

# Integrating Spatial Land Use Analysis and Mathematical Material Flow Analysis for Nutrient Management: A Case Study of the Bang Pakong River Basin in Thailand

Wallapa Kupkanchanakul · Suphaphat Kwonpongsoogoon · Hans-Peter Bader · Ruth Scheidegger

Received: 3 September 2014 / Accepted: 29 December 2014 / Published online: 9 January 2015  
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**Abstract** Rivers in developing and emerging countries often lack good water quality. Tools to assess the water quality in rivers, including identification of possible sources of pollution, are therefore of increasing importance. The aim of this study is to apply mathematical material flow and spatial land use analyses to identify and geographically locate the main nitrogen and phosphorus sources and processes in Bang Pakong Basin (BPB). Potential measures to mitigate the nitrogen and phosphorus loads to the water system can then be efficiently evaluated. The combination of these two methods reveals the overall nutrient load as well as local “hot spots.” This allows possible mitigation measures to be discussed with regard to their spatial location. This approach goes beyond previous work in which mathematical material flow analysis was shown to be a useful tool to investigate sources of nutrients regardless of their location. The results show that the main sources contributing nutrients to waterways are aquaculture, such as shrimp, tilapia, catfish, and sea bass farming,

as well as rice paddies along the main river. Additional sources contributing nutrients to this basin are field crops, livestock, aquaculture, households, and industry. High levels of nutrient inflows come from feeds and fertilizers through aquaculture and rice cultivation. The excess nutrients run into the waterways by direct discharge from aquaculture and runoff processes from rice paddies. Scenario analysis shows that management practices for aquaculture, rice, pig, and poultry farming are key drivers for reducing nutrients in the BPB.

**Keywords** Mathematical material flow analysis · Non-point source pollution · Nutrient balance · Spatial land use · River water pollution control

## Introduction

The quantity and quality of water is a major concern in emerging and developing countries, especially in densely populated areas around large cities. There are many reasons for this economic development coupled with population growth puts increasing pressure on water bodies. Water is used not only for domestic purposes but also to irrigate agricultural fields and by industry. There is also increasing demand for water for recreational purposes, which requires unspoiled natural areas.

In Thailand, the four main rivers discharging into the north of the Gulf of Thailand have been gradually polluted with nutrients, heavy metals, and organic substances such as pesticides (Hungspreugs et al. 1989, 1990; Cheevaporn and Menasveta 2003). These nutrient discharges are responsible for the occurrence of eutrophication, not only in the rivers but also in the estuaries (Buranapratheprat et al. 2002; Bordalo et al. 2001; Wongchumrus 2004;

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**Electronic supplementary material** The online version of this article (doi:10.1007/s00267-014-0441-5) contains supplementary material, which is available to authorized users.

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W. Kupkanchanakul · S. Kwonpongsoogoon (✉)  
Department of Sanitary Engineering, Faculty of Public Health,  
Mahidol University, 420/1 Rajavithree Road, Bangkok 10400,  
Thailand  
e-mail: suphaphat@hotmail.com

W. Kupkanchanakul · S. Kwonpongsoogoon  
Center of Excellence on Environmental Health and Toxicology  
(EHT), Ministry of Education, Bangkok 10400, Thailand

H.-P. Bader · R. Scheidegger  
Eawag, Swiss Federal Institute of Aquatic Science and  
Technology, Überlandstrasse 133, P.O. Box 611,  
8600 Dübendorf, Switzerland

Boonphakdee and Fujiwara 2008). For the last two decades, major efforts have been made to monitor and manage these rivers (Pollution Control Department Bangkok (PCD) 1994; 1999; Royal Irrigation Department Bangkok (RID) 2000; RID 2003; Office of Natural Resources and Environmental Policy and Planning (ONEP) 2006; Molle et al. 2009). In order to design suitable countermeasures, both the current state of the river and the sources of the various pollutants are of interest.

In Thailand, the traditional approach has been to implement mathematical water quality models as a tool for water quality management in order to evaluate the present and future water quality. Furthermore, monitoring samples along major rivers in the country provides data for determining water quality. However, as discussed in Schaffner et al. (2009a), neither these models nor these data identify the sources of existing pollutants nor evaluate the pollution-generating processes involved. Mathematical material flow analysis (MMFA) offers a complementary way of investigating water quality by identifying and quantifying the sources and pathways of pollutants. The procedure has been described in detail in Schaffner et al. (2009a, b, 2011). In these studies, the method was applied to point and non-point nutrient sources in the Tha Chin Basin, Thailand. These studies complemented the water quality measurements and simulations carried out along the river.

Just like for the Tha Chin River, many studies of the water quantity in the river also exist for the Bang Pakong River. In line with national water policy (PCD 2011), most stakeholders and researchers (from past to present) focus mainly on water quantity and allocation. However, the management of water quality has been considered after public appeals and implemented in the water bodies of concern to the public. However, all sources have not been identified nor has the whole system been assessed. Little is known about the sources discharging into the Bang Pakong River except for the industrial inflows (Molle et al. 2009). As a consequence, the water quality has deteriorated from year to year.

The objective of this study is consequently to identify the key sources and flows of nitrogen and phosphorus into the Bang Pakong Basin (BPB), Eastern Thailand, and to identify, discuss, and assess the options for mitigating their loads in the waterways flowing into the basin. This study is based on that presented in Schaffner et al. (2009a), who applied MMFA on a provincial scale and designed specific measures for the four provinces considered. In addition, our study shows how to focus beyond the provincial level by presenting a spatially distributed approach. The method combines the MMFA approach with a land use analysis. The result is a spatially distributed quantification of pollution sources and pathways forming the basis for possible geographically referenced mitigation options.

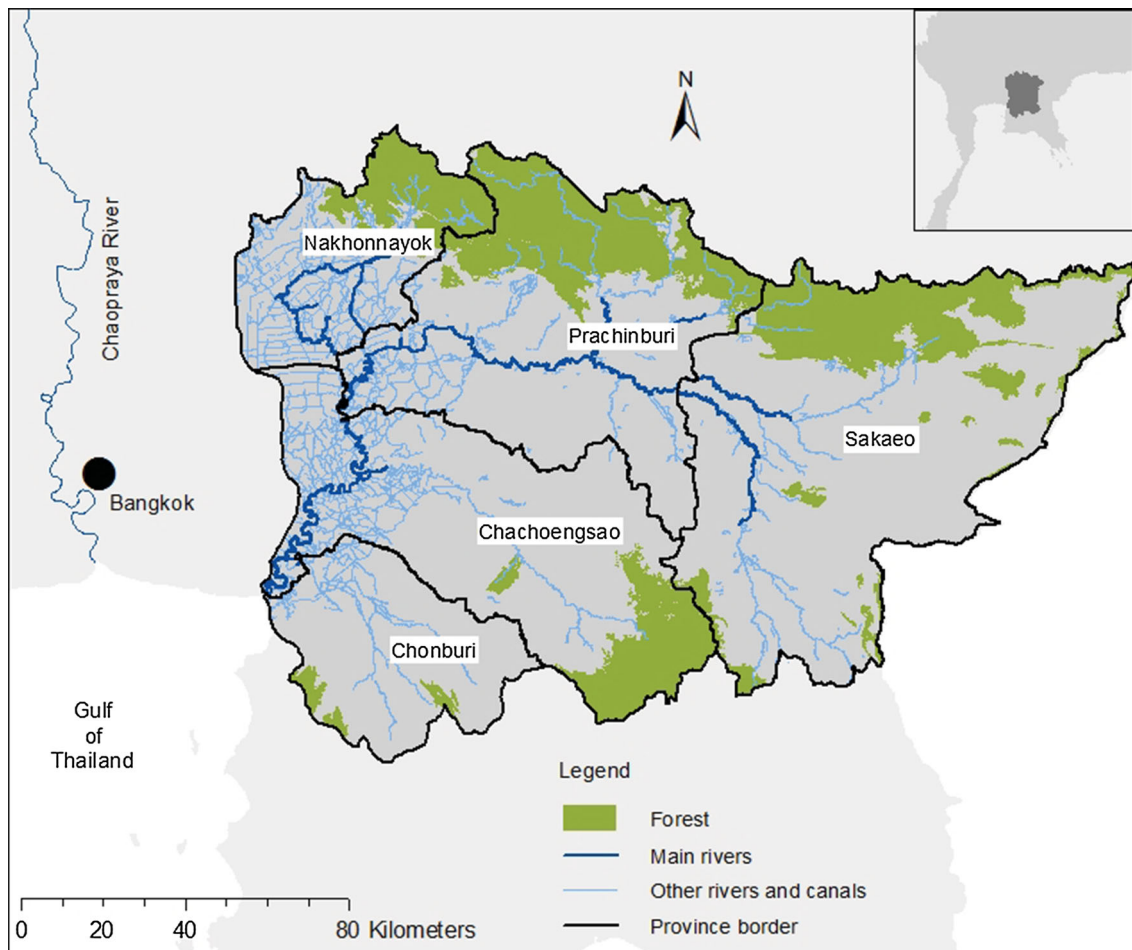
## Study Area: Bang Pakong Basin, Eastern Thailand

The Bang Pakong River, situated to the northeast of Bangkok (Fig. 1), is one of the four major rivers flowing into the inner Gulf. The BPB covers approximately 2.3 million hectares and consists of the five provinces of Nakhonnayok, Chachoengsao, Prachinburi, Sakaeo, and part of Chonburi. The small part of Saraburi province associated with the BPB was neglected. The two main tributaries forming the Bang Pakong River are the Nakhonnayok and Prachinburi Rivers. There are hills of up to 1,300 m in height toward the north and northeast of the basin. It then becomes flat toward the south and east, and there are plains along the main river, which are ideal for agricultural purposes. The climate is monsoonal with a wet season between June and November and a dry season from December to May. The annual rainfall varies between 1,000 and 2,000 mm/year with an average of 1,400 mm/year (Thai Meteorological Department (TMD) 2006). The average annual discharge into the Gulf of Thailand is 445 cubic meters per second (ONEP 2006), corresponding to an average runoff of about 44 %. During the dry season, the tidal influence reaches up to 170 km upstream past the confluence of the Nakhonnayok and Prachinburi Rivers. The population of the whole basin was 2.9 million in 2005 (Department of Provincial Administration (DOPA) 2007).

The land use is shown in Table 1. Agricultural land (rice, field crops, fruit, and vegetable) covers approximately 1.1 million hectares, accounting for 52 % of the basin's area. Approximately 65 % of the basin's main crop, namely rice, is cultivated in the two provinces of Chachoengsao and Sakaeo. Most of this is grown as rain-fed rice, only a smaller part of the fields are irrigated. Similar areas to those for rice are used for field crops such as sugarcane, cassava, and eucalyptus trees. Eucalyptus trees are cultivated especially in Prachinburi and Sakaeo provinces, to supply the pulp mill industry (ONEP 2006) there. The largest areas of fruits and vegetables (mangoes, bananas, and leaf vegetables) are grown in Prachinburi province, followed by Chachoengsao, Sakaeo and Chonburi provinces; see also Fig. 2b.

According to the Department of Livestock Development (DLD) (2005), about 20 % of Thailand's pork as well as about 14 % of its poultry is produced in the BPB. Aquaculture is located inland and along the rivers and produces shrimp, tilapia, catfish, and sea bass.

The majority (about 80 %) of the population live in rural areas producing agricultural products and fruit. Chonburi province is more densely populated (440 cap/km<sup>2</sup> compared to 200 Cap/km<sup>2</sup> in the other provinces). Industry is mainly located in Chonburi, Chachoengsao, and Prachinburi provinces, largely due to Thailand's eastern seaboard



**Fig. 1** Boundaries of Bang Pakong Basin (BPB showing the catchment area, the boundaries of the provinces and the forests, as well as the main rivers and important canals)

**Table 1** Land use in each province of Bang Pakong Basin (BPB)

Province	Nakhonnayok	Chachoengsao	Prachinburi	Sakaeo	Chonburi	Total	% of total area
Land area (ha)	212,000	535,000	476,000	720,000	283,000	2,226,000	
Agriculture							52
Rice	74,000	189,000	104,000	16,9000	8,000	544,000	24
Field crops	3,700	199,000	68,000	23,3000	55,000	558,700	25
Fruit and vegetable	2,890	10,690	12,730	9,500	9,280	45,090	2.0
Livestock and aquaculture							1.3
Pig farming	170	470	180	10	640	1,470	0.1
Poultry farming	440	1,490	1,700	260	5,060	8,950	0.4
Aquaculture	940	11,500	3,100	180	1,690	17,410	0.8
Household	16,600	25,900	48,400	27,700	15,400	134,000	6.0
Industry	170	2,520	4,860	1,270	6,280	15,100	0.7

development policy run by the National Economic and Social Development Board (NESDB) (1982).

Environmental problems associated with the Bang Pakong River and its tributaries are attributable to insufficient wastewater collection and treatment, as well as the

intensive development of livestock and agriculture (Molle et al. 2009; Simachaya 2003).

As a consequence of diverse and intensive land use, PCD (2002) reported that high nutrient levels from pig farming have severely impacted water quality in this area.

PCD has consequently monitored the water quality four times annually in the three rivers (Bang Pakong, Nakhonnayok, and Prachinburi River) since 1991. Nitrogen (in the form of  $\text{NO}_3\text{-N}$ ,  $\text{NO}_2\text{-N}$ , and  $\text{NH}_3\text{-N}$ ) and total phosphorus increased during the period from 1993 to 2008 (PCD 2010). Algal bloom and associated oxygen depletion has led to high fish mortality (fish kills) (ONEP 2006; PCD 2007).

## Method

As mentioned in the introduction, the method applied here is land use analysis combined with MMFA. The MMFA method provides a systematic description and modeling of the mass and substance flows through a system (Huang et al. 2007; Kwonpongsagoon et al. 2007; Neset et al. 2008, 2010; Schaffner et al. 2009a, b; Erni et al. 2011; Malde et al. 2011; Schaffner et al. 2011; Kenway et al. 2013). Such a systematic description is crucial in order to quantify the sources, pathways, and discharge of substances such as nutrients in a catchment. The approach is as follows:

1. For each province, the land use, urbanization, and industrialization were spatially analyzed and used as the basis for the MMFA system analysis as described in more detail in the section on land use analysis and MMFA system analysis.
2. For each province, the modified mathematical model of Schaffner et al. (2009a) for the Tha Chin River was applied, leading to provincial loads from agriculture, animal farming, households, and industries.
3. These provincial loads were then downscaled to specific loads per hectare, per animal, per household, and per industry.
4. The specific loads (loads per hectare and year) were used to estimate the spatially distributed loads according to the agricultural areas, animal farms, household density, and spatial distribution of the industries in the province. More details are given in the “[Land Use and MMFA System Analysis](#)” and “[Data Collection and Calibration](#)” sections.

### Land Use and MMFA System Analysis

The system borders are the hydrological boundaries of the Bang Pakong catchment area, see Fig. 1. The general characteristics of the land use are described in the “study area” section. The result is presented in Fig. 2b.

For the MMFA system analysis, the flows relevant for nutrient pollution have to be investigated for each component of Table 1. Since all nine components, namely (1) Rice, (2) Field crops, (3) Fruit and vegetable, (4) Water

plants, (5) Pig farming, (6) Poultry farming, (7) Aquaculture, (8) Households, and (9) Industry, had already been analyzed for the Tha Chin River by Schaffner et al. (2009a), their flow scheme could be used without any further change. The MMFA scheme is shown in Fig. 2a. As can be seen in that figure, nutrients enter the agricultural components (rice, field crops, fruit and vegetable, and water plants) via fertilizer and irrigation water and are discharged to the river via drainage. Nutrients enter the animal farming components (pig, poultry, and aquaculture) by feed and water input. Nutrient discharge is again via drainage and direct discharge. Food is the carrier of nutrients to humans and material input for industries. Nutrients from humans and industries are discharged to the river in treated or untreated wastewater.

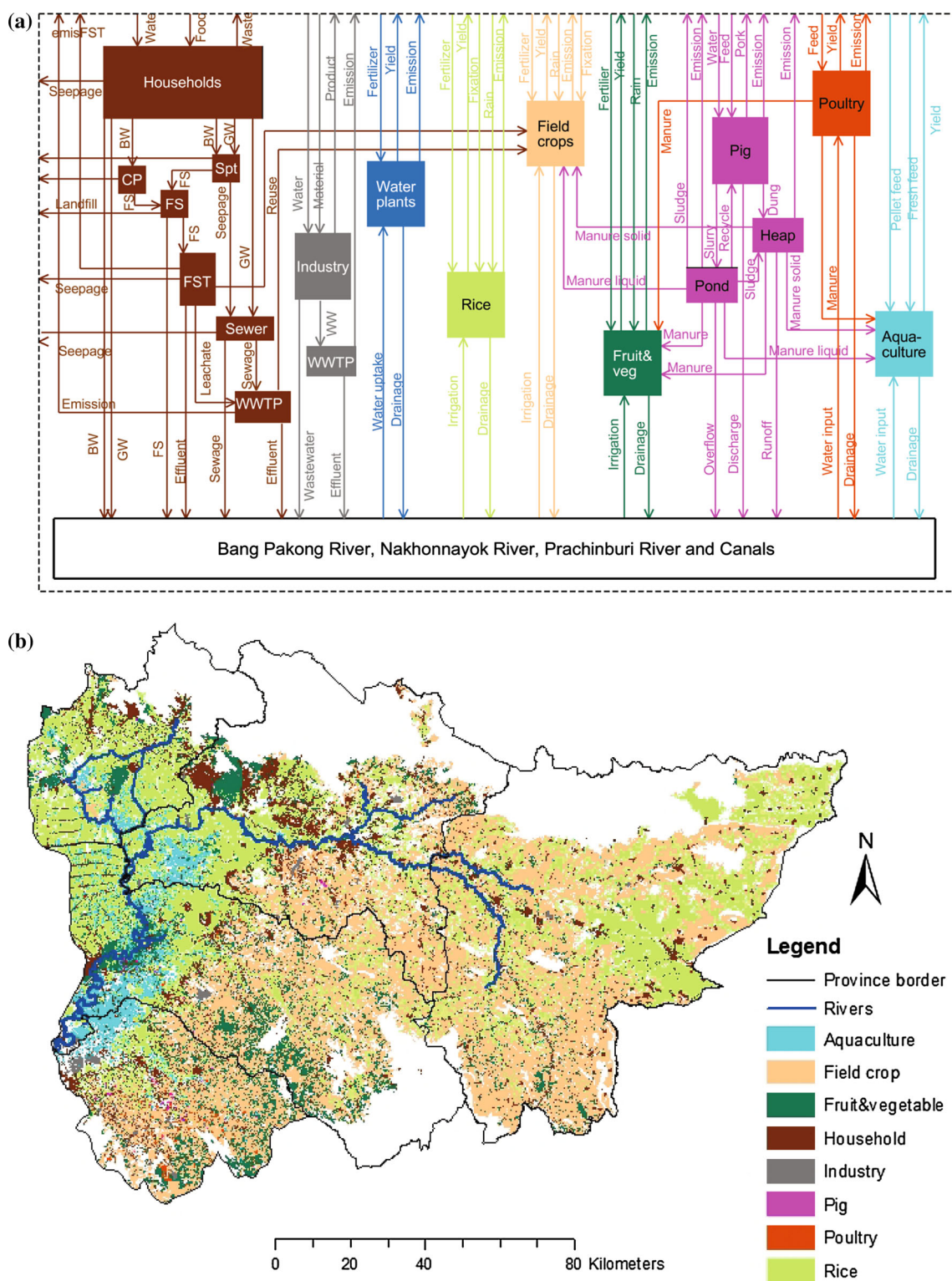
For a land use map corresponding to the MMFA system analysis and scheme mentioned above, a large land use database of a GIS map for ecosystem management in BPB, which was derived from ONEP (2006), was analyzed in this study. All data corresponding to those components stated in Table 1 and shown in the MMFA scheme (Fig. 2a), such as livestock raising area, crop planting area, and aquaculture area, were extracted, manipulated, and re-grouped for the different components for this study. Ultimately, the spatial distribution of the land use map according to the MMFA scheme was created as shown in Fig. 2b.

The MMFA scheme shown in Fig. 2a can either represent the whole catchment area, the single provinces or even smaller spatial units depending on the approximation level. In this study, the approximation level was constituted by the provinces, as described above. Therefore the boxes and flows shown in Fig. 2a represent the components for the single provinces, e.g., the “rice” box represents all the rice fields of the province, including their water and nutrient stocks. Similarly, the flows into and out of the “rice” box represent the water, fertilizer, and rice flows, including the nutrient flows.

### Model Approach: Material Flow Model

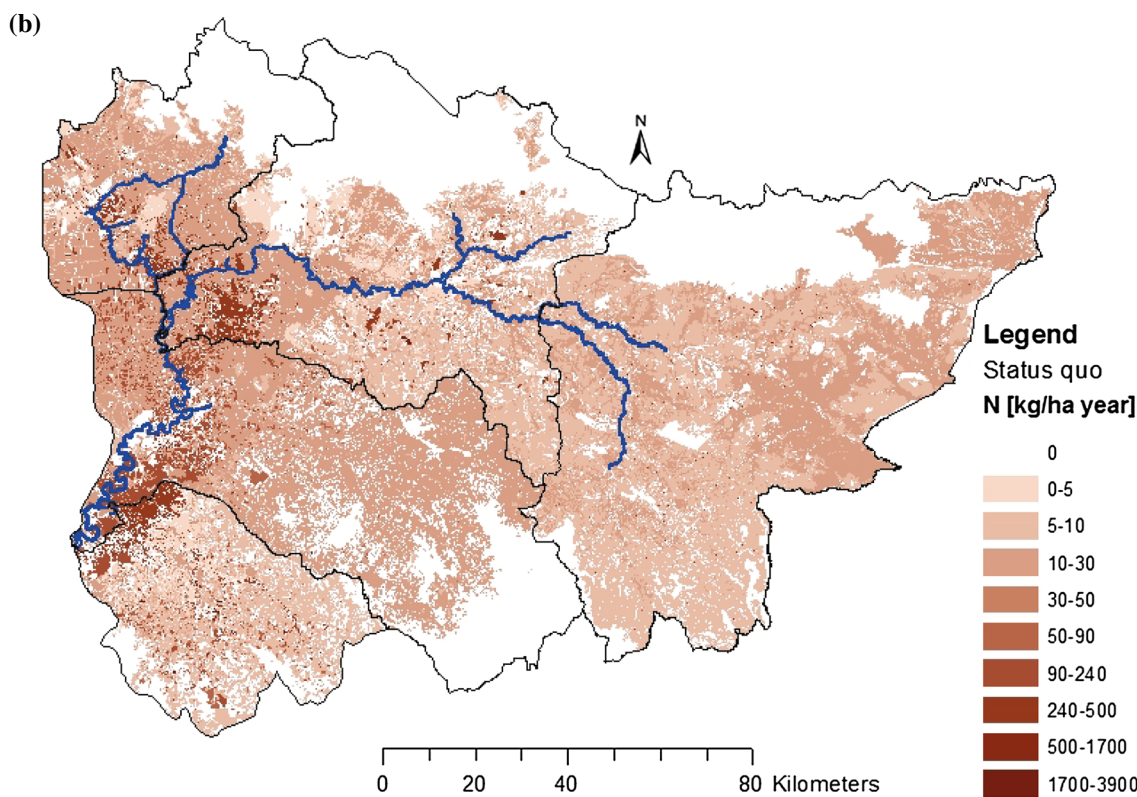
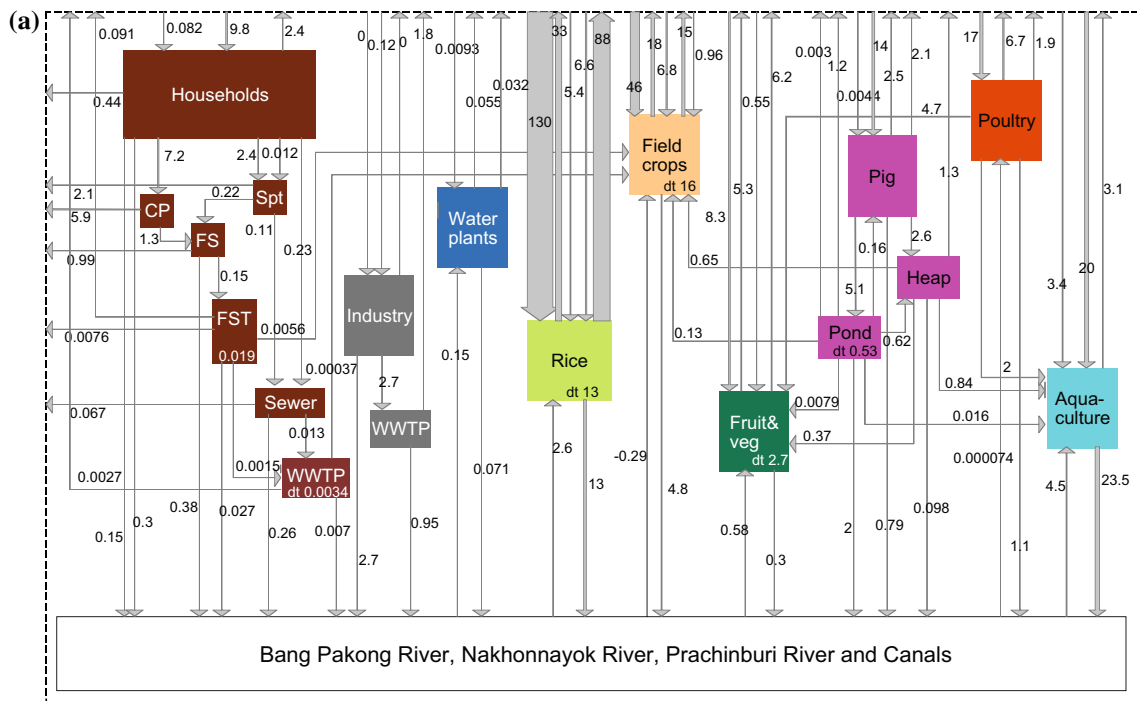
The approach chosen is stationary, since in a first step, we are interested in yearly discharges to the river. A dynamic approach would clearly be needed to simulate the discharges and concentrations, and in particular the peak loads, as a function of time. However, this is not the focus of the present study. Schaffner et al. (2009a) developed a mathematical material and substance flow model for the material flow scheme of Fig. 2a. In this model, a set of non-linear equations describes the water, food, fertilizer etc., flows, including their nutrient flows. The basis for formulating the equation was a system understanding gained via intensive field research by Monika Schaffner during 2005–2006 in





**Fig. 2** Result of system analysis in Bang Pakong Basin: **a** traditional MMFA system analysis, **b** spatial distribution of land use according to the components in Table 1 (note that forest is not shown). The colors in both figures represent the same components. The following

abbreviations were used in the household components: black water (BW), gray water (GW), septic tank (spt), cesspool (CP), fecal sludge (FS), fecal sludge treatment (FST), wastewater (WW), wastewater treatment plant (WWTP), sludge (sldg) (Color figure online)



**Fig. 3** Nitrogen load to Bang Pakong Basin (BPB). **a** material flow scheme showing total N flows [1,000 t/year] within the total basin. **b** spatial net loads [kg N/ha year] per land use in each province

Thailand. In this field campaign, all nine components were studied intensively through literature studies, field visits, discussions with farmers and experts, and own measurements if necessary (e.g., measurements of water discharge

and concentrations in the main river as well as in small side rivers and canals). The model equations describe, (a) demands (such as the food and water demand for animals), (b) agricultural management practices (such as

**Table 2** Simulation results for the nutrient (nitrogen and phosphorus) loads to the BPB (total loads, NET loads, and specific NET loads) for the year 2005

Subsystem	Specific amount	Unit	Nitrogen			Phosphorus		
			Total load to surface waters (t N/year)	NET load to surface waters (t N/year)	Specific NET load (kg N/ha * year)	Total load to surface waters (t P/year)	NET load to surface waters (t P/year)	Specific NET load (kg P/ha * year)
Rice	544,000	ha	13,400	10,700	20	2,100	1,380	2.5
Field crop	559,000	ha	4,800	5,100	9.1	500	590	1.1
Fruit and vegetable	45,000	ha	300	−270	−	150	−	−
Total agriculture	1,148,000	ha	18,500	15,530	13.5	2,750	1,970	1.7
Pig	742,000	cap	2,940	2,930		920	910	
	1,470	ha			1,993			619
Aquaculture	17,400	ha	23,500	19,000	1,092	7,000	5,800	333
Poultry	16,320,000	cap	1,100	1,100		220	220	
	8,950	ha			123			25
Total livestock and aquaculture	−	−	27,540	23,030	−	8,140	6,930	−
Household	2,680,000	cap	1,100	1,100		380	380	
	134,000	ha			8			2.8
Industry	2,870	unit	3,700	3,700		960	960	
	15,100	ha			245			64
Total others	−	−	4,800	4,800	−	1,340	1,340	−
Total system	1,324,900	km <sup>2</sup>	50,840	43,360	32.7	12,230	10,240	7.7

fertilizer applied to rice), (c) input–output relationships (such as those between food and water, food and excreta or fertilizer runoffs), and d) relationships between nutrients and the related mass flow. Mathematically, these equations represent a parameterization of the flows and stock change rates of the scheme shown in Fig. 2a by a set of parameters. These parameters quantify either the demands (such as the amount of feed per animal) and the management practices (amount of fertilizer applied per hectare of rice) or the transfer coefficients (characterizing the input–output relationships) and the concentrations of the nutrients. A detailed description of the model equations, variables, and parameters can be found in Schaffner (2007) and Schaffner et al. (2009a, b, 2011). Based on the detailed land use analysis (“[Land Use and MMFA System Analysis](#)” section), the model of Schaffner et al. (2009a) had to be slightly adapted as follows: (i) field crops: eucalyptus trees replaced corn, (ii) fruit and vegetables: bananas replaced grapes and specific leafy vegetables were used instead of unspecific vegetables, and (iii) aquaculture: sea bass instead of snakehead fish. The equations for these different sub-compartments were the same; only the meaning of some parameters was different. The values of the parameters for the Bang Pakong River catchment were clearly different from those of the Tha Chin River and had to

be changed according to the data evaluation during the land use analysis (“[Land Use and MMFA System Analysis](#),” “[Data Collection and Calibration](#)” sections).

#### Data Collection and Calibration

Data have to be calculated to calibrate the model. The data collection (see more details below for parameter types and sources) together with the spatial databases for ecosystem management set up by the national government (ONEP 2006) was analyzed and re-grouped for different components in accordance with the MMFA system analysis in this study as shown in Fig. 2a. The corresponding spatial distribution of the area used among the nine compartments is presented in Fig. 2b. The parameter data of the material flow model for the provinces (such as amount of fertilizer for rice or amount of feed per animal, see “[Model Approach: Material Flow Model](#)” section above) were collected similarly as in Schaffner et al. (2009a).

The input data for these parameters are acquired from all available sources, published, and unpublished. These include a wide variety of secondary sources such as literature data, statistics at both local (provincial and district) and national level (e.g., DOAE 2005, 2007; DLD 2005;

OAE 2005; ONEP 2006; PCD 2003, 2005), farmer interviews, discussions with experts, and estimates. These parameters can be divided up into four groups: (1) production amounts (e.g., number of livestock raised, agriculture and aquaculture production, and crop planting areas) collected from both local and national statistics. When available, these values were verified by cross-checking with various government sectors: (2) the amount of fertilizer use, amount of feed for animals, and number of crops per year obtained from the literature, interviews, and discussions with local experts, (3) transfer coefficient is the fraction of nutrients transferred from a process to the environment, derived from Schaffner et al. (2009a), as well as specific local information, and (4) special information, namely the amount of water hyacinths in the waterways estimated on the basis of a specific study undertaken by two governmental sectors—the Thailand Pollution Control Department incorporated into the Royal Irrigation Department (PCD&RID 2004). Additionally, spatial land use databases of GIS mapping data for ecosystem management from ONEP (2006) were used to create a map for this study by analyzing and regrouping. For example, the area cultivated for rice was determined from spatial land use (ONEP 2006). The rice yields and number of crops per year were obtained from DOAE (2005) and DOAE (2007), and crosschecked with OAE (2005). The applied fertilizer amounts were derived from official recommendations, and then discussed and verified with local experts.

The MMFA model for the Bang Pakong River Basin was implemented using the SIMBOX simulation program (Schaffner et al. 2009a).

## Results and Discussion

### Simulation of the Current State

The compiled dataset and the material flow model were used to simulate the nutrient flows for the nine components in the five provinces. The flows of the five provinces can be added up, resulting in the flows for the whole catchment. Figure 3a and Table 2 show the results of the potential discharge for the whole catchment for the year 2005. The nutrient discharges into the river are of particular interest. Table 2 shows the total loads as well as the NET loads to the surface water. The total loads are the sum of all nutrient flows from the different sources to the surface water. The NET loads are the total loads minus all nutrient loads used from the river for the components as shown by the outflows from the river to the components in Fig. 2a. Table 2 consequently also presents the specific net loads per hectare and year, following directly from the net loads and the land use for each compartment in the catchment. (These land

uses are the result of the land use analysis presented in Fig. 2b.) The potential discharge of each unit in the catchment is obtained from the land use of each area unit as well as these specific discharge flows per hectare and compartment. The result is the spatial distribution of the nutrients potentially discharged into the river. Figure 3a gives a good overview of all relevant nitrogen flows presented in units of 1,000 tonnes per year in the Bang Pakong catchment area, as discussed below. As already noted, the nutrient discharges to the river are particular interest. If we look at the household box for instance (see Fig. 3a), it can easily be seen that nitrogen leaves the household in seven flows. The largest one carried 7,200 tons per year in black water to the cesspool. The septic tank received nitrogen from black water and gray water, accounting for 2,400 and 12 tons per year, respectively. About 150 tons per year in black water and 300 tons per year in gray water were directly discharged to the water bodies. Solid waste and seepage from the household carried nitrogen out of the system, accounting for 2,400 and 440 tons per year, respectively. Figure 3b presents the results for the net nitrogen loads per hectare and year. The corresponding results for phosphorous are shown in the Supplementary Information.

In principle, this approach should have been applied at single farm level. However, no data were available at this level, but only at an “average farm level” for the provinces. Parameters at “average farm level” were therefore used for these simulations. The variability between individual farms can be estimated on the basis of the uncertainty analysis.

Note that all flows into surface waters represent the potential discharge to these waters and therefore form the upper limits of the discharge into the main rivers. This is because the potential phosphorous sedimentation and nitrogen loss from the source to the river has been neglected. Indeed, Schaffner et al. (2009a) showed that phosphorous sedimentation is in the range of 20–60 %, and up to 30 % of the nitrogen can be lost by emissions.

### *Nitrogen and Phosphorous Flows*

Table 2 and Fig. 3a show that aquaculture (19,000 t N/year), followed by rice (10,700 t N/year) and field crops (5,100 t N/year), are the main nitrogen sources for the basin. The contribution of pig and poultry farms, fruits and vegetables, household, and industry together amounts to about 8,500 t N/year. Note that fruits and vegetables have a negative NET load since this subsystem takes up more nutrients from the irrigation water than it releases back to the water bodies. The most important sources of phosphorous are aquaculture (5,800 t P/year), followed by rice (1,380 t P/year), industry (960 t P/year) and pig farming



**Table 3** Land use and nutrient loads from areas adjacent to the main river in three different provinces

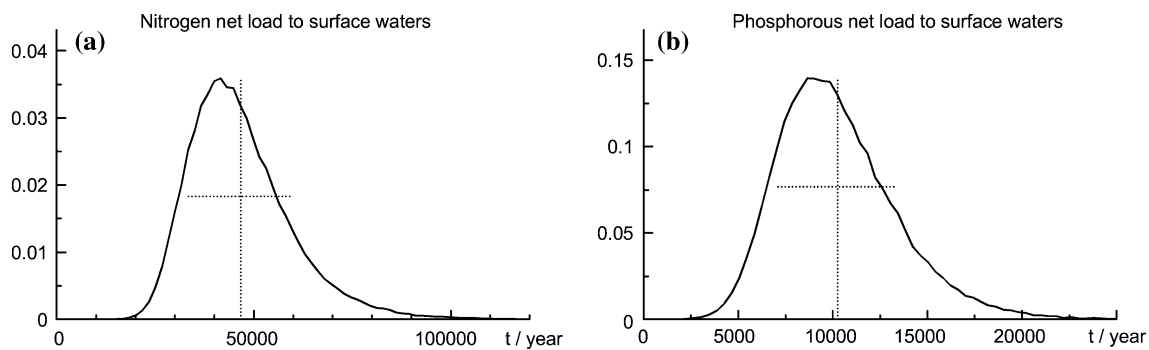
Province	Land use	Area agriculture		Nitrogen load			Phosphorous load		
		% area of province		% of total N in province			% of total P in province		
		10 km adjacent to river (%)	5 km adjacent to river (%)	Total province (%)	10 km adjacent to river (%)	5 km adjacent to river (%)	Total province (%)	10 km adjacent to river (%)	5 km adjacent to river (%)
Chachoengsao	Aquaculture	91	60	52	47	31	68	62	41
	Field crops	0	0	14	0	0	7	0	0
	Fruit & veg	23	21	-1	0	0	-1	0	0
	Household	49	32	2	1	1	4	2	1
	Industry	36	32	1	1	0	2	1	1
	Pig	74	55	7	5	4	10	7	5
	Poultry	34	14	1	0	0	1	0	0
	Rice	66	21	23	15	5	9	6	2
	Total	35	17	100	69	41	100	78	50
Prachinburi	Aquaculture	96	45	43	42	20	53	51	24
	Field crops	53	28	6	3	2	4	2	1
	Fruit & veg	70	27	-1	0	0	0	0	0
	Household	79	46	2	1	1	2	2	1
	Industry	83	51	20	17	10	20	17	10
	Pig	94	5	5	4	0	6	5	0
	Poultry	78	52	3	2	1	2	2	1
	Rice	90	56	22	19	12	13	12	7
	Total	75	43	100	88	46	100	90	45
Nakhonnayok	Aquaculture	95	85	65	62	56	74	70	63
	Field crops	85	70	0	0	0	1	0	0
	Fruit & veg	79	49	0	0	0	1	1	0
	Household	92	50	2	2	1	2	2	1
	Industry	70	43	1	0	0	1	0	0
	Pig	74	45	9	6	4	10	7	4
	Poultry	74	41	2	2	1	2	1	1
	Rice	101	54	20	20	11	11	11	6
	Total	96	55	100	93	73	100	92	76

(910 t P/year). The rest, namely field crops, poultry farms, and households, together contribute 1,190 t P/year. However, the picture is different as regards the potential discharge per unit area. It follows from Table 2 that pig farms show the highest values, followed by aquaculture. Nevertheless, pig farms do not dominate in the spatial maps because their total area is smaller than that of aquaculture by a factor of 12. The average specific net loads for agriculture are more than two orders of magnitude smaller than for pig farming. Their values are 14 kg N/(ha year) and 1.7 kg P/(ha year), which are much smaller than the average specific net loads for the whole catchment, which are 33 kg N/(ha year) and 7.7 kg P/(ha year), respectively.

Figure 3a shows also that the discharges of nitrogen in the nine compartments originate from fertilizer and food.

For instance, 240,000 t N/year in fertilizer and feed are used and 39,000 t N/year (16 %) are discharged into the river. For households, the input is about 10,000 t N/year in food and the discharge to the river is about 1,100 t N/year which is about 10 % of the input.

An important question is the geographical location of the nutrient sources. The spatial distribution map in Fig. 3b shows that nitrogen sources are present in the whole catchment (except the forest). However, Fig. 3b also indicates that the main polluters are located in areas adjacent to the river for about 10 km. Figure 2b shows that this zone is the main cultivation area for rice and aquaculture. The results of a more careful analysis for the three main provinces having the largest areas next to the main river are shown in Table 3. In the province of Prachinburi, for



**Fig. 4** Probability density distribution (*solid line*), and mean and standard deviation (*dashed line*) for **a** total NET N flow and **b** total NET P flow into the surface waters. The area under the *curve* is equal to 1

example, 46 and 88 % of the total nitrogen load originate from the areas adjacent to the main river within 5 and 10 km, respectively. Further away from the river, the specific net loads per ha and year are between 5 and 30 kg N/(ha year), which is below the catchment average of 32 kg N/(ha year). The details shown in Table 3 give us more comprehensive information at provincial level. In other words, the set of results in each province, including the percentage nutrient contributions, location, together with land use types, can provide better supporting information for nutrient management of the area. This would be useful for making any decisions as to where and what to focus on in the area.

#### *Spatially Referenced Mathematical Material Flow Analysis*

The MMFA schemes (Fig. 3a) and the spatial map (Fig. 3b) are complementary. The MMFA scheme shows all relevant flows aggregated for the provinces or the whole catchment. It allows the nutrient flows of the various compartments such as rice farming, animal farming, or households to be compared. In particular, the main sources for the discharges to the river can be identified and quantified. On the other hand, the spatial maps show the potential *specific* net loads to the surface waters per hectare and year as well as the geographically referenced intensity of the nutrient sources. Such maps complete the overall flow scheme, since they also show the geographical location of the main discharge sources in the catchment. It is now evident how the whole flow scheme, not only the discharge flows, can be spatially referenced: a corresponding spatial map can be allocated to each category of flows. By categories, we mean flows with a defined “purpose.” Examples are nutrient discharges, inputs such as fertilizer or feed, or product outflows such as rice, poultry, and fish. For the nitrogen discharge, the spatial map (Fig. 3b) shows the spatial distribution of the source intensity for potential discharges into the river.

This map corresponds to the output flows of all nine compartments in the flow scheme for the river (Fig. 3a). Figure SII presents the corresponding spatial map for the nitrogen input in food, feed, and fertilizer to the nine compartments of the flow scheme (Fig. 3a). A comparison of the “input” map (Supplementary Fig. SII) with the “discharge” map (Fig. 3b) shows the fraction of the input which is potentially discharged into the receiving water. This fraction is roughly 10 % except for the aquaculture (dark spots) in Fig. 3b, where the input and potential discharge are about the same. This is in agreement with the input-discharge ratios in the flow scheme shown in Fig. 3a.

#### *Uncertainty Analysis*

The previous sections showed the mean values of the calculated flows in all diagrams, tables, and discussions. This means that the variability by sources and locations has been neglected in the sense of the first approximation. However, as mentioned at the beginning of the section dealing with the “results and discussions,” an uncertainty analysis can be used to estimate the variability of the results between farms. Therefore, the uncertainty of the parameters represents the variability from farm to farm rather than the uncertainty of the data for a single farm. This variability has been estimated based on field observations and statistical data. The uncertainty analysis was carried out by Monte Carlo calculations for a sample size of 100,000. The mean value, the standard deviation, and shape of the distribution (normal, lognormal, or uniform) were estimated for each parameter on the basis of statistical data, literature data, and expert knowledge acquired during data collection. This information uniquely defines the distribution of each parameter. The Monte Carlo calculation then determines the distributions of the various flows, such as loads. The results are shown in Fig. 4 for the total net N and P flows into surface waters.

**Table 4** Parameters changed for the four scenario calculations

Scenario	Parameter name	Parameter values for status quo	Parameter assumed for scenarios
(1) Drainage reduced during harvest of aquaculture	TC harvest Tilapia	0.50	0.25
	TC harvest Shrimp	0.96	0.48
	TC harvest Catfish	0.93	0.47
	TC harvest Seabass	0.67	0.36
(2) Reduce fertilizer to recommended value, improve water management during rain	NPK fertilizer	213	200
	Urea fertilizer	190	150
	Runoff surplus rain	0.43	0.2
(3) Increase of manure collection, treatment of all wastewater in pig farms (including slaughterhouses)	TC slurry collected to pond	0.65	0.76
	TC leaching of pond	0.10	0.05
	TC farm separating dung to heap	0.80	0.99
	TC runoff from heap	0.05	0
	TC reuse pond water and effluent AD	0.06	0.99
(4) Increase of manure collection in connection with commercial poultry production and its use for crops	Manure collected and sold	0.875	1

*TC* transfer coefficient, *AD* anaerobic digester

The percentiles can be determined from these distributions. For instance, the statistical probability that the N and P flows are below 56,100 and 12,700 tonnes per year, respectively, is 80 %, and the figure for below 63,500 and 14,400 tonnes per year, respectively, is 90 %. The 5–95 % confidence interval is between 29,000 and 71,000 tonnes per year for the total N-load, and between 5,900 and 16,000 tonnes per year for the total P load. These values, referred to the average, clearly also apply to the load maps for nitrogen and phosphorus. As already pointed out by Schaffner et al. (2009a), rather large uncertainties are typical for material flow studies and do not allow the individual pollution sources to be simulated very accurately. However, this is not the focus of these studies. They aim to quantify and understand the range of the flows and loads in order to identify and classify the origin of the pollution in a specific catchment.

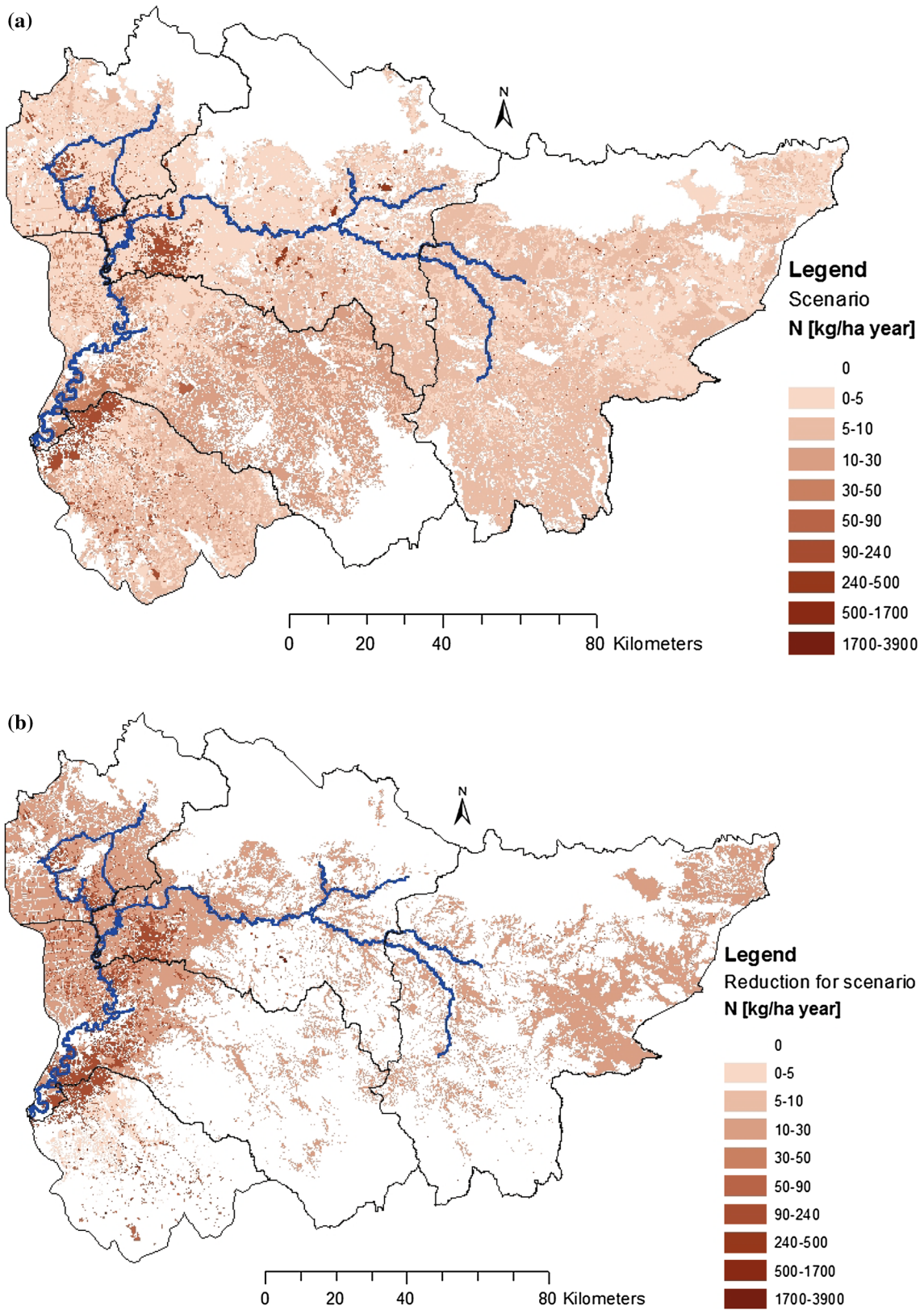
#### Scenarios

A scenario analysis was performed for the Bang Pakong catchment using the most sensitive parameters determined by a sensitivity analysis (more details in Kwonpongsagoon et al. 2007; Schaffner et al. 2009a). Only “realistic” changes were considered for each parameter. The “realistic” range for the parameters was defined in interviews with farmers and experts. It turned out that the following four possible measures, and in particular their combination, would reduce the loads dramatically.

(1) Reduction of nutrient transfer in drainage during aquaculture harvesting. More details of this scenario can be seen in Wittmer (2005). This measure was first chosen as the

results of our MMFA calculation in the previous section (see “Simulation of the Current State” section for the nitrogen and phosphorus flows) showed that the current aquaculture practice is the main nitrogen and phosphorus source in the basin. Neither emission control (treatment) nor good aquaculture practices have yet been applied proactively in Thailand. (2) Reduction of fertilizer application and runoff in rice cultivation. Again rice farming was shown to be one of the main polluters in the basin (see “Simulation of the Current State” section for the nitrogen and phosphorus flows). So this could be another potential measure for this area. (3) Increase of manure collection, including collection and treatment of all wastewater in pig farms (including slaughterhouses). Our study found that the emission-control technology of the pig farms in the BPB is quite different from that applied in the Tha Chin Basin. Several measures to improve the pollution treatment were applied in the Tha Chin Basin, such as a closed system of manure collection to produce biogas. In contrast, the BPB uses only a simple pond to collect the manure, dry it out, and let it degrade naturally or be discharged to the surface water. And (4) Increase of manure collection in connection with commercial poultry production and its use for crops. This scenario was considered since our discussion with farmers reveals that they would prefer to use poultry manure as a fertilizer for their crops. It would therefore be useful to increase the rate of waste recycling and selling in this basin. Table 4 shows the parameters changed for the four scenario calculations (see Appendix).

According to the simulation results for each condition mentioned above, Scenario 1 shows the highest potential reduction of nutrients (N and P), accounting for 27 and



**Fig. 5** **a** NET nitrogen load [kg per year] to Bang Pakong Basin (BPB) for the combined scenarios, **b** reduction of net nitrogen flows for the combined scenario



34 %, respectively. This reduction is due to the largest nutrient contribution during aquaculture harvesting in the basin as seen in the MMFA current state simulation. In Scenario 2, the result indicated that only nitrogen can be reduced by about 23 %, which is not much compared to the Tha Chin Basin (see Schaffner et al. 2009a). This is because the application of fertilizers in the BPB is lower than the guideline values suggested to farmers for different types of crops. Only in Chachoengsao, Prachinburi, and Sakaeo provinces, the use of fertilizer is slightly higher. In Scenarios 3 and 4, both measures also show a potential to reduce N and P flows at the pig farms (7 % for N and 6 % for P) and poultry farms (2 % for both N and P), respectively.

#### *Results for the Combined Scenarios 1–4*

The calculations for the whole basin show that the potential reduction would be about 60 % for nitrogen, namely from 43,300 to 18,200 tonnes per year, and about 42 % for phosphorous, namely from 10,300 to 6,000 tonnes per year. This reduction is presented for the case of nitrogen in geographically referenced terms in Fig. 5. The highest reduction is along the river in the western part of the basin where rice and aquaculture dominate. As an example, the area with nitrogen loads exceeding 240 kg/(ha year) is reduced from 42,000 to 5,900 ha. The advantage of the spatial map presentation is that it shows the area in which specific loads would be reduced and not only the total reduction for the whole catchment area, as shown in the MMFA schemes.

Such maps can serve local government agencies as follows: (1) to identify the geographical areas of the main contributors, (2) as a basis for discussions with stakeholders of possible measures, and (3) to select locations where reduction is feasible and realistic. For instance, it might be reasonable to take measures only for locations closer to the main rivers, but not for remoter areas.

This geographically referenced analysis goes beyond that of Schaffner et al. (2009a) who studied only the provinces as a whole.

#### **Conclusions**

The analysis has shown that 70 % of the NET nutrient contribution in the Bang Pakong river catchment area came from aquaculture and rice paddy fields. The key nutrient inflows to aquaculture and rice are carried by feed (pellet and fresh feed) and fertilizer, respectively.

In geographical terms, most polluters are located along the main rivers (Bang Pakong, Nakhonnayok and Prachinburi). The material flow analysis combined with the spatial

land use analysis has shown that a dramatic reduction of the net nutrient discharge of about 50–70 % would require changes in the management practices of aquaculture, rice, pig, and poultry production (reduction of fertilizer and nutrient transfer). In a geographical sense, this change would make sense for non-point sources such as rice, principally along the main rivers. For aquaculture and pig farms, which are often located along small canals, the measure should be applied across the whole catchment area. To change anything, it would be much easier to do something with either the pig farms or poultry farms, since they resemble point sources. Aquaculture involves the problem that nutrients as well as all other substances are already in the water or sediment (in close contact with the water).

The presented results are a first approximation since “average farm level” data were used instead of data at single farm level. The variability from farm to farm was discussed based on uncertainty calculations. Clearly also the suggested measures apply at the “average farm” level, for instance, the measure is applied to certain farms and not to others, depending on the level of nutrient flows and management. Applying the procedure to single farm level would require the following: (a) data from all single farms concerning the nutrient flows, and (b) the automatization of the MMFA modeling of the farms. Task (a) would be a tremendous amount of work whereas task (b) would be relatively simple (running the model in a batch mode). The other limitation of the study is the stationary approach, leading to yearly discharges to the water bodies. To discuss also peak loads and discharges in function of time, the model would have to be formulated dynamically requiring also time series rather than yearly average values.

This study has shown that the spatially referenced MMFA, i.e., the combination of the material flow analysis approach with spatial land use analysis yields the following main benefits: (1) it shows not only the overall nutrient flows, but also their spatially distributed contributions, (2) possible mitigation measures can also be discussed with regard to their spatial location, (3) spatial maps of pollutant flows are much more attractive to local stakeholders than overall schemes since they can easily identify themselves with their local area, and (4) the overall system understanding of the material flow analysis is extended to a geographically referenced context.

**Acknowledgments** The authors would like to thank Monika Schaffner for the use of her model of the Tha Chin River Basin. Many thanks also go to M. Bader for carefully checking the maps. This research work is supported in part by a Grant from the Center of Excellence on Environmental Health and Toxicology, the Science & Technology Postgraduate Education and Research Development Office (PERDO), Ministry of Education. This study was partially supported for publication by the China Medical Board (CMB), Faculty of Public Health, Mahidol University, Bangkok, Thailand.

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