

Title	Transition of human and livestock waste management in rural Hanoi: a material flow analysis of nitrogen and phosphorus during 1980–2010
Author(s)	Pham, Huong Giang; Harada, Hidenori; Fujii, Shigeo; Nguyen, Pham Hong Lien; Huynh, Trung Hai
Citation	Journal of Material Cycles and Waste Management (2017), 19: 827-839
Issue Date	2017-4
URL	<a href="http://hdl.handle.net/2433/245758">http://hdl.handle.net/2433/245758</a>
Right	This is a post-peer-review, pre-copyedit version of an article published in 'Journal of Material Cycles and Waste Management'. The final authenticated version is available online at: <a href="https://doi.org/10.1007/s10163-016-0484-1">https://doi.org/10.1007/s10163-016-0484-1</a> ; The full-text file will be made open to the public on 12 March 2017 in accordance with publisher's 'Terms and Conditions for Self-Archiving'; This is not the published version. Please cite only the published version. この論文は出版社版ではありません。引用の際には出版社版をご確認ご利用ください。
Type	Journal Article
Textversion	author

1 **Transition of waste management in rural Hanoi: A material flow analysis**  
2 **of nitrogen and phosphorus during 1980-2010**

3

4 Pham Huong Giang<sup>a</sup>, Hidenori Harada<sup>a, 1\*</sup>, Shigeo Fujii<sup>a</sup>, Nguyen Pham Hong  
5 Lien<sup>b</sup>, Huynh Trung Hai<sup>b</sup>

6 <sup>a</sup> Graduate School of Global Environmental Studies, Kyoto University,  
7 Yoshida-honmachi, Sakyo, Kyoto, 606-8501 Japan

8 <sup>b</sup> School of Environmental Science and Technology, Hanoi University of  
9 Science and Technology, No 1, Dai Co Viet street, Hanoi, Vietnam

10

11 \*Corresponding author: Hidenori Harada, Überlandstrasse 133, CH-8600

12 DübendorfCH-8600 Dübendorf, Switzerland (E-mail:

13 hidenori.harada@eawag.ch, Tel: +41 58 765 5909)

---

<sup>1</sup> Present address: Eawag, Swiss Federal Institute of Aquatic Science and Technology, CH-8600 Dübendorf, Switzerland.

14 **Abstract**

15 Human and livestock excreta were intensively used as a source of nutrients in  
16 crop cultivation in Asia over the years. However, rapid economic growth  
17 induced changes in waste management and subsequently in nutrient flow.  
18 Recently, chemical fertilizers became a more popular source of nutrients than  
19 human and livestock excreta. In northern Vietnam, a large amount of human  
20 and livestock excreta have been traditionally applied to paddy fields, but much  
21 of them are not used currently and especially a significant amount of the latter  
22 is discharged directly into ponds for fish farming. Fish ponds, in this context,  
23 may play an important role for waste management and material cycle in the  
24 area. This study investigated the historical changes in waste management and  
25 clarified the impact of fish ponds on those changes as a case study in an  
26 agricultural community in suburban Hanoi, Vietnam. A material flow model of  
27 nitrogen and phosphorus was applied to the study area. The results showed that  
28 the crop-livestock system that intensively used human and livestock excreta in  
29 the area changed between 1980 and 2010, which led to an increase of pollution  
30 loads to open water body. In 2010, nitrogen and phosphorus loads to open  
31 water body were 1.9- and 3.2-fold higher, respectively, than those in 1980.  
32 Nutrients inputs to fish ponds were 41.7 kg-N·ha<sup>-1</sup> and 9.8 kg-P·ha<sup>-1</sup> in 2010;  
33 these values were 7.2- and 6.2-fold higher than those in 1980, respectively.

34 Beside, 41% of nitrogen and 82% of phosphorus released to fish ponds still  
35 remained in the sediment or discharged unintentionally after a heavy rainfall.  
36 As a conclusion, the system was transformed from crop-livestock system into  
37 crop-livestock-fish system, and fish ponds has play a role of nutrient sink in  
38 the system. The use of pond sediment as a source of nutrients in paddy fields  
39 would improve the material cycle.

40

41 **Keywords:** material flow analysis, fish pond, historical changes, nitrogen,  
42 phosphorus.

## 43 **1. Introduction**

44 Human and livestock excreta was widely used as a source of nutrients in  
45 crop cultivation in Asia over the years, and the system that involved the  
46 intensive use of human and livestock excreta as a source of nutrients in crop  
47 cultivation was called crop-livestock system (Berg, 2002; Devendra and  
48 Thomas, 2002; Edwards *et al.*, 1990). However, rapid economic growth  
49 induced changes in waste management and subsequently in nutrient flow. In  
50 northern Vietnam, chemical fertilizers recently became more popular than  
51 human and livestock excreta as a source of nutrients. While human excreta are  
52 currently preferred to be treated in septic tanks, a large amount of livestock  
53 excreta is released into fish ponds for fish farming although a significant  
54 amount of them are still used for agriculture. Crop-livestock system is likely  
55 to be replaced by crop-livestock-fish system.

56 Since farming activities changed and likely affected material balance, it is  
57 required to understand the transitions of waste management manners and  
58 clarify the impact of fish ponds on those transitions from the aspect of  
59 pollution control and nutrient management. Recently, several studies have been  
60 conducted using material flow analysis (MFA) that is a systematic tool for  
61 quantifying flows and stocks of materials within a well-defined system in  
62 space and time (Brunner and Rechbenger, 2004). Yan *et al.* (1999) and Chen *et*

63 *al.* (2008) applied MFA to estimate nutrient budget in agricultural systems and  
64 their environmental impact in China. Briggs and Fvng-Smith (2008) applied  
65 MFA to estimate nutrient balance in shrimp ponds in Thailand. Similarly,  
66 Montangero *et al.* (2007), Harada *et al.* (2010), and Nga *et al.* (2011) applied  
67 MFA to develop nutrient flows and estimate nutrient loads delivered to the  
68 environment in northern Vietnam.

69 Although material balances of farming activities likely changed in many  
70 Asian countries, due to the rapid socio-economic development, previous  
71 studies focused on current waste and nutrient management and evaluated their  
72 impact on environmental pollution at a specific time. Little is known about the  
73 role of fish ponds in a system along with the historical changes in waste  
74 management, and subsequently in nutrients flow. The objective of this study  
75 was to understand the historical changes in waste management from 1980 to  
76 2010 and the impact of fishponds on the nutrient management and water  
77 pollution by a material flow model of nitrogen (N) and phosphorus (P).

78

## 79 **2. Materials and methods**

### 80 **2.1 Study area**

81 The study area was Trai hamlet, Phu Xuyen district, which is 40km south  
82 of central Hanoi, the capital of Vietnam and extends approximately 1 km along

83 the bank of the Nhue River (**Figure 1**). This hamlet is located at a typical  
84 suburban agricultural district, where farming is the main occupation of locals  
85 and rice is the dominant crop. Paddy fields, which did not change in area from  
86 1980 to 2010, cover more than 90% of the total area. Nhue river is a main  
87 irrigation source for paddy fields in the area. Some general information on Trai  
88 hamlet is summarized in **Table 1**.

89

90 (**Figure 1** Map of Hanoi and Trai hamlet)

91

92 (**Table 1** General information in the study area)

93

94 Recently, rapid socio-economic development and modernization in this  
95 area led to changes in farming systems. Along with crop cultivation and small-  
96 scale livestock breeding, fish farming has been practiced in many households.  
97 The hamlet has 21 ponds, which were originally excavated prior to 1980 to  
98 obtain soil materials to construct dikes (Local socio-economic report, 2010).  
99 The area of the ponds has not changed from 1980 to 2010 and out of 21, 18  
100 ponds are currently utilized for fish cultivation. At the beginning of fish  
101 farming season, water from irrigation channel is used to fill up the ponds  
102 before adding new fish stock. Livestock excreta are these days commonly

103 discharged to these ponds along with commercial fish feed. When fish are  
104 harvested, pond water flows back into the irrigation channels and ends up to  
105 the Nhue River. After fish harvesting, a new fish-farming season starts.

106

## 107 **2.2 Material flow model**

108 A material flow model for N and P was developed based on Harada *et al.*  
109 (2010) and applied to the study area for nutrients balance flows from 1980 to  
110 2010. Conceptual framework of the model was illustrated in **Figure 2**. The  
111 model is composed by eight components ( $X_j$ ), of which household ( $X_1$ )  
112 including two sub-components: septic tanks and biogas systems, livestock  
113 (pigs, poultry, and cattle) ( $X_2$ ), fish pond ( $X_3$ ), and paddy field ( $X_4$ ) are within  
114 the boundary, while market ( $X_5$ ), open water bodies including Nhue river and  
115 drainage systems ( $X_6$ ), soil/ground water ( $X_7$ ), and atmosphere ( $X_8$ ) are out of  
116 the boundary. The arrows represent for the flows/reaction processes of relevant  
117 goods such as human excreta, livestock excreta, chemical fertilizers, etc.  
118 transferred from one component to other components. Within the system, the  
119 net reaction rate of a single component may be affected by a number of  
120 different input or output processes. Based on the principle of Mass  
121 Conservation Law, the net reaction rate for a component inside the boundary is  
122 considered to be the mass balance:



123 
$$\sum_1^n I_i = \sum_1^m O_j \quad (\text{Eq.1})$$

124 Most of flows can be calculated by unit value method:

125 
$$I_i = \sum(U_k \times C_k \times R_k) \quad (\text{Eq.2})$$

126 
$$O_j = \sum(U_l \times C_l \times R_l) \quad (\text{Eq.3})$$

127 where  $I_i$ : an input flow of a component (g/ha/year)

128  $O_j$ : an output flow of a component (g/ha/year)

129  $U_k, U_l$ : composition of good  $k, l$  (g/unit amount/year)

130  $C_k, C_l$ : amount of good  $k, l$  (amount)

131  $R_k, R_l$ : ratio of good  $k, l$  transferred from a component to another  
 132 component.

133  $n, m$ : total number of input and output flows of a component

134 The flow which could not be calculated by unit value method was calculated

135 based on mass conservation law:

136 
$$I_i = \sum_1^m O_j - (\sum_1^{i-1} I_i + \sum_{i+1}^n I_i) \quad (\text{Eq.4})$$

137 Thus, the details description of each reaction process of the material flow  
 138 model is shown in **Table 2**.

139

140 **(Figure 2 A flow model in the study)**

141 **(Table 2 Description of reaction processes of the material flow more via**  
 142 **matrix expression)**

143 **2.3 Data collection**

144 **2.3.1 Characterization of fish ponds**

145 All the 18 fish ponds owners were interviewed on daily activities and  
146 management practices, including the intensity of excreta use and the frequency  
147 of water exchange. Each interviewee was asked to describe the current (in  
148 2010) and past activities around 1980, 1990 and 2000, and the answers were  
149 used as data in 2010, 1980, 1990 and 2000, respectively. Also, all the fish  
150 ponds were surveyed from October to November 2012 to identify the pond  
151 shape, depth, area, and water quality. Pond shape was marked using on-site  
152 Global Positioning System (GPS) plotting and then pond area was calculated  
153 using a Geographical Information System (GIS). Pond depth was measured by  
154 a flow rate meter (AEM213-D, JFE Advantech Co., Ltd) at the central point of  
155 the pond, in cases that it was accessible by boat. The depth of 11 ponds was  
156 measured, while for the other seven ponds information on the depth was  
157 collected from the interviewees due to the difficulties in accessibility. Water  
158 samples were collected from all ponds ( $n=18$ ) and irrigation canals ( $n=1$ ) to  
159 measure the total nitrogen and total phosphorus concentrations using Hach DR  
160 2800 and DRB 200 (Hach Ltd).

161

162

### 163 **2.3.2 Secondary data**

164 Secondary data that used in this study are presented in **Table 3**. Some of  
165 data were only available at a single year. Among these, greywater and kitchen  
166 waste composition had a larger possibility of the significant change but the  
167 impact of these composition change on the whole material balance was limited  
168 according to the sensitivity analysis of the model. Therefore, we assumed that  
169 data of waste composition did not change from 1980 to 2010. For the N and P  
170 concentration in the Nhue River water quality, although N and P concentration  
171 data in 2010 were available, the available oldest data were those in 2007 by  
172 VEA (2012). Since the socio-economic growth in the area has been  
173 accelerated from the middle of 2000s, we assumed that the concentrations had  
174 not changed significantly from 1980 to 2007; and the concentration data in  
175 2007 were used as those in 1980, 1990 and 2000, as the impact of N and P  
176 concentrations in 2007 was limited on the flows.

177

178 (Table 3 Secondary data used in the material flow model)

179

## 180 **3 Results and Discussion**

### 181 **3.1 Characteristics of fish ponds and harvesting manner**

182 The study area included 18 fish ponds and their characteristics are

183 presented in **Table 4**. Fish ponds regularly received greywater, kitchen waste,  
184 human excreta, livestock excreta, and commercial fish feed. When fish were  
185 harvested, pond water was pumped out to the irrigation channels. The  
186 frequency of fish harvesting ranged from zero to three times per year. However,  
187 in 1980, fish were harvested without water removal, probably due to the small  
188 scale of fish farming, and as a result, no water exchange occurred.

189

190 (Table 4 Characteristics of fish ponds in the study area)

191

### 192 **3.2 Historical changes in nutrients flow**

193 N and P flows in the study area are illustrated in **Figure 3** and **4**. The  
194 dominant input to the system was chemical fertilizer from market both with N  
195 and P flow in 1980 and 2010; dominant output from the system was paddy field  
196 runoff to open water bodies with N and soil accumulation and discharge with P  
197 both in 1980 and 2010. It was indicated that paddy fields, which cover more  
198 than 90% of the total area, played a major role in nutrient flow in the study  
199 area. Additionally, fish ponds covering only 6% of the total area had the  
200 highest contribution of P load to open water bodies.

201

202

203 (Figure 3 Flow of nitrogen in 1980 (left) and 2010 (right) ( $\text{kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ).

204 Abbreviations in the figure indicate as follows. Exc.: Excreta; F: Food; P:

205 Product; CF: Chemical fertilizer; Re.: Residue; Ir.: Irrigation; Acc. & Dis.:

206 Accumulation and Discharge; Ro.: Runoff; Em: Emission.)

207

208 (Figure 4 Flow of phosphorus in 1980 (left) and 2010 (right) ( $\text{kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ).

209 Abbreviations in the figure indicate as follows. Exc.: Excreta; F: Food; P:

210 Product; CF: Chemical fertilizer; Re.: Residue; Ir.: Irrigation; Acc. & Dis.:

211 Accumulation and Discharge; Ro.: Runoff.)

212

213 The biggest differences between N and P flows in 1980 and those in 2010

214 were the appearance of septic tanks and biogas systems in 2010, leading to the

215 changes of compost and manure recycling manners. As a custom in Vietnam,

216 the application of compost to paddy fields has a long history. In 1980, 97% of

217 total N and P from human excreta ( $25.8 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$  and  $3.8 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$

218  $\cdot\text{year}^{-1}$ ) were applied to paddy fields. Those ratios were decreased to 50% in

219 case of N and 49% in case of P in 2010. Instead of being used to intensively

220 apply to paddy fields, human excreta were flowed to septic tanks or fish ponds.

221 From the effects of modernization, 44% of households changed their traditional

222 dry chamber toilets to flush toilets connected to septic tanks in 2010. Similar

223 to compost, the recycling practices of manure have also changed remarkably.  
224 Although the amount of manure increase since the government has a policy of  
225 livestock production increase (ACI, 2002), the ratio of N and P derived-manure  
226 apply to paddy fields decreased from 54 and 80% in 1980 to 30 and 42% in  
227 2010. Instead, those to biogas systems or fish ponds were increased because  
228 biogas promotion program were implemented in 2006 in the study area (Dung  
229 *et al.*, 2009) and fishing activities became more popular in many households in  
230 2010. Indeed, under the modernization process, the farming system has  
231 changed from crop-livestock system to crop-livestock-fish one and fish ponds  
232 seemed to become more important in waste and nutrient management in the  
233 study area.

234 As shown in **Figure 5**, the differences in N and P loads to open water  
235 bodies were significant between 1980 and 2010. Total N and P load to open  
236 water bodies increased by 2.1- and 4.0-fold, respectively between 1980 and  
237 2010. In addition, N load derived from the paddy fields accounted for a large  
238 proportion of the total N load; 131.3 kg-N·ha<sup>-1</sup>·year<sup>-1</sup> in 2010, which was 1.8-  
239 fold higher than that in 1980. In contrast, fish ponds were the main contributor  
240 of P, which accounted for 59% of total P load to open water bodies. In 2010, P  
241 load from fish ponds to open water bodies was 6.2-fold higher than that in  
242 1980.

243

244

(**Figure 5** Nutrient inputs to open water bodies)

245

246

Thus, significant differences were observed between N and P balances.

247

The differences can be partly explained by the higher runoff ratio of N to

248

surface water and the larger proportion of P that is accumulated in the

249

sediment. (Carpenter *et al.*, 1998). The increase in N load from the paddy

250

fields was probably a result of the excessive application of N. As shown in

251

**Figure 3** and **4**, chemical fertilizers was already a major source of nutrients

252

than human and livestock excreta even in 1980. N input from chemical

253

fertilizers in paddy fields was  $174.3 \text{ kg}\cdot\text{ha}^{-1}$  in 2010, which was 1.3-fold higher

254

than that in 1980, and also exceeded the optimum levels ( $100\text{-}140 \text{ kg N}\cdot\text{ha}^{-1}$

255

$\text{year}^{-1}$ ; Huan *et al.*, 2000).

256

The dramatic increase in P load to open water bodies could be explained by

257

the increase in livestock excreta discharged into the fish ponds. **Figure 6**

258

shows the historical changes of P load derived from livestock excreta from

259

1980 to 2010. Based on the national policy on the increase of livestock

260

production (ACI, 2002), livestock number in the study area greatly increased in

261

2000 as presented in **Table 1**. Corresponding to this increase, P load from

262

livestock excreta in 2000 was 2.9-fold higher than that in 1980. A slight

263 decrease from 2000 to 2010 can be explained by poultry influenza H5N1 and  
264 pig diseases by porcine reproductive and respiratory syndrome virus. Practices  
265 of livestock excreta use for paddy field also changed significantly. The ratio of  
266 P flowed from livestock to paddy fields decreased from 80% in 1980 to 42% in  
267 2010; in contrast, the load to fish ponds and biogas system greatly increased. P  
268 input of livestock excreta to fish ponds in 2010 was 30-fold higher than that in  
269 1980. In 2010, livestock excreta were contributed  $3.9 \text{ kg P}\cdot\text{ha}^{-1}$  to fish ponds,  
270 which accounted for 40% of the total P load into fish ponds.

271

272 **Figure 6** Phosphorus (P) load derived from livestock excreta

273

274 Biogas promotion program in the Vietnam Livestock Sector, especially for  
275 pigs, was implemented in 2003 for suburban and rural areas, aiming to increase  
276 farm income and reduce environmental pollution (Dung *et al.*, 2009). This  
277 program was introduced to the study area in 2006, resulted in significant  
278 increase of the load from livestock to biogas system. However, in 2010, only  
279 16% of households breeding pigs had a biogas system to treat livestock excreta,  
280 and 53% of households discharged pig excreta into fish ponds. According to  
281 Vu *et al.*, (2010), some fish farmers in northern Vietnam breed pigs mainly to  
282 obtain excreta for their fish ponds because they believe that livestock excreta



283 help fish to grow faster than other feed. Thus, fish ponds likely received more  
284 P from livestock excreta.

285

### 286 **3.3 Historical changes in nutrient balance of fish ponds**

287 Differences in the nutrient balance of the fish ponds between 1980 and  
288 2010 are presented in **Table 5**. In 2010, the total nutrient input to fish ponds  
289 was 41.7 kg N·ha<sup>-1</sup>·year<sup>-1</sup> and 9.8 kg P·ha<sup>-1</sup>·year<sup>-1</sup>, which was 7.2- and 6.2-fold  
290 higher, respectively, than those in 1980. In 1980, when nutrient from  
291 household and livestock were intensively applied to paddy fields (**Figure 3, 4**  
292 **and 6**), nutrient inputs to fish ponds were mainly from commercial fish feeds.  
293 In 2010, livestock excreta became a source of feed for fish ponds together with  
294 commercial feed and accounted for 41% of the N and 40% of the P inputs.  
295 Although livestock excreta became the main source of nutrients for fish ponds,  
296 the nutrients derived from commercial fish feed increased rapidly too and was  
297 4.0- and 4.3-fold higher for N and P, respectively, in 2010 than in 1980.  
298 Nutrients in fish production were 8.5 kg N·ha<sup>-1</sup> and 1.3 kg P·ha<sup>-1</sup> in 2010, which  
299 accounted only for 20% and 13% of the N and P inputs, respectively. The  
300 results of this study were in accordance with those reported by Briggs and  
301 Fvng-Smith (2008), who reported that only 24% of nitrogen and 13% of  
302 phosphorus inputs were incorporated into shrimp harvest. Jackson *et al.* (2002)

303 also showed that shrimps could use only 22% of N input. The remaining N and  
304 P are either accumulated in the sediment or discharged intentionally during the  
305 removal of water from the pond and unintentionally after a heavy rainfall.

306

307 (Table 5 Nutrient balances of fish ponds in the study area)

308

309 Excessive application of nutrients to fish ponds led to the high  
310 accumulation in the sediment. If the sediment is used as a nutrient source in  
311 paddy fields, it may have a positive impact on not only nutrient management  
312 but also the control of water pollution; however, this practice was not popular  
313 in the study area. According to our interview, 61% of fish ponds never  
314 practiced sediment removal, 39% did at least once before, and only 11% did  
315 regular removal, every two or three years. Removed sediment were mostly  
316 used for the construction of dikes in the area. Only one out of 18 pond owners  
317 used the sediment as a vegetable fertilizer. Some recent studies investigated  
318 the possibility of utilizing the sediment as a crop fertilizer. According to  
319 Rahman *et al.* (2004), plants absorbed 62%, 67%, and 64% of available  
320 nitrogen, phosphorus and potassium in sediment, respectively. Phu *et al.*  
321 (2012) confirmed the possibility to use the sediment from catfish  
322 (*Pangasianodon hypothalamus*) ponds for paddy field fertilization. Thus, the

323 use of the sediment to paddy fields could be promoted for establishing better  
324 nutrient cycle and reducing water pollution in the area, especially of P, because  
325 of its higher accumulation in sediment compared to N.

326

#### 327 **4 Conclusions**

328 By developing a material flow model of nitrogen and phosphorus, this  
329 study showed the historical changes in nutrient flow of the study area and  
330 estimated the impact of fish ponds on these temporal changes. Due to  
331 modernization, farming systems changed from a crop-livestock system to a  
332 crop-livestock-fish system. As a result, traditional waste recycling manners  
333 changed and led to changes in material balance in the study area. Nitrogen and  
334 phosphorus loads in open water body gradually increased by 1.9- and 3.2-fold,  
335 respectively, from 1980 to 2010. In 2010, fish ponds were considered the  
336 largest contributor of phosphorus, which accounted for 71% of phosphorus  
337 load in open water body. The results show that fishponds play an important  
338 role in nutrient cycle within the study area, especially for phosphorus, because  
339 of its higher accumulation in the sediment than nitrogen.

340 Nutrient input into and accumulation in the fish ponds were highly  
341 increased from 1980 to 2010. A large amount of nutrients was estimated to  
342 remain in the sediment and to be released unintentionally after a heavy rain,

343 accounted for 41% and 82% of total nitrogen and phosphorus inputs in 2010,  
344 respectively. If sediments were applied in paddy fields, the application of  
345 equivalent amount of chemical fertilizers could be potentially reduced,  
346 accounting for 10% for nitrogen and 14% for phosphorus. It would not only  
347 improve a material cycle, but also would lead to an improved water quality in  
348 the study area, especially for phosphorus, because of its higher accumulation  
349 compared to nitrogen. Thus, fish ponds play a key role in material cycle and  
350 water pollution control in the area.

351

### 352 **Acknowledgments**

353 This study was funded by the Japan Society for the Promotion of Science,  
354 Grants-in-Aid for Scientific Research, KAKENHI (Research Projects:  
355 24254004 and 25870377).

356

### 357 **References**

358 Agrifood Consulting International (ACI), 2002. *Livestock Policy Briefs for*  
359 *Vietnam. Project Brief Series.*

360 Anh V T L, Toda H, 2005. Nitrogen and phosphorus concentration in rivers  
361 and wells in the Red River Delta, north of Vietnam. *Journal of Japan*  
362 *Society on Water Environment* **28**(8), 523-527.

363 Berg H, 2002. Rice monoculture and integrated rice-fish farming in the  
364 Mekong Delta, Vietnam-Economic and ecological considerations.  
365 *Ecological Economics*, 41, 95-107.

366 Boyd C E, 1995. *Bottom soils, sediment, and pond aquaculture*. Chapman and  
367 Hall, New York NY, pp 348.

368 Briggs M R P and Fvnge-Smith S J, 2008. A nutrient budget of some intensive  
369 marine shrimp ponds in Thailand. *Aquaculture Research*, 25, 789-811.

370 Brunner P H and Rechbenger H, 2004. *Practical handbook of material flow*  
371 *analysis*. Lewis Publishers pp318.

372 Busser S, Nga P T, Morel A and Anh N V, 2006. Characteristic and quantities  
373 of domestic wastewater in urban and peri-urban households in Hanoi. In:  
374 *Proceedings of the Environmental Science & Technology for*  
375 *Sustainability of Asia*, The 6th General Seminar of the Core University  
376 Program, Kumamoto, October 2-4, 2006.

377 Carpenter S R, Caraco N F, Correll D L, Howarth R W, Shrapley A N and  
378 Smith V H, 1998. Nonpoint pollution of surface water with phosphorus  
379 and nitrogen. *Ecological Application*, **8**(3), 559-568.

380 Chen M, Chen J, and Sun F, 2008. Agricultural phosphorus flow and its  
381 environmental impacts in China. *Science of The Total Environment*, **405**,  
382 140-152.

383 Devendra C, Thomas D, 2002. Crop-animal interactions in mixed farming  
384 systems in Asia. *Agricultural Systems*, **71**, 27-40.

385 Dung T. V., Hung H. V., and Hoa H. T. L., 2009. *Biogas user survey 2007-*  
386 *2008*. Biogas development Programme for Livestock Sector in Vietnam  
387 2007-2011.

388 Edwards C A, Lal R, Madden P, Miller R H and House G, 1990. *Sustainable*  
389 *agriculture systems*. Soil and Water Conservation Society, Ankeny IA, pp  
390 696.

391 FAO, 2003. Food energy-methods of analysis and conversion factors. *FAO*  
392 *Food and Nutrient Paper 77*, Rome, Italy, pp 87.

393 FAO, 2013. AQUASTAT database,  
394 <http://www.fao.org/nr/water/aquastat/main/index.stm> (accessed May16,  
395 2014)

396 Giang P H, Harada H, Fujii S, Lien N P H, Hai H T, Tanaka S and Kunacheva  
397 C, 2012. Waste and wastewater management and its impacts in a sub-  
398 urban community in Hanoi, Vietnam: A nitrogen and phosphorus flow  
399 analysis. *Environmental Engineering Research*, **68**(7), 741-749.

400 GSO, 2010. *Statistical Yearbook of Vietnam 2009*. Statistical Publishing  
401 House, Hanoi, Vietnam.

402 GSO, 2008. *Statistical Yearbook of Vietnam 2007*. Statistical Publishing House,

403 Hanoi, Vietnam.

404 GSO, 2004. *Vietnam Statistical Data in 20th Century*. Statistical Publishing  
405 House, Hanoi, Vietnam.

406 GSO & ISD, 2005. *Social-Economic Statistical Data of 671 Districts, Towns,  
407 and Cities under the Authority of Provinces in Vietnam*. Statistical  
408 Publishing House, Hanoi, Vietnam.

409 HSO, 2010. *Hanoi Statistical Yearbook 2009*. Hanoi Statistic Office, Hanoi,  
410 Vietnam.

411 Harada H, Adachi T, Fujii S, Lien N P H and Hai H T, 2010. Phosphorus flow  
412 analysis in Hanoi focusing on wastewater, agriculture, and stock breeding.  
413 *Environmental Engineering Research*, **47**, 465-474 (In Japanese).

414 Huan T N, Tan P S and Hiraoka H, 2000. Optimum fertilizer nitrogen rate for  
415 high yielding rice based on growth diagnosis in wet seeded culture of rice.  
416 In: *Proceedings of the 2000 annual workshop of JIRCAS Mekong Delta  
417 Project*, 60-68.

418 Huong L L, Thanh T T and Nga N T T, 2007. Eutrophication assessment and  
419 prediction of Bay Mau Lake using mathematical models. *VNU Journal of  
420 Science. Earth Sciences*, **23**, 116-121.

421 IPCC, 2000. *Good Practice Guidance and Uncertainty Management in  
422 National Greenhouse Gas Inventories*. IPCC National Greenhouse Gas

423 Inventories Program.

424 Jackson C, Preston N, Thompson P J, and Burford M, 2003. Nitrogen budget  
425 and effluent nitrogen components at an intensive shrimp farm,  
426 *Aquaculture*, **218**, 397-411.

427 Kawai K, 2007. *A proposal for the promotion of municipal solid waste  
428 recycling in Hanoi, Vietnam*. Ph.D Dissertation, Kyoto University, Japan.

429 Khanh H N, 2000. Air emission and the acidity of rainwater of Hanoi City.  
430 Global environment and nuclear energy systems-3 proceedings of the third  
431 international symposium. *Progress in Nuclear Energy*, **37**(1-4), 19-24.

432 Montangero A, Cau L N, Anh N V, Tuan V D, Nga P T and Belevi H, 2007.  
433 Optimizing water and phosphorus management in the urban environmental  
434 sanitation system of Hanoi, Vietnam. *Science of the Total Environment*,  
435 **384**, 55-66.

436 Montangero A and Belevi H, 2007. Assessing nutrient flows in septic tanks by  
437 eliciting expert judgment: A promising method in the context of  
438 developing countries, *Water research*, **41**(5), 1052-1064.

439 Ministry of Education, Culture, Sports, Science, and Technology, Japan, 2008.  
440 *Teizouho nihon shokuhin hyoujyun seibunhyou*, Tokyo, Japan (In  
441 Japanese).

442 Nakamura M and Yuzuyama Y, 2005. Development of biomass database,



443        *Noukoukengihou*, **203**, 57-80 (In Japanese).

444    Nga D T, Antoine M, Hung N V, Phuc P D, Kei N and Thamarat K, 2011.

445        Assessing nutrient fluxes in a Vietnamese rural area despite limited and

446        highly uncertain data. *Resources, Conversation, and Recycling*, **55**, 849-

447        856.

448    Nhan D K, Verdengem M C J, Milstein A and Verreth J A V, 2008. Water and

449        nutrient budgets of ponds in integrated agriculture-aquaculture systems in

450        the Mekong Delta, Vietnam. *Aquaculture*, **39**(11), 1216-1228.

451    Phu T. Q., Tinh T. K., Giang H. T., 2012. Possibility to reuse Pangasianodon

452        Hypophthalmus fish ponds for agriculture. *Journal of Science and*

453        *Technology* **24a**, 135-143.

454    Rahman M., Amararatne Y., Ranamukhaarachchi S. L., 2004. Agricultural use

455        of fishpond sediment for environmental amelioration. *Thammasat*

456        *International Journal of Science and Technology*, **9**(4).

457    Schouw L, Tjell S N, Mosbaek J C and Danteravanich H, 2002. Availability

458        and quantity of solid waste and wastewater in southern Thailand and its

459        potential use as fertilizer, *Waste Management & Research*, **20**, 332-340.

460    Takamura Y, Tabuchi T, Harigae Y, Otsuki H, Suzuki S and Kubota H, 1976.

461        Studies on balance sheets and losses of nitrogen and phosphorus in the

462        actual paddy field in the Shintone River basin. *Japanese Journal of Soils*

463           *Science and Plant Nutrition*, **48** (9-10), 431-436.

464   Takeuchi M, 1997. Nitrate and phosphate outflow from arable land. *Japanese*  
465           *Journal of Soils Science and Plant Nutrition*, **68**(6) 708-715.

466   Thuy N T T, Wu M H, Lai T V, 1998. Northern Vietnam, The World  
467           Vegetable Center, AVRDC, Tainan.

468   USDA, 2014. *National nutrient database for standard reference release 27*.  
469           [http://www.nal.usda.gov/fnic/foodcomp/cgi-bin/list\\_nut\\_edit.pl](http://www.nal.usda.gov/fnic/foodcomp/cgi-bin/list_nut_edit.pl) (accessed  
470           May 16, 2014).

471   Van Tu commune, 2010. *Socio-Economic Annual Report*. Van Tu People  
472           Committee, PhuXuyen, Hanoi, Vietnam (in Vietnamese).

473   Vietnam Environment Administration (VEA), Centre for Environmental  
474           Monitoring, 2012. *Monitoring Results of Project on Environmental*  
475           *Protection of River Basins in Vietnam*, VEA, Hanoi.

476   Vu T K V, Tran M T, Dang T T S, 2007. A survey of manure management on  
477           pig farms in northern Vietnam. *Livestock Science*, **112**, 288-297.

478   World Bank, 2004. *Vietnam Environmental Monitor 2004 Solid Waste*, Hanoi,  
479           Vietnam.

480   Yan W, Yin C, and Zhang S, 1999. Nutrient budgets and biogeochemistry in  
481           an experimental agricultural watershed in southeastern China.  
482           *Biogeochemistry*, **45**, 1-19.

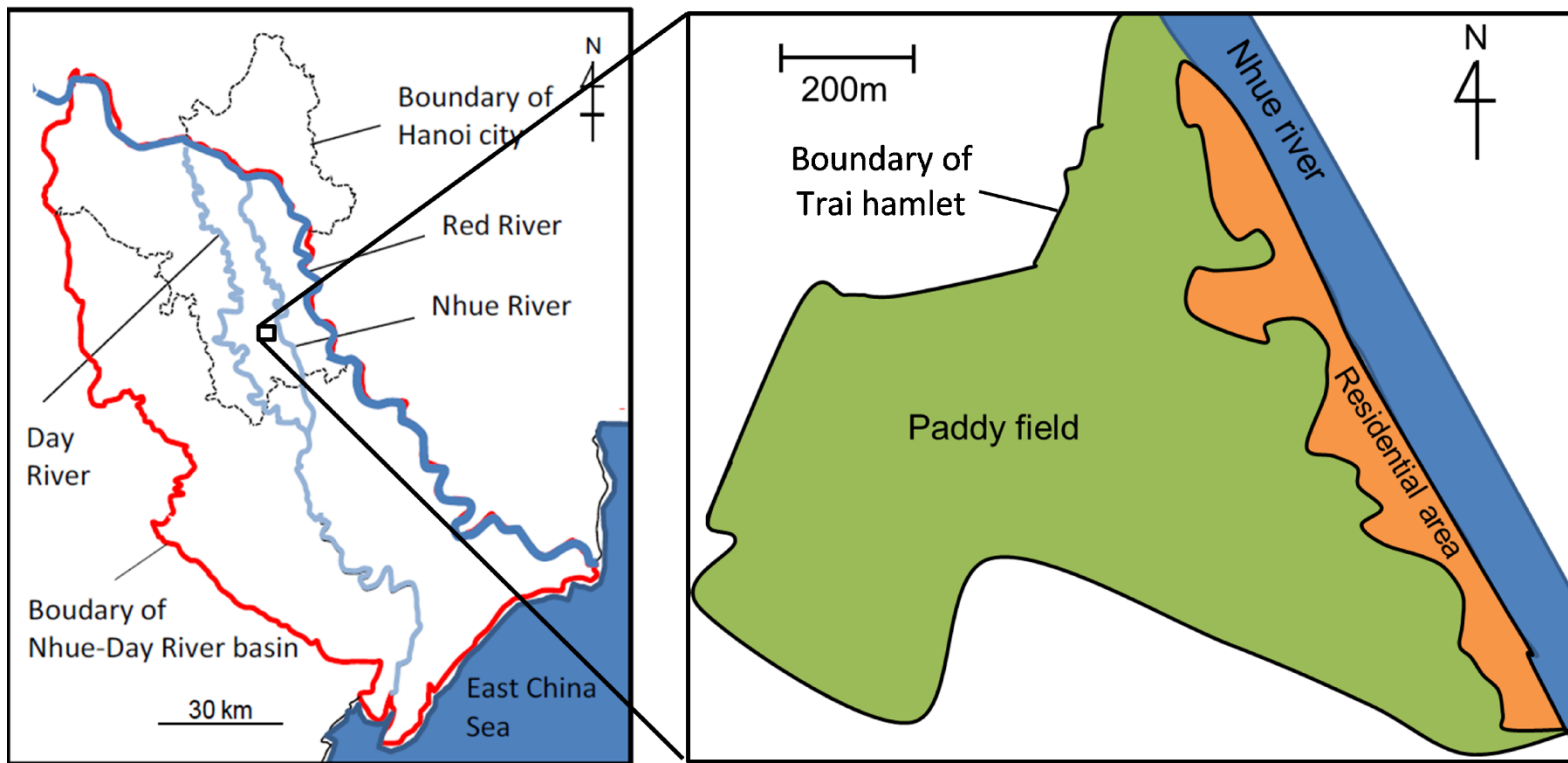
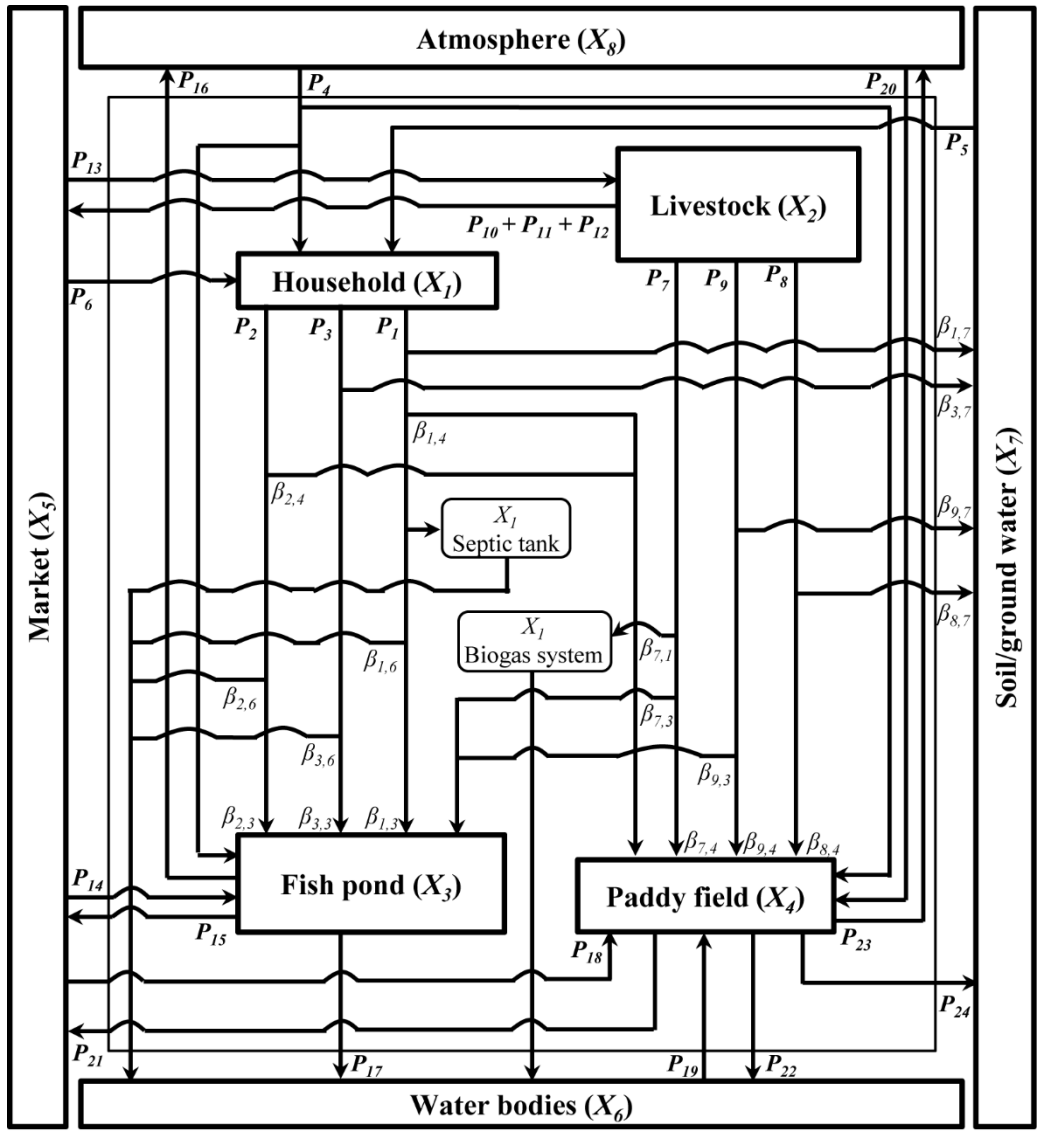


Figure 1 Map of Hanoi and Trai hamlet



- System boundary
- $\overrightarrow{P_i}$  Process  $i$
- $X_j$  Component  $j$
- $\beta_{i,j}$ : Proportion of process  $P_i$  distributed to component  $X_j$
- Sub-component

Figure 2 A material flow model in this study

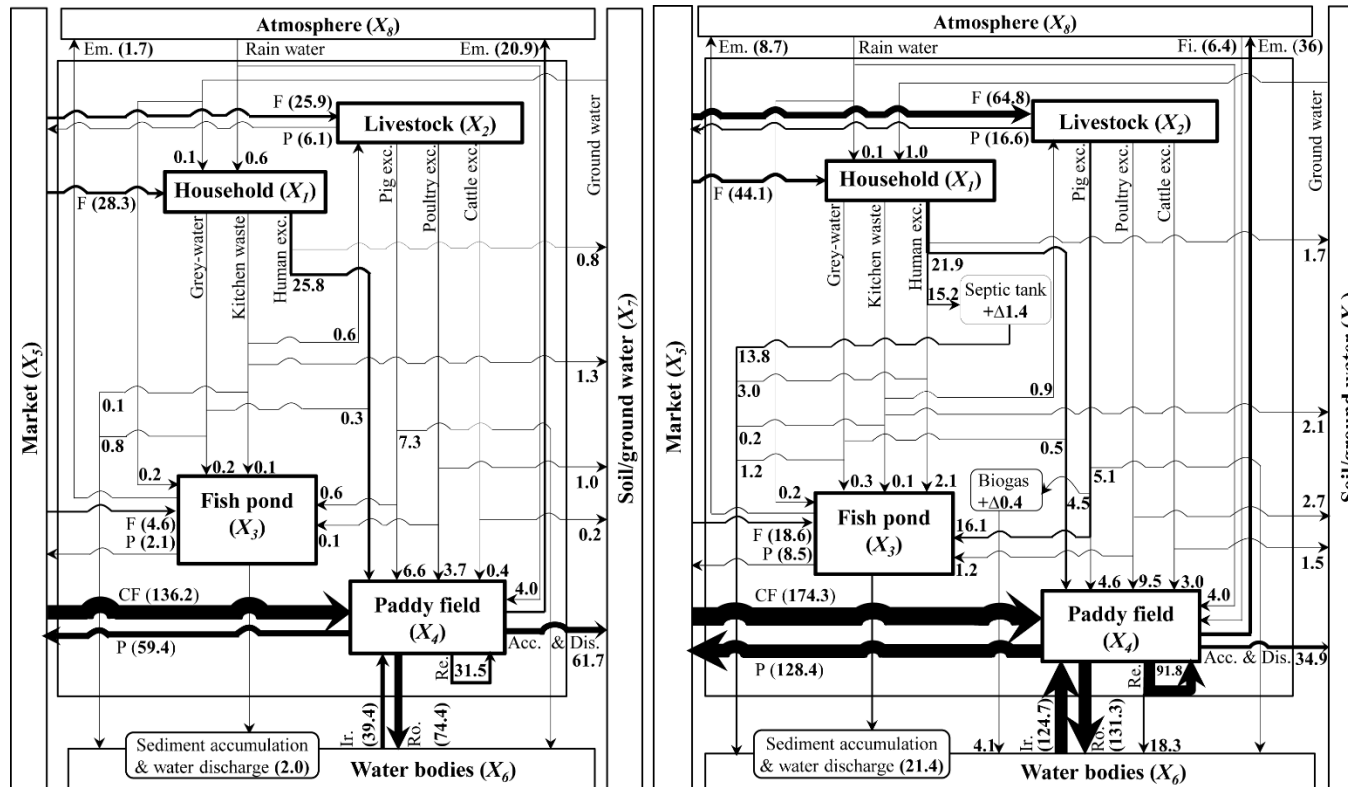


Figure 3 Flow of nitrogen in 1980 (left) and 2010 (right) ( $\text{kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ). Abbreviations in the figure indicate as follows. Exc.: Excreta; F: Food; P: Product; CF: Chemical fertilizer; Re.: Residue; Ir.: Irrigation; Acc. & Dis.: Accumulation and Discharge; Ro.: Runoff; Em: Emission.

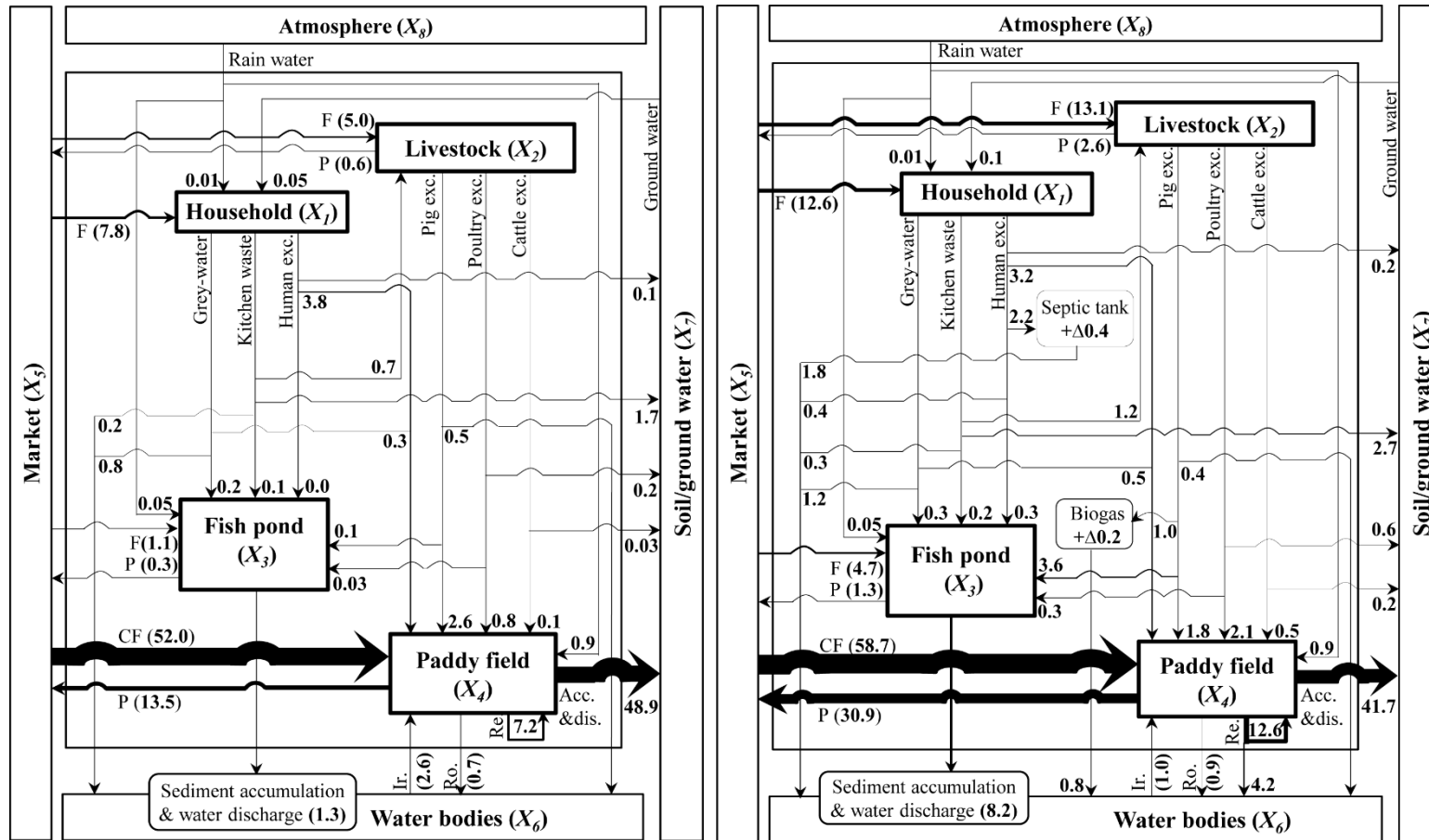


Figure 4 Flow of phosphorus in 1980 (left) and 2010 (right) ( $\text{kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ). Abbreviations in the figure indicate as follows. Exc.: Excreta; F: Food; P: Product; CF: Chemical fertilizer; Re.: Residue; Ir.: Irrigation; Acc. & Dis.: Accumulation and Discharge; Ro.: Runoff.

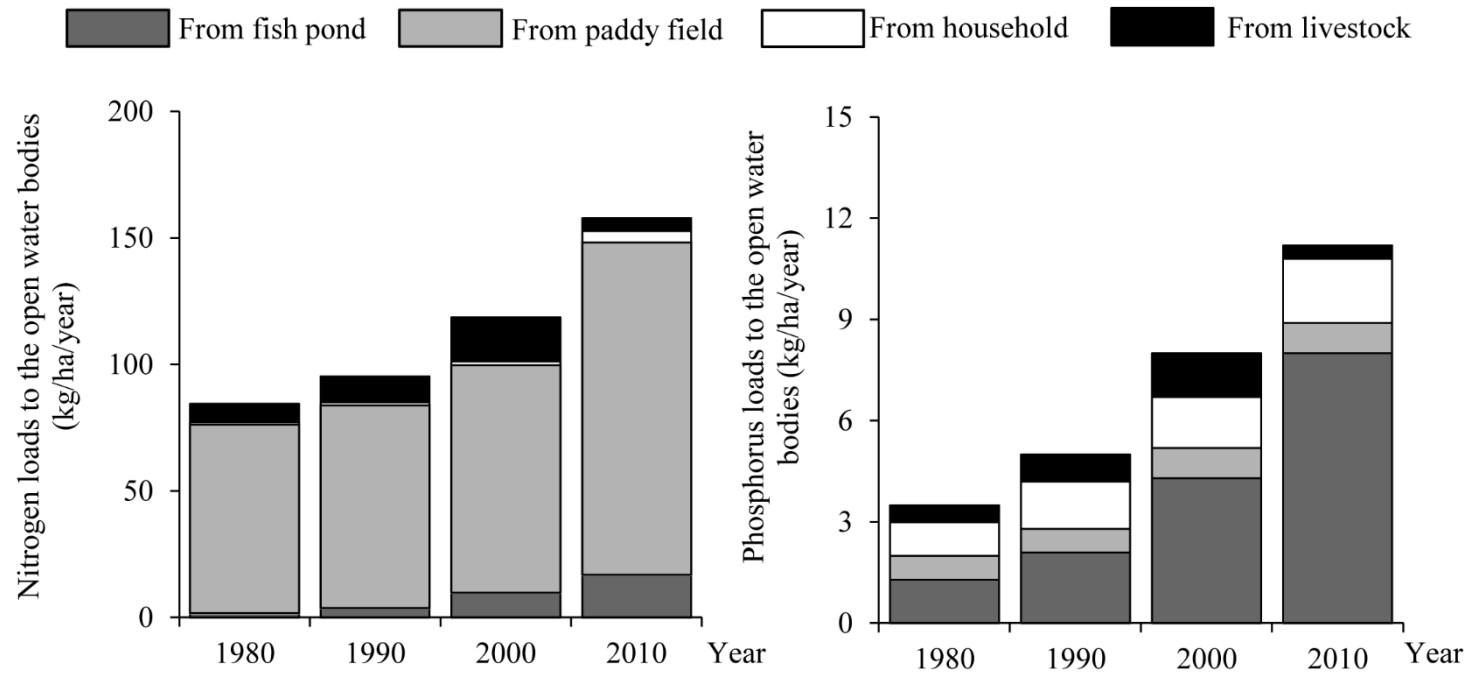


Figure 5 Nutrient input to open water bodies

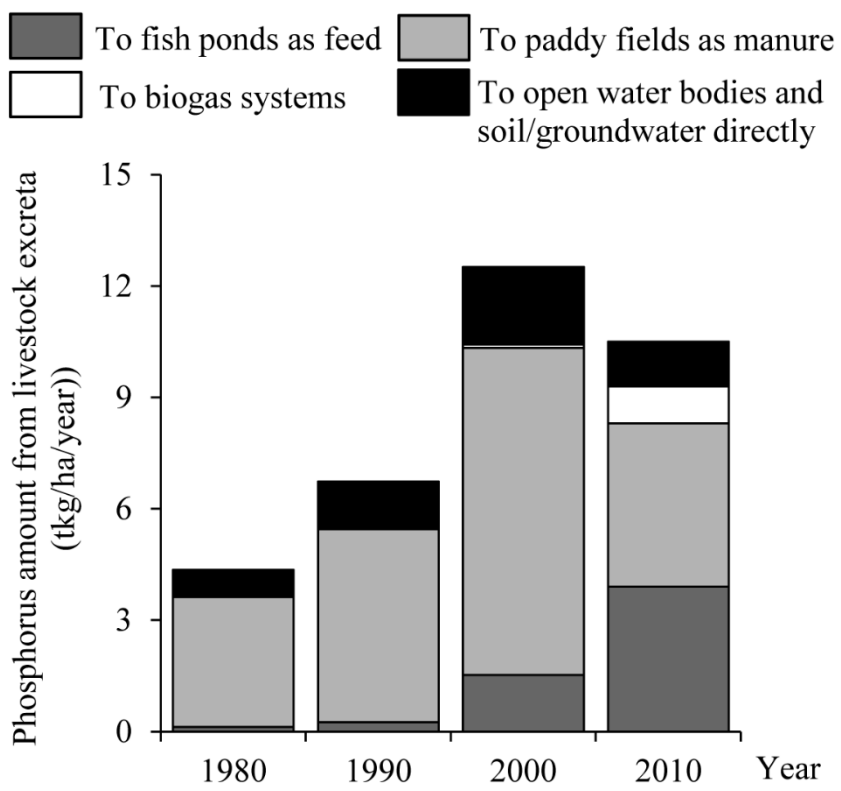


Figure 6 Phosphorous load derived from livestock excreta



## List of tables

Table 1 General information in the study area

Table 2 Description of reaction processes of the material flow more via matrix expression

Table 3 Secondary data used in the material flow model

Table 4 Characteristics of fishponds in the study area

Table 5 Nutrient balances of fish ponds in the study area

**Table 1** General information in the study area

Information	Symbol	Unit	Data			
			1980	1990	2000	2010
Population	$P_o$	People	505	686	782	800
Number of household	$N_{hh}$	Household	240	240	240	240
Number of livestock						
Pig	$N_{pi}$	Head	109	152	293	229
Poultry	$N_{po}$	Head	2101	3342	6106	5810
Cattle	$N_{ca}$	Head	3	12	16	22
Residential area	$S_{hh}$	1,000 m <sup>2</sup>	8	8	8	8
Paddy field area	$S_a$	1,000 m <sup>2</sup>	526	526	526	526
Total area	$\sum S$	1,000 m <sup>2</sup>	561	561	561	561

**Table 2** Description of reaction processes of the material flow model via matrix expression

Component [ $X_j$ ] → Process [ $P_i$ ] ↓		$X_1$	$X_2$	$X_3$	$X_4$	$X_5$	$X_6$	$X_7$	$X_8$	Reaction rate of $P_i$ [ $\rho_i$ ] (kg-N/year or kg-P/year)
$P_1$	Human excreta discharge	- 1 + $\beta_{1,st}$		$\beta_{1,3}$	$\beta_{1,4}$		$\beta_{1,6}$	$\beta_{1,7}$		$C_{1,N(P)} \times P_o \times 365 \times 10^{-3}$
$P_2$	Greywater discharge	- 1		$\beta_{2,3}$	$\beta_{2,4}$		$\beta_{2,6}$			$C_{2,N(P)} \times P_o \times 365 \times 10^{-3}$
$P_3$	Kitchen waste discharge	- 1	$\beta_{3,2}$	$\beta_{3,3}$			$\beta_{3,6}$	$\beta_{3,7}$		$C_{3,N(P)} \times P_o \times 365 \times 10^{-3}$
$P_4$	Rain water supply	$\frac{S_{hh}}{\sum S}$		$\frac{S_p}{\sum S}$	$\frac{S_a}{\sum S}$				- 1	$C_{4,N(P)} \times Q_r \times \sum S \times 10^{-6}$
$P_5$	Ground water supply	+ 1						- 1		$C_{5,N(P)} \times Q_{gr} \times P_o \times 365 \times 10^{-6}$
$P_6$	Food supply to households	+ 1				- 1				$P_1 + P_2 + P_3 - \frac{S_{hh}}{\sum S} \times P_4 - P_5$
$P_7$	Pig excreta discharge	$\beta_{7,bio}$	- 1	$\beta_{7,3}$	$\beta_{7,4}$					$C_{7,N(P)} \times N_{pi} \times 365 \times 10^{-3}$
$P_8$	Cattle excreta discharge		- 1		$\beta_{8,4}$			$\beta_{8,7}$		$C_{8,N(P)} \times N_{ca} \times 365 \times 10^{-3}$
$P_9$	Poultry excreta discharge	$\beta_{9,bio}$	- 1	$\beta_{9,3}$	$\beta_{9,4}$			$\beta_{9,7}$		$C_{9,N(P)} \times N_{po} \times 365 \times 10^{-3}$
$P_{10}$	Pig product		- 1			+ 1				$C_{10,N(P)} \times N_{pi} \times W_{pi}$
$P_{11}$	Poultry product		- 1			+ 1				$C_{11,N(P)} \times N_{po} \times W_{po}$
$P_{12}$	Cattle product		- 1			+ 1				$C_{12,N(P)} \times N_{ca} \times W_{ca}$
$P_{13}$	Food supply to livestock		+ 1			- 1				$P_7 + P_8 + P_9 + P_{10} + P_{11} + P_{12} - \beta_{3,2} \times P_3 - P_{13} - \alpha_{res} \times \beta_{17,2} \times P_{23}$
$P_{14}$	Water filling in fish ponds			+ 1			- 1			$\sum [C_{14,N(P)} \times S_{Pk} \times D_{Pk} \times f_{Pk} \times 10^{-3}]$
$P_{15}$	Commercial feed for fish ponds			+ 1		- 1				$C_{15,N(P)} \times P_f \times FCR$
$P_{16}$	Water removal from fish ponds			- 1			+ 1			$\sum [C_{16k,N(P)} \times S_{Pk} \times D_{Pk} \times f_{Pk} \times 10^{-3}]$
$P_{17}$	Fish harvesting			- 1		+ 1				$C_{17,N(P)} \times P_f$
$P_{18}$	N emission from pond surface			- 1					+ 1	$(P_1 \times \beta_{1,3} + P_2 \times \beta_{2,3} + P_3 \times \beta_{3,3} + P_4 \times \frac{S_{pi}}{\sum S} + P_7 \times \beta_{7,3} + P_9 \times \beta_{9,3} + P_{14} + P_{15}) \times k_{N,emis}$
$P_{19}$	Sedimentation & unintentional discharge from fish ponds			- 1			+ 1			$(P_1 \times \beta_{1,3} + P_2 \times \beta_{2,3} + P_3 \times \beta_{3,3} + P_4 \times \frac{S_{pi}}{\sum S} + P_7 \times \beta_{7,3} + P_9 \times \beta_{9,3} + P_{14} + P_{15}) - P_{16} - P_{17} - P_{18}$
$P_{20}$	Chemical fertilizer application				+ 1	- 1				$C_{20,N(P)} \times m_{cf} \times S_a$
$P_{21}$	Irrigation water to paddy fields				+ 1		- 1			$C_{21,N(P)} \times Q_{ir} \times S_a$
$P_{22}$	N fixation				+ 1				- 1	$337 \times e^{-0.0098 \times P_{20}/S_a} \times S_a$
$P_{23}$	Agricultural product harvesting		$\alpha_{res} \times \beta_{23,2}$		$-(1 + \alpha_{res}) + \alpha_{res} \times \beta_{23,4}$	+ 1		$\alpha_{res} \times \beta_{23,7}$		$C_{23,N(P)} \times P_a$

$P_{24}$	Agricultural runoff				- 1		+ 1		$(P_1 \times \beta_{1,4} + P_2 \times \beta_{2,4} + P_3 \times \beta_{3,4} + \frac{S_a}{\Sigma S} \times P_4 + P_7 \times \beta_{7,4} + P_8 \times \beta_{8,4} + P_9 \times \beta_{9,4} + P_{20} + P_{21} + P_{22} + P_{23} \times \beta_{17,4} \times \alpha_{res}) \times R$
$P_{25}$	N emitted from paddy fields				- 1			+1	$(P_1 \times \beta_{1,4} + P_7 \times \beta_{7,4} + P_8 \times \beta_{8,4} + P_9 \times \beta_{9,4}) \times k_{N,ex} + P_{20} \times k_{N,cf}$
$P_{26}$	Soil accumulation & discharge from paddy fields				- 1		+ 1		$(P_1 \times \beta_{1,4} + P_2 \times \beta_{2,4} + P_3 \times \beta_{3,4} + \frac{S_a}{\Sigma S} \times P_4 + P_7 \times \beta_{7,4} + P_8 \times \beta_{8,4} + P_9 \times \beta_{9,4} + P_{20} + P_{21} + P_{22} + P_{23} \times \beta_{23,4} \times \alpha_{res}) (1 - R) - (1 + \alpha_{re}) \times P_{23} - P_{25}$
Net reaction rate (kg/yr)		$r_j = \sum_i (v_{ij} \times \rho_i) = 0$ ( $i = 1, 2, \dots, 26$ )			$r_j = \sum_i (v_{ij} \times \rho_i)$ ( $i = 1, 2, \dots, 26$ )				

Note: Details of symbols are explained in Figure 2 and Table 1,3 and 4.

**Table 3** Secondary data used in the material flow model

Explanation	Unit	1980	1990	2000	2010		
$\beta_{1,3}$	Ratio of human excreta going to fish ponds	-	0.00	0.00	0.00	0.05	1)
$\beta_{1,4}$	Ratio of human excreta going to paddy fields	-	0.97	0.97	0.93	0.52	1)
$\beta_{1,6}$	Ratio of human excreta going to water bodies	-	0.00	0.00	0.00	0.07	1)
$\beta_{1,st}$	Ratio of human excreta going to septic tank	-	0.00	0.00	0.00	0.36	1)
$\beta_{2,3}$	Ratio of greywater going to fish ponds	-	0.16	0.16	0.16	0.16	1)
$\beta_{2,4}$	Ratio of greywater going to paddy fields	-	0.25	0.25	0.25	0.25	1)
$\beta_{2,6}$	Ratio of greywater going to water bodies	-	0.59	0.59	0.59	0.59	1)
$\beta_{3,2}$	Ratio of kitchen waste going to livestock	-	0.27	0.27	0.27	0.27	1)
$\beta_{3,3}$	Ratio of kitchen waste going to fish ponds	-	0.04	0.04	0.04	0.04	1)
$\beta_{3,6}$	Ratio of kitchen waste going to water bodies	-	0.07	0.07	0.07	0.07	1)
$\beta_{3,7}$	Ratio of kitchen waste going to soil/groundwater	-	0.62	0.62	0.62	0.62	1)
$\beta_{7,bio}$	Ratio of pig excreta going to biogas system	-	0.01	0.01	0.01	0.15	1)
$\beta_{7,3}$	Ratio of pig excreta going to fish ponds	-	0.04	0.04	0.15	0.53	1)
$\beta_{7,4}$	Ratio of pig excreta going to paddy fields	-	0.96	0.95	0.84	0.32	1)
$\beta_{8,4}$	Ratio of cattle excreta going to paddy fields	-	0.67	0.67	0.67	0.67	1)
$\beta_{8,7}$	Ratio of cattle excreta going to soil/groundwater	-	0.33	0.33	0.33	0.33	1)
$\beta_{9,bio}$	Ratio of poultry excreta going to biogas system	-	0.00	0.00	0.00	0.01	1)
$\beta_{9,3}$	Ratio of poultry excreta going to fish ponds	-	0.03	0.04	0.07	0.09	1)
$\beta_{9,4}$	Ratio of poultry excreta going to paddy fields	-	0.76	0.75	0.73	0.70	1)
$\beta_{9,7}$	Ratio of poultry excreta going to soil/groundwater	-	0.21	0.21	0.20	0.20	1)
$\beta_{11,2}$	Ratio of agricultural residue going to livestock	-	0.03	0.03	0.03	0.03	1)
$\beta_{11,4}$	Ratio of agricultural residue going to paddy fields	-	1.00	1.00	1.00	0.73	1)
$\beta_{11,7}$	Ratio of agricultural residue going to soil/groundwater	-	0.00	0.00	0.00	0.27	1)
$a_{res}$	Ratio of agricultural residue to production (rice)	-		0.53			1)
	Ratio of agricultural residue to production (bean)	-		1.00			1)
$C_{1,N}$	N amount in human excreta	g/cap/d		8.10			2)
$C_{1,P}$	P amount in human excreta	g/cap/d		1.20			2)
$C_{2,N}$	N amount in grey water	g/cap/d		0.40			3)
$C_{2,P}$	P amount in grey water	g/cap/d		0.40			3)
$C_{3,N}$	N amount in kitchen waste	g/cap/d		0.65			4)
$C_{3,P}$	P amount in kitchen waste	g/cap/d		0.83			4)
$C_{4,N}$	N amount in rain water	mg/L		0.25			5)
$C_{4,P}$	P amount in rain water	mg/L		0.06			5)
$C_{5,N}$	N amount in ground water	mg/L		4.60			6)
$C_{5,P}$	P amount in ground water	mg/L		0.40			6)
$Q_{gr}$	Ground water consumption	L/cap/d		60.00			1)
$Q_r$	Average rainfall	mm/year		1,612			7)
$C_{7,N}$	N amount in pig excreta	g/head/d		20.33			1)
$C_{7,P}$	P amount in pig excreta	g/head/d		4.59			1)
$C_{8,N}$	N amount in cattle excreta	g/head/d		31.66			1)
$C_{8,P}$	P amount in cattle excreta	g/head/d		5.13			1)
$C_{9,N}$	N amount in poultry excreta	g/head/d		0.36			1)
$C_{9,P}$	P amount in poultry excreta	g/head/d		0.08			1)
$C_{10,N}$	N amount in pig	kg/kg		0.022			8)
$C_{10,P}$	P amount in pig	kg/kg		0.0018			8)
$C_{11,N}$	N amount in poultry	kg/kg		0.0248			8)
$C_{11,P}$	P amount in poultry	kg/kg		0.0016			8)
$C_{12,N}$	N amount in cattle	kg/kg		0.024			8)
$C_{12,P}$	P amount in cattle	kg/kg		0.01			8)
$W_{pi}$	Pig meat product	kg/head		96			9)
$W_{po}$	Poultry meat product	kg/head		1.6			9)
$W_{ca}$	Cattle meat product	kg/head		410			9)
$C_{15,N}$	N amount in commercial feed for fish	kg/kg		0.04			10)
$C_{15,P}$	P amount in commercial feed for fish	kg/kg		0.01			10)
$C_{17,N}$	N amount in fish	kg/kg		0.03			10)
$C_{17,P}$	P amount in fish	kg/kg		0.0045			10)
$P_f$	Fish production	kg/year	3,875	6,200	9,900	15,850	11)
$FCR$	Feed conversion ratio	-		1.65			10)

$k_{N,emis}$	N emission from surface water	-	0.2				10)
$C_{20,N}$	N amount in chemical fertilizer	%	5–46% (depended on fertilizer types)				1)
$C_{20,P}$	P amount in chemical fertilizer	%	10–16% (depended on fertilizer types)				1)
$C_{21,N}$	N amount in irrigation water (Nhue river)	mg/L	2.60	2.60	2.60	7.7	12)
$C_{21,P}$	P amount in irrigation water (Nhue river)	mg/L	0.17	0.17	0.17	0.66	12)
$Q_{ir}$	Irrigation water consumption	m <sup>3</sup> /ha	16,200				13)
$C_{23,N}$	N amount in rice	kg/kg	0.0114				14)
	N amount in bean	kg/kg	0.0064				14)
$C_{23,P}$	P amount in rice	kg/kg	0.0026				15)
	P amount in bean	kg/kg	0.0019				15)
$P_a$	Rice production	ton/year	292	342	571	631	11)
	Bean production	ton/year	0	0	0	50	11)
$k_{N,ex}$	N emission factor of excreta	-	0.2				16)
$k_{N,cf}$	N emission factor of chemical fertilizer	-	0.1				16)
$R_N$	Ratio of runoff in case of N	-	0.3				17)
$R_P$	Ratio of runoff in case of P	-					
	Rice	-	0.01				17)
	Bean	-	0.02				17)

<sup>1)</sup>Giang *et al.*,2012 <sup>2)</sup>Montangero *et al.*,2007 <sup>3)</sup>Busser *et al.*,2006 <sup>4)</sup>Show *et al.*, 2002; World Bank, 2004; Nakamura and Yuzuyama, 2005; Kawai, 2007 <sup>5)</sup>Khanh, 2000; Huong *et al.*,2007<sup>6)</sup>Anh and Toda, 2005 <sup>7)</sup>HSG, 2010 <sup>8)</sup>MEXT, 2008 <sup>9)</sup>GSO, 2008; Harada *et al.*, 2008 <sup>10)</sup>Nga *et al.*, 2011 <sup>11)</sup>GSO, 2010; GSO, 2004 <sup>12)</sup>VEA, 2012<sup>13)</sup>FAO, 2013 <sup>14)</sup>FAO, 2003; FAO, 2004; Thuy *et al.*, 1998); Nakamura and Yuzuyama, 2005 <sup>15)</sup>USDA, 2014 <sup>16)</sup>IPCC, 2000<sup>17)</sup>Takamura *et al.*,1976.

**Table 4** Characteristics of fishponds in the study area

<b>Characteristics</b>	<b>Unit</b>	<b>Data</b>
Total area of fish pond	1,000 m <sup>2</sup>	27 ( <i>S<sub>p</sub></i> )
Surface area	1,000 m <sup>2</sup> (avg. ± s.d.)	1.5 ± 1.0
Depth	m (avg. ± s.d.)	1.04 ± 0.10
Frequency of water exchange & fish harvesting	times/year	0 (Prior to 2010) 2 ± 1 (After 2010)

**Table 5** Nutrient balances of fish ponds in the study area

		N				P			
		1980		2010		1980		2010	
		kg/ha	(%)	kg/ha	(%)	kg/ha	(%)	kg/ha	(%)
<b>Input</b>	Commercial feed	4.6	(79)	18.6	(45)	1.1	(69)	4.7	(48)
	Livestock excreta	0.7	(12)	17.3	(41)	0.1	(6)	3.9	(40)
	Household waste	0.3	(5)	2.5	(6)	0.3	(19)	0.8	(8)
	Water filling	-	-	3.1	(7)	-	-	0.3	(3)
	Precipitation	0.2	(3)	0.2	(1)	0.1	(6)	0.1	(1)
	<b>Total input</b>	<b>5.8</b>	<b>(100)</b>	<b>41.7</b>	<b>(100)</b>	<b>1.6</b>	<b>(100)</b>	<b>9.8</b>	<b>(100)</b>
<b>Output &amp;Accumulation</b>	Fish production	2.1	(36)	8.5	(20)	0.3	(19)	1.3	(13)
	N release	1.7	(29)	8.7	(21)	-	-	-	-
	Water removal	-	-	7.5	(18)	-	-	0.5	(5)
	Sediment accumulation &Unintentional discharge	2.0	(34)	17.0	(41)	1.3	(81)	8.0	(82)
	<b>Total output &amp;Accumulation</b>	<b>5.8</b>	<b>(100)</b>	<b>41.7</b>	<b>(100)</b>	<b>1.6</b>	<b>(100)</b>	<b>9.8</b>	<b>(100)</b>