.6	3.9	2.6	5.0
Forest, %	54.2	74.4	22.4	17.8	51.6
Rocky areas, %	4.1	6.2	6.4	5.9	5.4
Urban area, %	1.4	0.3	0.6	6.8	1.2
Population (in 1997)					
Population density, inhab/km²	150	101	132	1174	192

(Ruelland et al., 2007). The Riverstrahler being embedded within the SENEQUE GIS interface allows the user to run the model with any structure of basins and branches and to select on line according to the geographical resolution required for the studied question. The new version of the model requires however to assemble a complete set of geo-referenced data on the different constraints under the form of a GIS data base. Owing to this new software, the functionalities of the RIVERSTRAHLER model are multiplied by those of a GIS, allowing an easy extraction of the data required for separate runs of the Riverstrahler.

SITE DESCRIPTION – DATABASE CONSTRUCTION

Geomorphology

The area of the whole Red River basin takes different values depending on the authors, because of the different ways of estimating, within the delta, the complex hydrographic network of the Red-ThaiBinh River system, i.e., the Red River delta from the ThaiBinh river network. In this study, the total area of the Red River catchment was first estimated to 156 451 km^2.

A subsequent analysis based on the treatment of the digital elevation model of the NASA (global SRTM 3" resolution) leads to a slightly different watershed area of 142 950 km^2. Within the Red River watershed area, 47.9% is in Chinese (Chinadata, 1998), 51.2% in Vietnamese (MOSTE, 2003) and 0.9% is Laotian territories.

In this approach, the Red River basin is divided into 4 sub-basins. The 4 sub-basins with their characteristics are presented in the Table 1.

Meteorological Data

Present situation

The climate in the Red River basin is controlled by the North East monsoon in winter and South West monsoon in summer and is well described in Le et al. (2006).

We have gathered the meteorological data from 13 meteorological stations in the Red River basin. The annual mean temperature varies from 14 to 27 °C. The humidity always remains in high level (from 82 to 84% all over the year in the Vietnamese part of the basin and about of 67÷70 % in the Chinese part (Ruelland et al., 2007; IMH 2004).

The rainy season cumulates 85 – 90% of the total annual rainfall in the Red River catchment. The mean annual rainfall is 1590 mm in the whole Red River basin.

Possible change in climate in the 2050s

The hydrological cycle is much influenced due to the increased greenhouse gas concentrations in the atmosphere and consecutive global warming. According to the Intergovernmental Panel on Climate Change (IPCC, 2001), an annual mean rainfall will increase about 3 ± 1% in the 2020s and 11 ± 3% in the 2080s and a mean temperature will increase about a 2-5°C in Asia, in particular. We applied the increasing of annual mean rainfall of 10% and of mean temperature of 3°C to the scenario in 2050s.

Hydrographical Network

Present situation

The hydrographic network of the Red River and its elementary watersheds, constitute the first and basic layer of the GIS database. The details for the construction of the hydrographic network representation are described in Le et al. (2007). An important work has been realized to geo-reference all the Vietnamese streams of the drainage network and to connect them towards the direction of water flux. This network was then simplified, in order to adjust the resolution to the one available for the Chinese part of the basin, finally producing the simplified map.

The daily discharge data at the outlet of the 3 main branches and in the main branch of the Red River (Figure 1) in the period from 1997 to 2004 will be utilized to valid the model. In the period 1997-2003, the mean annual discharge at the Son Tay station was of 3577 $m^3.s^{-1}$.

The Hoa Binh and Thac Ba reservoirs are the two largest dam-reservoirs located in the Red River basin. The detail about the hydrology and suspended solid transfers and some characteristics of these dams are showed in Le et al. (2006).

Possible change in hydrological management

The construction of two new large dams is planned for the next decade. The Son La dam, with a volume of 9.3 - 25.5 10^9 m^3 will be constructed on the upper course of the Da river, upstream from the Hoa Binh reservoir. The Tuyen Quang dam, with a volume of 0.5 - 3 10^9 m^3 will be constructed on the Gam river, a tributary of the Lo river. Some main characteristics of two new reservoirs are presented in Le et al. (2006).

Wastewater Point Source: Population and Urbanization

Present situation

The total population of the Red River basin is estimated at 30 million inhabitants and is growing with the annual rate of about 2.0 %. About 65% of the Red River population is Vietnamese, 34% is Chinese and 1% is from Laos. Population density differs from upstream basin (101 inhabitants.km^{-2}) to delta area (1174 inhabitants.km^{-2}) (Table 1). The analysis of the population data base by villages in the Vietnamese Red River basin shows indeed that 80% of the population lives in agglomerations of less than 10 000 inhabitants.

Possible change in population in the 2050s

According to FAO statistics (2004), the total population in Vietnam increased from 27.4 10^6 in 1950 to 83.6 10^6 in 2005, and will reach 117.7 in 2050s. The Vietnamese population should thus increase by a factor 1.4 in the years 2050s. Urban population, however, has increased at a higher rate in the last decades than rural population. We estimate that urban population in Vietnam will represent about 40% and the fraction of rural population should be 60% by the year 2050s. The total population in the Red River basin considered in the Seneque data base will increase from 16.10^6 inhabitants to 23.10^6 inhabitants by 2050s.

Land Use and Non-point Source

Present situation

Land use differs considerably between 3 upstream sub-basins and the Delta of the Red River. In the Da sub-basin, forest area dominates (74.4 %), and industrial crops (58.1 %) mainly occupies in the Lo sub-basin. In the Thao sub-basin, forest, rice fields and industrial cultures hold a large share (54.2; 18.7; and 14.4% respectively) while the Delta area is mainly characterized by the rice fields (63%) (Table 1, (Le et al., 2005)).

According to the FAO database (FAO, 2004), use of nitrogen and phosphorus fertilizers in Vietnam has much increased during a period from 1961 to 2000 (Fig. 3). Application of chemical fertilizers may dramatically increase nutrient concentrations in soils which may subsequently be removed by leaching and transferred to the river water. Further, serious erosion and soil loss in watersheds accelerate the removal of nutrient elements.

Possible change in agricultural intensification in the 2050s

Accordingly, we established a “2050” land use GIS file, by increasing the urban area, for each elementary watershed unit of the ‘2003’ land use file, at the expense of paddy rice fields or other agricultural surface if necessary. In order to account for the intensification of agricultural practices, we also assumed that the nitrate concentration resulting from soil leaching of dry agricul-

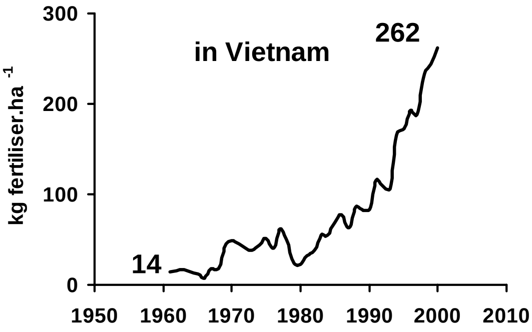

Fig. 3 Evolution of fertilizer application (N and P) in Vietnam (FAO, 2004)

-tural soils (all crops excepted paddy rice) would have reached the levels typically observed in West European countries (10 mgN.L^{-1}l), and we considered a 25% increase of the export of total phosphorus from agricultural soils.

MODELLING RESULTS AND DISCUSSION

Modelling the Present Situation of the Ecological Functioning of the Red River System

We run the Seneque/Riverstrahler model with all constraints described above for the present situation of the Red River. The modelling results are shown in Fig. 4 for the year 2003 as an example. The observation data obtained during the sampling campaigns in two years 2003-2004 at the outlet of the Thao river, the Da River, the Lo River and in the main branch Hong River are showed to compare with the simulation results. The agreement between observed and calculated concentrations is rather good: the model is able to reproduce the observed general levels of nutrient concentrations. The difference between the modelling simulation and the observation values are caused by the lack of data of the Red River basin in the Chinese part such as meteorology, population and also of the industrial wastewater data in the whole Red River basin, as well shown in (Le et al., 2006 ; Le et al. 2007).

Modeling the Prospective Situation of the Ecological Functioning of the Red River System

Impacts of the dams on the water quality of the Red River basin

We have run the Seneque/Riverstrahler model for two scenarios differing from the standard validated scenario of the year 2003 in that (i) no dams at all are considered (scenario called “1970”), or (ii) the four large dams are considered operating (scenario called ”2050”). Excepted for this aspect, all the other constraints (hydrology, land use, point sources of waste water) were taken identical with those of the reference “2003” scenario. The annual flux of suspended solid and total phosphorus delivery were calculated and given in Table 2. The results show a clear decrease of both suspended solid and total phosphorus fluxes at the outlet of the Da and Lo Rivers, as well as in the main branch, at Hanoi. The effect of the Son La dam is less apparent than that of the Tuyen Quang dam (compare sc 2003 and sc 2050), because the Hoa Binh dam already reduced severely the suspended solid load of the Da River at its outlet (compare sc 1970 and 2003). The impoundment of the Tuyen Quang dam will result in 50% reduction of the suspended solid flux of the Lo River. These conclusions are in agreement with those of other authors (Nguyen and Nguyen, 2001; Nguyen et al., 2003; Pham, 1999).

Impacts of the new dams, agricultural intensification, and population increase on the water quality of the Red River basin

The Seneque/Riverstrahler model has been run for a hypothetical “2050” scenario characterized by the hydrological conditions by the climatic change in 2050s, the presence of 4 large dams, and a 40% increase of population distributed between rural and urban centres, land use and agricultural practices as discussed above. The results show the trends of the changes to be expected from this “business as usual” scenario of the future evolution of the human activity in the Red River basin, compared to the present “2003” situation (Fig. 5). Note that we have not considered any difference in wastewater treatment practices in 2050 compared to 2003, i.e. the same hypothesis concerning the release of wastewater in urban (no treatment and total release to surface waters) and rural areas (75% recycling in agriculture) has been made.

The results show a very important increase in nitrate and ammonium contamination of the Red River, while the level of phosphorus contamination remains nearly the same.

Apparently, the retention of phosphorus by the two additional dams counterbalance to a large extends of the increased release of phosphorus by agricultural soils and human population.

Table 2 Simulated fluxes of suspended solid and total phosphorus delivery at the outlet of the Da and Lo rivers and at the Hanoi station, calculated for the conditions of the year 2003, without any dam (“1970”), with the two presently existing dams (“2003”) and with two additional dams (“2050”)

	Suspended solid 10^6 ton SS.y^{-1}			Total phosphorus 10^3 ton P.y^{-1}		
	1970	2003	2050	1970	2003	2050
Da	58.1	7.4	6.7	39.6	9.3	8.8
Lo	41.5	35	21.5	27.9	24	11.6
Hong	113.8	35	44.5	81.6	48.2	39.7

Calculation of the Flux and the Redfield Ratio

The calculated fluxes of nutrient delivery by the Red River and its main tributaries show that nitrogen fluxes will be considerably increased at the outlet of the Thao, Da, Lo Rivers and in the main branch of the Hong River, while phosphorus flux at the outlet of Da and Lo Rivers tends to decrease.

Only at the outlet of the Thao basin, the most populated and free of dam basin, phosphorus flux increased in 2050 with respect to 2003. The resulting total phosphorus flux at the Hanoi station is nearly unchanged. Silica fluxes are also predicted to remain essentially unchanged in response to the 2050 scenario.

The resulting nutrient ratios obviously reflect these trends (Table 3). A clear increase of the N/P ratios is predicted for the 2050 scenario with respect to the 2003 situation, along with a clear decrease of the Si/N ratios at the outlet of the three rivers Thao, Lo and Da. At the Hanoi station (downstream of the Red River in the main branch), the N/P ratio (4.8) is lower far from the Redfield ratio (16) (Redfield et al., 1963) indicating N potentially limiting factor of algal growth in the Tonkin Bay while the Si/N ratio (2.1) indicating the excess over the requirements of marine diatoms growth (when Si/N is around 1) (Conley et al., 1993).

CONCLUSION

Our results show that the Seneque/Riverstrahler model was successfully applied for the first time to a tropical river system, the Red River for assessing the link between human activity in the watershed and water quality of the river system. The modelling results are validated, and are a rather good agreement with the observed data of water quality, at the outlet of the three sub-basins and in the main branch of the Red River.

The model has allowed exploring a variety of scenarios describing potential changes in the watershed, in terms of river water quality and overall export of nutrients. We have restricted ourselves to three important aspects:

(1) the impoundment of new large dams on the drainage network of the Red River; (2) the increase of the population and its degree of urbanization; (3) the

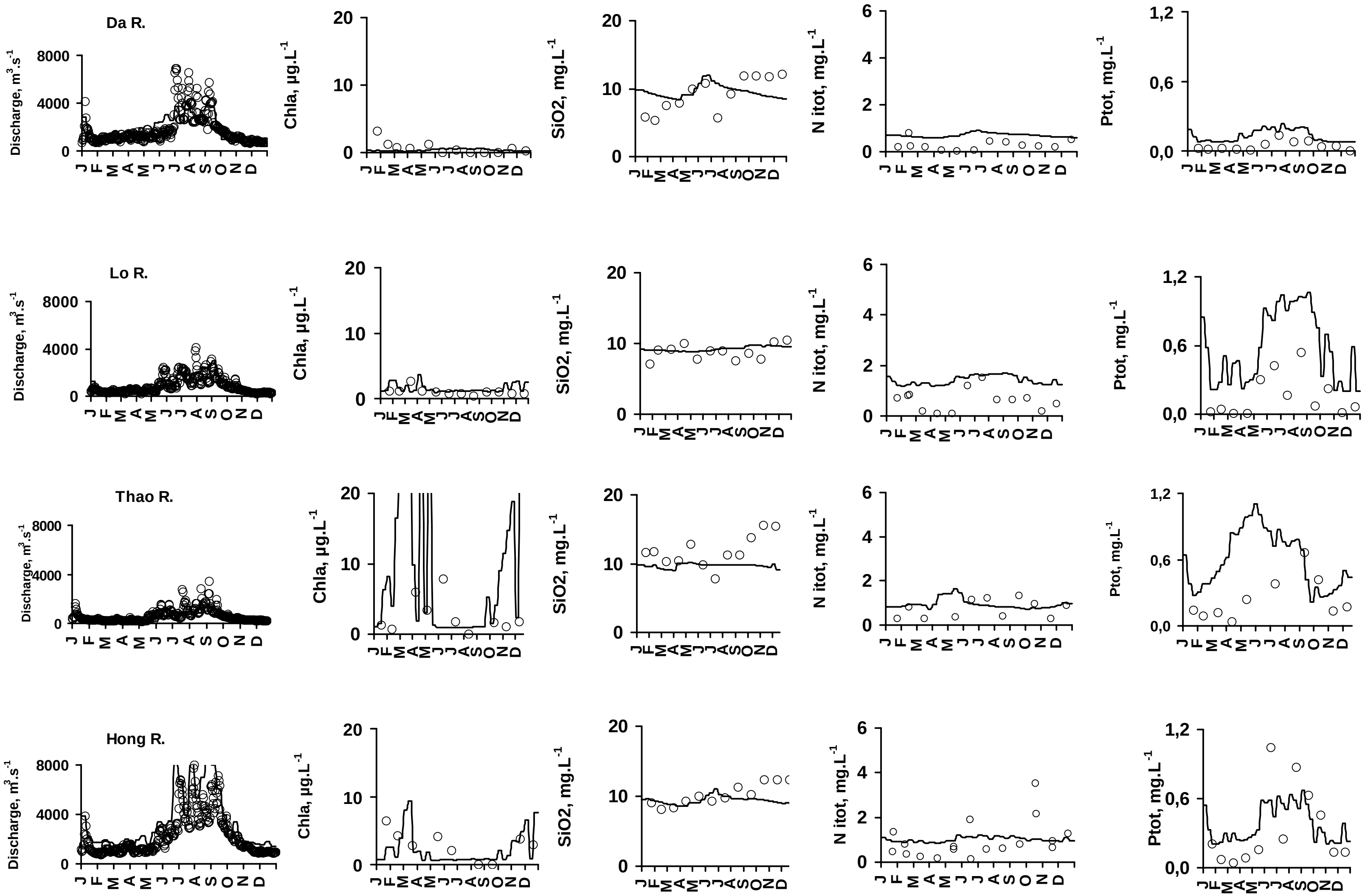

Fig. 4 Simulation and observation results of water quality in 2003 as the present situation the Red River at the stations Hoa Binh (in the Da River), Vu Quang (in the Lo River) , Yen Bai (in the Thao river) and Hanoi (in the Hong River): discharge ($m^3.s^{-1}$), chlorophyll a ($\mu g.L^{-1}$), silica (SiO_2, $mgSiO_2.L^{-1}$), total inorganic nitrogen (Nitot , $mgN.L^{-1}$), and total phosphorus (Ptot, , $mgP.L^{-1}$).

Table 3 Molar nutrient ratio of fluxes delivered at the outlet of the sub-basins and the main branch of the Red River as calculated by the model for the reference year of 2003 and in the '2050' scenario with the same hydrological conditions

	N/P		Si/N	
	in 2003	in 2050	in 2003	in 2050
Thao	1.9	2.8	3.7	2.2
Lo	2.3	5.8	2.3	1.2
Da	6.6	7.8	4.5	4.0
Hong	3.0	4.8	3.3	2.1

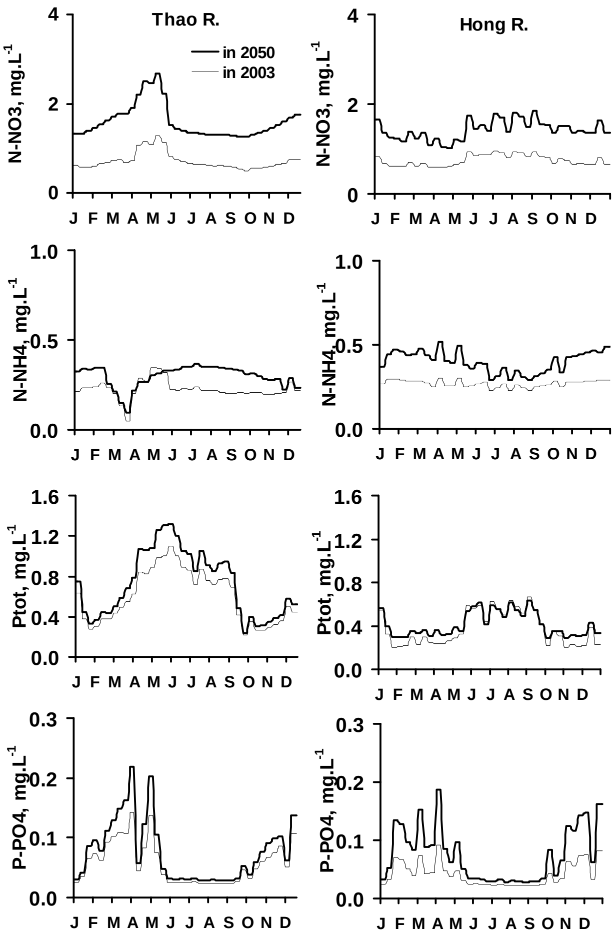

Fig. 5 Simulation results obtained at the Yen Bai station in the Thao River and at Hanoi station for the '2050' and the 'reference 2003' scenarios

changes in land use and the intensification of agricultural practices. The modelling results for the year 2050 show clear increase of N/P ratios and clear decrease of Si/N ratios with respect to the 2003 situation. The N/P ratio (4.8) indicates N potentially limiting factor of algal growth in the Tonkin Bay while the Si/N ratio (2.1) indicating the excess over the requirements of marine diatoms growth.

The Seneque/Riverstrahler model implemented on the Red River basin enables the diagnostic of the N:P:Si nutrient balance, which is the key for the control of freshwater and coastal marine eutrophication problems. The implementation of such a water quality model at the regional scale can offer an excellent framework for initiating and developing the dialogue, both between scientists of different disciplines but also between scientists, decision-makers and the public.

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