Preliminary analysis of phosphorus flow in Hue Citadel

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Abstract
Characteristics of waste and wastewater management can affect material flows. Our research investigates the management of waste and wastewater in urban areas of developing countries and its effects on phosphorus flow based on a case study in Hue Citadel, Hue, Vietnam. One hundred households were interviewed to gain insight into domestic waste and wastewater management together with secondary data collection. Next, a phosphorus flow model was developed to quantify the phosphorus input and output in the area. The results showed that almost all wastewater generated in Hue Citadel was eventually discharged into water bodies and to the ground/groundwater. This led to most of phosphorus output flowed into water bodies (41.2 kg P/(ha·year)) and ground/groundwater (25.3 kg P/(ha·year)). Sewage from the sewer system was the largest source of phosphorus loading into water bodies while effluent from on-site sanitation systems was responsible for a major portion of phosphorus into the ground/groundwater. This elevated phosphorus loading is a serious issue in considering surface water and groundwater protection.

Keywords
Greywater, Hue Citadel, material flow analysis, phosphorus, water bodies

INTRODUCTION

Phosphorus is an essential element for all living creatures. Phosphorus is also important to agriculture, as the majority of the world's agriculture relies on fertilizers derived from phosphate rock. Although phosphate rock is expected to be depleted in 60-130 years (Schroder *et al.*, 2010), the demand for phosphorus is increasing globally due to the increase in population and subsequent food demand. Thus, phosphorus has been regarded as a critical global resource, alongside water and energy resources (Cordell, 2008). However, the widespread use of phosphorus poses concerns for the quality of the aquatic environment. Phosphorus is one of the major culprits causing eutrophication, which adversely affects surface water.

The flow of phosphorus through urban systems is a concern in many countries. The phosphorus flow through the municipality of Gävle, Sweden was quantified, and results showed that two-thirds of phosphorus accumulated mainly at waste dumps while the remaining third left the system as outflows to the Baltic Sea or to the market as a product (Nilsson, 1995). A study on phosphorus balance in Sydney, Australia revealed that 80% of phosphorus inputs to the system were derived from foods and detergent; 90% of outputs from the system were discharged to the ocean as effluent from wastewater treatment plants (Tangsubkul *et al.*, 2005). In China, the phosphorus flows in two cities (Hefei and Chaohu) located near Chaohu Lake were studied; excessive chemical fertilizers from farming operations and sewage discharge from household activities were identified as the most critical sources of phosphorus loading into surface water (Li *et al.*, 2010; Yuan *et al.*, 2011). In

Vietnam, phosphorus flows have been quantified for several areas in the northern part of the country, *e.g.*, Hanoi city and Hanam province, which mainly focused on the interaction between environmental sanitation and agricultural systems (Giang *et al.*, in press; Montangero *et al.*, 2007; Nga *et al.*, 2011); they revealed that the harmonization between these systems can increase nutrient recovery and reduce the nutrient loading to the environment.

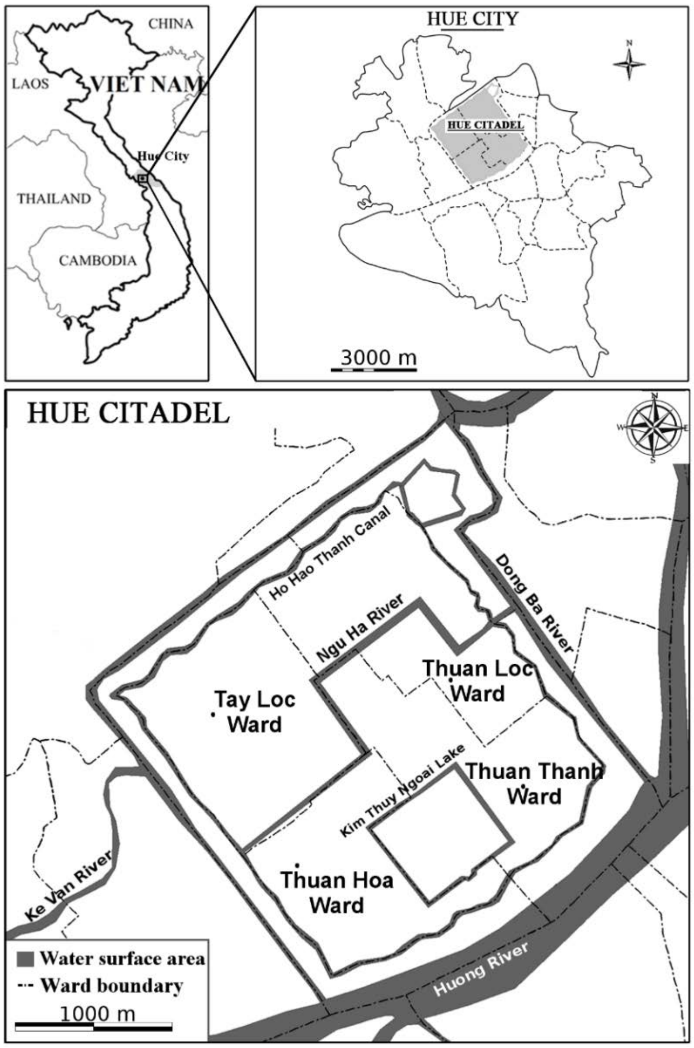

Figure 1. Hue Citadel area (CIT, 2013a)

Currently, the development of many urban areas in developing countries has led to changes in lifestyles, infrastructures, and the characteristics of waste and wastewater management. For example, in Vietnam, access to an improved water source and toilet has increased from 90% and 64% in 1990 to 98% and 93% in 2012, respectively (WHO and UNICEF, 2014), likely resulting in material flow changes, including phosphorus flow. A study in a suburban community in Hanoi, Vietnam showed that the shift from traditional agricultural practices of reusing waste to the application of chemical fertilizers had led to an increase of phosphorus input to paddy fields, an increase of 1.3 times from 1980 to 2010, which exceeded the recommended level 3.5 times (Giang *et al.*, in press). Thus, it is crucial to study waste and wastewater management and the effects on phosphorus flow to improve urban environments in developing areas.

Hue city, which is located in central Vietnam, is famous for its historical and cultural values. Hue Citadel is the center of the historic city of Hue and is on the list of UNESCO World Cultural Heritage sites. The Citadel has recently undergone development. However, the infrastructure development is still in its infancy. Along with the urbanization and development of this area, the phosphorus flow is likely changing as lakes and rivers in Hue Citadel are in hyper-eutrophic states (trophic state index > 70) (Hop *et al.*, 2012). Thus, this study aims to understand the waste and wastewater stream and to describe the phosphorus flow in Hue Citadel as a case study representing urbanization in developing countries.

MATERIALS AND METHODS

Study area description

The study area was Hue Citadel, Hue, Vietnam (**Figure 1**). The total area of Hue Citadel is 520 ha, of which more than 90% is residential and historic land. The area consists of four wards (Thuan Thanh, Thuan Loc, Thuan Hoa, and Tay Loc) with a 2013 population of 60,106 distributed in

13,311 households (People's Committee of Wards, 2013). The proportion of households in each ward was 22%, 26%, 22%, and 30% for Thuan Thanh, Thuan Loc, Thuan Hoa, and Tay Loc, respectively, in 2013. There were six markets in the area with a total area of 17,969 m^2 (CIT, 2013b), which play a role in importing goods (food, detergent, *etc.*) from outside of the area and distributing them to local households.

All households in the study area had access to tap water supplied by Thua Thien Hue Construction and Water Supply, a state-owned limited company (HUEWACO, 2013). Each household had a toilet connected to an on-site sanitation system such as a septic tank or a cesspool (Thua Thien Hue Center for Preventive Medicine, 2013). Desludging was performed with on-site sanitation systems by a state-owned company, Hue Urban Environment and Public Works State Limited Company (HEPCO), and private companies. HEPCO disposed of fecal sludge legally in landfills, while most of the private companies were suspected of disposing it illegally into waterways (AECOM International Development, Inc. and Eawag-Sandec, 2010). However, the exact number of private companies desludging and the collected amount of sludge is unavailable.

A combined sewer system covering 40% of the city's area collected wastewater and stormwater (HEPCO, 2013a). Since Hue did not have any wastewater treatment plants, all wastewater eventually drained into Ngu Ha River and 41 lakes (51 ha).

Municipal solid wastes were generated in Hue Citadel at a rate of 0.73 kg/(cap·day), and kitchen waste accounted for 60.1% of total municipal waste (HEPCO, 2013b). HEPCO was responsible for collecting all solid wastes in Hue. Each day in late afternoon, HEPCO workers pushed carts passing through door-to-door to collect solid waste. The HEPCO waste carts were then taken to designated locations to transfer wastes into trucks to be transported and disposed of at a city landfill outside the Citadel.

Data collection

Structured interview. A structured interview survey was conducted for households in Hue Citadel in March 2014 to obtain information on household waste and wastewater management in 2013. Sample size was determined based on Yamane's formula at 95% confidence level (Yamane, 1967):

$$n = N/(1 + Ne^2) \quad \text{(Eq.1)}$$

Where *n*: sample size
N: size of household (13,695)
e: level of precision or error limit (0.1)

Since *n* is calculated as 99.3, the sample size of this study was determined to be 100. The number of interviewed households in each ward was proportional to the total number of households in each ward, which was 22, 26, 22, and 30 for Thuan Thanh, Thuan Loc, Thuan Hoa, and Tay Loc, respectively. The households in each ward to be interviewed were randomly selected. The survey criteria used in the interviews is shown in **Table 1**.

Table 1. Contents of questionnaire and expected results

Item	Content	Expected result

Kitchen waste management	- Collected by public services - Disposed of by a household to ground/groundwater or water bodies - Used as a resource (identification of the purpose)	- Ratio of kitchen wastes that went to landfill: $R_{7(kw)}$ - Ratio of kitchen wastes disposed to ground/groundwater or water bodies: $R_{6(kw)}$, $R_{5(kw)}$ - Ratio of kitchen wastes reused: $R_{9(kw)}$
Greywater management	- Discharged to a sewer system - Discharged to ground/groundwater or water bodies - Used as a resource (identification of the purpose)	- Ratio of greywater that went to sewer system: $R_{3(gw)}$ - Ratio of greywater that went to ground/groundwater or water bodies: $R_{6(gw)}$, $R_{5(gw)}$ - Ratio of greywater reused: $R_{9(gw)}$
Toilet waste management	- Toilet type - Connection to an on-site sanitation system - Desludging experience - Desludging interval - Handling of on-site sanitation system effluent: + Discharged to a sewer system + Discharged into ground/groundwater or water bodies + Used as a resource (identification of the purpose)	- Ratio of each toilet type - Ratio of each/no on-site sanitation system - Ratio of households with desludging experience: h_{de} - Average desludging interval year: f_{fs} - Ratio of toilet wastes flowing to sewer system: $R_{3(tw)}$ - Ratio of toilet wastes flowing to ground/groundwater or water bodies: $R_{6(tw)}$, $R_{5(tw)}$ - Ratio of on-site sanitation system effluent used as a resource: $R_{9(tw)}$

Secondary data collection. **Table 2** summarizes the secondary data collected for this study. Demographic, socioeconomic, and meteorological information on the Citadel was obtained from official city reports. Phosphorus concentration data of wastes, wastewater, and other environmental media were obtained from references to calculate a phosphorus flow.

Table 2. Secondary data

Contents	Unit	Value	Source	Symbol
Population in 2013	people	60,106	1)	P
Total Citadel area in 2013	ha	520	1)	S
Average rainfall in 2013	mm/year	2,730.7	2)	C_{rw}
Unit phosphorus rate by human excreta	g/(cap·day)	1.2	3)	$U_{1(he)}$
Phosphorus transfer coefficient in fecal sludge from septic tank	-	0.18	3)	$U_{2(fs)}$
Unit phosphorus rate by greywater	g/(cap·day)	0.59	4)	$U_{1(gw)}$
Unit phosphorus rate by market wastewater	g/(m^2·day)	0.064	4)	$U_{4(ww)}$
Unit phosphorus rate by kitchen wastes	g/(cap·day)	0.16	5)	$U_{1(kw)}$
Unit phosphorus rate by rainwater	mg/L	0.0625	6)	$U_{8(rw)}$
Unit phosphorus rate by sewer sludge	g/kg	2.84	7)	$U_{3(ss)}$
Phosphorus ratio in market solid wastes	-	0.0022	8)	$U_{4(sw)}$
Amount of market solid wastes	kg/year	521,286	9)	C_{sw}
Amount of sewer sludge	kg/year	312,000	10)	C_{ss}
Water surface area	m^2	690,190	11)	S_{wb}
Pervious surface area	m^2	52,141	11)	S_{pe}
Impervious surface area	m^2	4,457,669	11)	S_{im}
Market area	m^2	17,969	11)	S_{ma}

1) People's Committee of Wards (2013); 2) Thua Thien Hue Hydrometeorological Center (2013); 3) Montangero and Belevi (2007); 4) Hang (2013); 5) Schouw *et al.* (2002); 6) Huong *et al.* (2007); 7) Huy (2007); 8) Karthikeyan *et al.* (2007); 9) HEPCO (2013b); 10) HEPCO (2013a); 11) CIT (2013b).

Phosphorus flow development

In this study, a material flow model was introduced to quantify the phosphorus flow in Hue Citadel by modifying the model by Giang *et al.* (in press) (**Figure 2**). The model had four components -

households (j=1), on-site sanitation systems (j=2), a sewer system (j=3), and markets (j=4) - inside the calculation boundary, and it had six components - water bodies (river and lakes) (j=5), ground/groundwater (j=6), landfill (j=7), atmosphere (j=8), and outside market (j=9) - outside the calculation boundary.

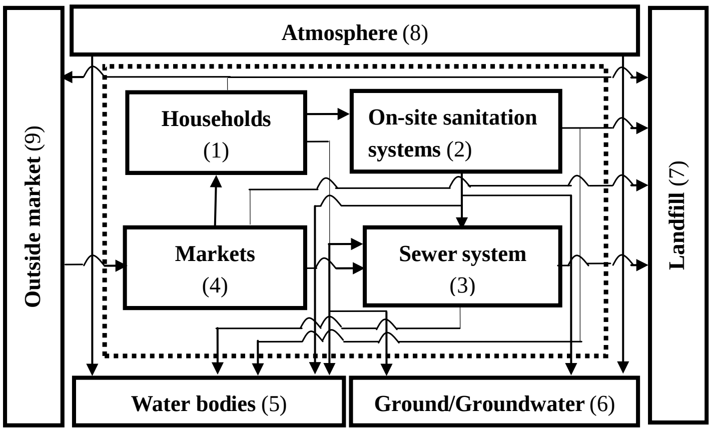

Figure 2. A material flow model

Each individual phosphorus flux was calculated using the unit value method. The phosphorus flux of a material k from component i to component j, $P_{i,j(k)}$, was calculated as follows:

$$P_{i,j(k)} = \left(U_{i(k)} \times C_{(k)} \times R_{j(k)}\right)/S \qquad \text{(Eq.2)}$$

Where $U_{i(k)}$: unit phosphorus discharge (transfer) rate of material k from component i (kg P/(unit amount·year))

$C_{(k)}$: discharge amount of material k (unit amount)

$R_{j(k)}$: ratio transferred to component j (dimensionless)

S: total area of the study site (ha)

The fluxes, which could not be calculated by unit value method, were calculated based on mass conservation law, which is as follows:

$$Total\ input\ to\ component\ m\ \left(\sum_k \sum_i P_{i,m(k)}\right) = Total\ output\ from\ component\ m\ \left(\sum_{k'} \sum_j P_{m,j(k')}\right) \qquad \text{(Eq.3)}$$

Details of each equation are shown in **Table 3**.

Table 3. Equations for the calculation of individual phosphorus fluxes (kg P/(ha·year))

Component (j) from-to	**Material**	**Equation**	
Households to on-site sanitation systems	Toilet waste (tw)	$P_{1,2(tw)} = \left(U_{1(he)} \times P \times 365 \times 10^{-3}\right)/S$	(Eq.4)
Households to sewer system	Greywater (gw)	$P_{1,3(gw)} = \left(U_{1(gw)} \times P \times R_{3(gw)} \times 365 \times 10^{-3}\right)/S$	(Eq.5)
Household to water bodies	Greywater (gw)	$P_{1,5(gw)} = \left(U_{1(gw)} \times P \times R_{5(gw)} \times 365 \times 10^{-3}\right)/S$	(Eq.6)
Households to ground/groundwater	Greywater (gw)	$P_{1,6(gw)} = \left(U_{1(gw)} \times P \times R_{6(gw)} \times 365 \times 10^{-3}\right)/S$	(Eq.7)
Households to landfill	Kitchen waste (kw)	$P_{1,7(kw)} = \left(U_{1(kw)} \times P \times R_{7(kw)} \times 365 \times 10^{-3}\right)/S$	(Eq.8)
Households to outside market	Kitchen waste (kw)	$P_{1,9(kw)} = \left(U_{1(kw)} \times P \times R_{9(kw)} \times 365 \times 10^{-3}\right)/S$	(Eq.9)
Markets to households	Food, detergent (fd)	$P_{4,1(fd)} = P_{1,9} + P_{1,7} + P_{1,2} + P_{1,3} + P_{1,6} + P_{1,5}$	(Eq.10)
On-site sanitation systems	Fecal sludge (fs)	$P_{2,2(fs)} = \left(P_{1,2} \times U_{2(fs)}\right) - P_{2,7}$	(Eq.11)

storage			
On-site sanitation systems to sewer system	Effluent (*ef*)	$P_{2,3(ef)} = [P_{1,2} - (P_{1,2} \times U_{2(fs)})] \times R_{3(tw)}$	(Eq.12)
On-site sanitation systems to water bodies	Effluent (*ef*)	$P_{2,5(ef)} = [P_{1,2} - (P_{1,2} \times U_{2(fs)})] \times R_{5(tw)}$	(Eq.13)
On-site sanitation systems to ground/groundwater	Effluent (*ef*)	$P_{2,6(ef)} = [P_{1,2} - (P_{1,2} \times U_{2(fs)})] \times R_{6(tw)}$	(Eq.14)
On-site sanitation systems to landfill	Fecal sludge (*fs*)	$P_{2,7(fs)} = [(P_{1,2} \times U_{2(fs)} \times h_{de} \times 10^{-3})/f_{fs}]/S$	(Eq.15)
Sewer system to landfill	Sewer sludge (*ss*)	$P_{3,7(ss)} = (C_{ss} \times U_{3(ss)} \times 10^{-3})/S$	(Eq.16)
Sewer system to water bodies	Sewage (*sg*)	$P_{3,5(sg)} = P_{1,3} + P_{4,3} + P_{2,3} + P_{8,3} - P_{3,7}$	(Eq.17)
Markets to sewer system	Wastewater (*ww*)	$P_{4,3(ww)} = (U_{4(ww)} \times S_{ma} \times 365 \times 10^{-3})/S$	(Eq.18)
Markets to landfill	Solid waste (*sw*)	$P_{4,7(sw)} = (C_{sw} \times U_{4(sw)})/S$	(Eq.19)
Outside-market to markets	Food, detergent (*fd*)	$P_{10,4(fd)} = P_{4,1} + P_{4,3} + P_{4,7}$	(Eq.20)
Atmosphere to water bodies	Rainwater (*rw*)	$P_{8,5(rw)} = (C_{rw} \times U_{8(rw)} \times S_{wb} \times 10^{-6})/S$	(Eq.21)
Atmosphere to sewer system	Rainwater (*rw*)	$P_{8,3(rw)} = (C_{rw} \times U_{8(rw)} \times S_{im} \times 10^{-6})/S$	(Eq.22)
Atmosphere to ground/groundwater	Rainwater (*rw*)	$P_{8,6(rw)} = (C_{rw} \times U_{8(rw)} \times S_{pe} \times 10^{-6})/S$	(Eq.23)

RESULTS AND DISCUSSION

Waste and wastewater management in Hue Citadel

Household kitchen waste management. **Table 4** describes household kitchen waste management in the study area. The kitchen waste from 82% of the households was collected through solid waste collection conducted by HEPCO. Eighteen percent of the households separated kitchen waste from other waste and stored it in a bucket, to be collected daily to be used as feed for pig farmers outside of the Citadel. The practice of kitchen waste recycling for pig breeding is a good way to reduce solid wastes entering the landfill and to enhance nutrients recovery.

Table 4. Kitchen waste management (*n*=100)

Type of management	Proportion
Public collection	82%
Collection by pig farmers	18%

Greywater management. Discharge locations of greywater from the interviewed households are outlined in **Table 5**. Fifty-two percent of the houses were connected to the combined sewer system for discharge of greywater. The houses in the area that were not connected to the sewer system discharged greywater directly to the environment. Those living in small lanes utilized nearby vacant land or a simply constructed canal or channel for direct discharge of greywater to the ground at a distance from their houses (29%). For the households close to a lake or a river, direct discharge of greywater to these open water bodies usually occurred (19%). Greywater was not reused for any purposes in this area.

Table 5. Greywater management (*n*=100)

Discharge location	Proportion
Discharged to city sewer system	52%
Discharged to ground/groundwater	29%
Discharged to water bodies	19%

Toilet waste management. The toilet waste stream of 100 households is shown in **Figure 3**. Human excreta were flushed into a cistern-flush toilet (67%) or a pour-flush toilet (33%). Each toilet was connected to an on-site sanitation system, either a septic tank (80%) or a cesspool (20%). The ratio of septic tank connections in the area was similar to that in urban areas of Hanoi (90%) (Harada *et al.*, 2008) and Da Nang (80%) (Quang, 2010) in Vietnam, and Metro Manila in the Philippines (85%) (AECOM International Development, Inc. and Eawag-Sandec, 2010). It was also found that 62% of septic tanks in this area had desludged in the past with desludging intervals of 14±12 years (Avg.±S.D.). According to a recommendation from the U.S. Environmental Protection Agency (2000), a septic tank should be desludged every two to five years to recover its performance. However, only 34% of the already desludged septic tanks in this study met the criterion due to poor management, which led to poor performance. Septic tanks were managed improperly in Hue Citadel similarly to tank mismanagement in other cities in Vietnam and developing countries.

Effluent of on-site sanitation systems mainly flowed into the local environment: 44% to the ground/groundwater through a cesspool (20%) and through a septic tank (24%), and 16% to water bodies through a septic tank. It is evident that a large proportion of toilet waste in Hue Citadel was not managed properly.

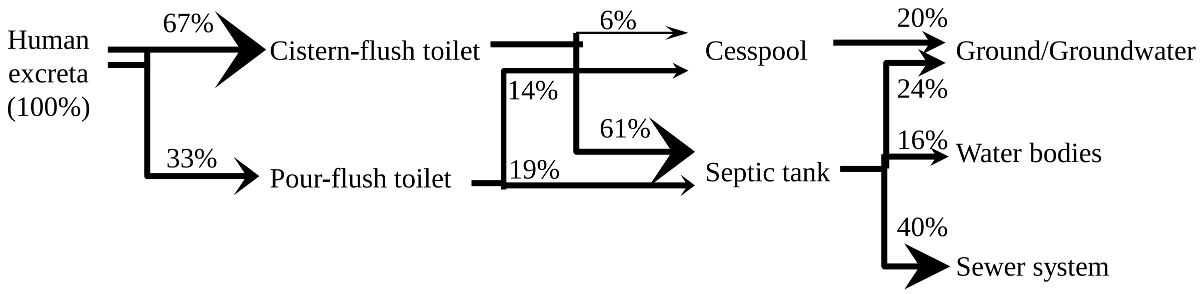

Figure 3. Toilet waste stream in Hue Citadel (*n*=100)

Phosphorus flow in Hue Citadel in 2013

The estimated phosphorus flow in Hue Citadel in 2013 is shown in **Figure 4**. Households discharged a large amount of phosphorus (81.5 kg P/(ha·year)), which was derived from toilet waste (50.6 kg P/(ha·year)), greywater (24.2 kg P/(ha·year)), and kitchen waste (6.7 kg P/(ha·year)). Therefore, the control of pollution loading from households is an important consideration.

As evident in **Figure 4**, on-site sanitation systems (septic tanks and cesspools) received the greatest amount of phosphorus from households (62.1%). The phosphorus loading of effluent from the sanitation systems was 41.5 kg P/(ha·year), of which 60% was discharged into water bodies or to the ground/groundwater, and the rest went into the sewer system. The phosphorus loading of fecal sludge was 9.1 kg P/(ha·year). Since the amount of fecal sludge collected by private companies cannot accurately be determined, we assumed that fecal sludge was only collected by HEPCO and dumped at a city landfill (0.3 kg P/(ha·year)); the rest (8.8 kg P/(ha·year)) remained in the facilities of on-site sanitation systems. Therefore, the phosphorus loading from on-site sanitation systems to water bodies would potentially increase if we take into account the unknown amount of fecal sludge collected by private companies. Proper monitoring of fecal sludge collection and its adequate treatment are crucial. Nevertheless, even if not considering this unknown effluent from on-site sanitation systems, the effluent was the second largest source of phosphorus loading to the water bodies and ground/groundwater. A measure to reduce the pollution loading from on-site sanitation systems is a major challenge to be addressed.

The sewer system received phosphorus mostly from households as greywater (12.7 kg P/(ha·year)) and from on-site sanitation systems effluent (16.6 kg P/(ha·year)). The sewer system played an important role in conveying phosphorus from several sources to the local receiving water bodies, which are a series of lakes and Ngu Ha River. As indicated in our calculation, 94.6% of phosphorus (29.9 kg P/(ha·year)) in the sewer system traveled to lakes and Ngu Ha River, while 5.4% (1.7 kg P/(ha·year)) accumulated in the system and was partly removed from the system and transferred to a landfill by dredging work of HEPCO. In our calculation, the sewer system was the largest source of phosphorus loading to the water bodies. However, the phosphorus flow from the sewer system to water bodies was calculated by the mass conservation law. Since many in-sewer processes potentially affect the phosphorus loading, the actual phosphorus loading through the sewer system should be studied further.

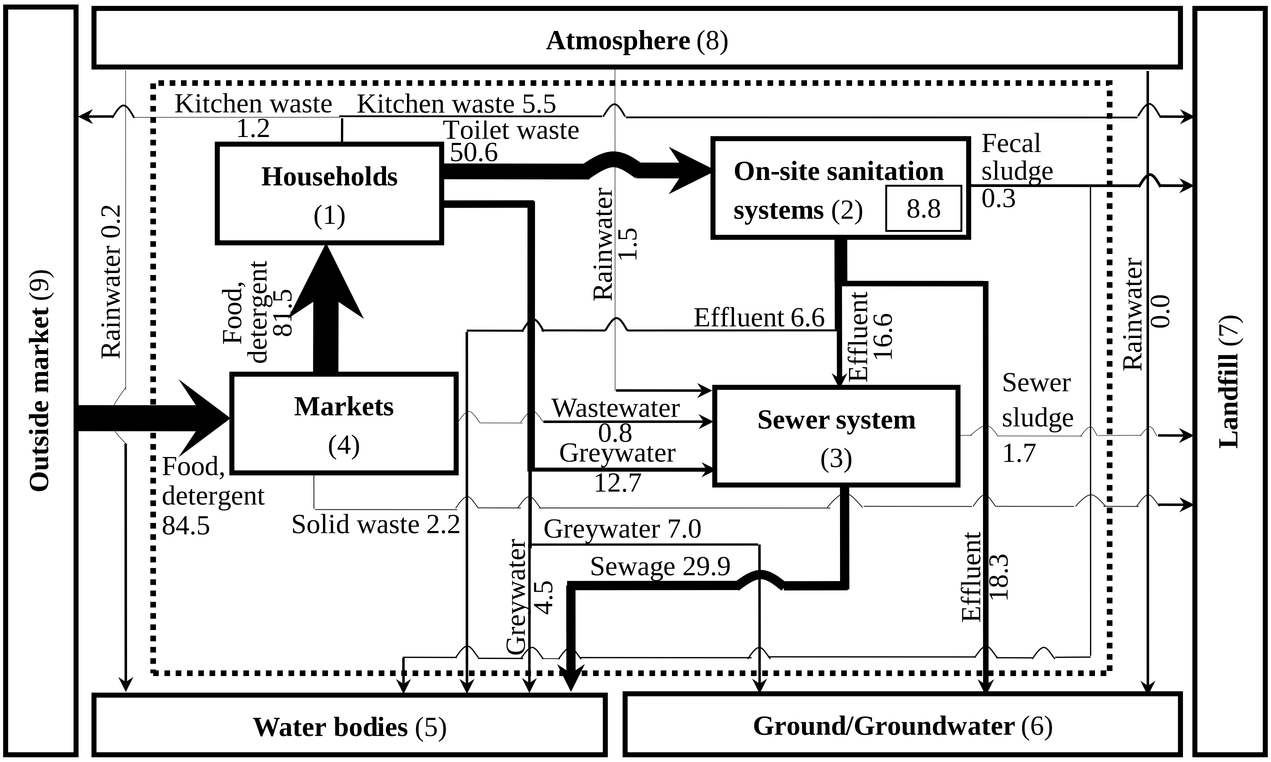

Figure 4. Phosphorus flow in 2013 (kg P/(ha·year))

Phosphorus destinations

The final destinations of phosphorus in Hue Citadel are shown in **Figure 5**. A large proportion of phosphorus was ultimately discharged into water bodies (41.2 kg P/(ha·year)), which is associated with deterioration of water quality in the Citadel. According to Hop *et al.* (2012), most water bodies in Hue Citadel are seriously eutrophicated with a trophic state index > 70 and an average phosphorus concentration of 1.5 mg/L. Among contributing factors, the sewer system added the greatest amount of phosphorus to water bodies (72.6%).

On the other hand, the phosphorus loading to the ground/groundwater was 25.3 kg P/(ha·year), and the majority of the phosphorus loading flowing to ground/groundwater was derived from effluent from on-site sanitation systems (72.3%), hence a major source of contamination to groundwater in the area. Better management of effluent from on-site sanitation systems will play an important role in reducing the loading to the ground/groundwater.

Kitchen waste from households was disposed of in a landfill and also used as a resource in pig breeding. Since kitchen waste contributed a large percentage of phosphorus to the landfill (56.7%), the resource recovery flow used for pig feed significantly reduced phosphorus loading to the landfill. Further use of kitchen waste is recommended for additional resource recovery.

Figure 6 compares the phosphorus loading to water bodies in Hue Citadel with the loading in other areas. The phosphorus loading to water bodies in Hue Citadel was higher than that in Trai hamlet, a suburban community of Hanoi (Giang *et al.*, 2012) and Hanam province (Nga *et al.*, 2011) in Vietnam. The loading was also higher in Hue Citadel than in other urban areas of developing countries such as Kumasi in Ghana (Belevi, 2002), and Chaohu (Yuan *et al.*, 2011) and Hefei (Li *et al.*, 2010) in China. These results were reflected by the phosphorus concentration in nearby water bodies. The average phosphorus concentration of water bodies in Hue Citadel was 1.5 mg/L (Hop *et al.*, 2012), surpassing both the Nhue River (0.66 mg/L) (VEA, 2012) and Chaohu Lake (0.16 mg/L) (Yang *et al.*, 2013), to which wastewater flowed from Hanoi and Hanam province, and from the cities of Hefei and Chaohu, respectively.

Phosphorus loading to water bodies was largely affected by the waste and wastewater management practices. The practice of utilizing phosphorus from domestic waste could have resulted in a lower phosphorus loading to water bodies in the communities of Hanoi, Hanam, Kumasi, Hefei, and Chaohu. However, this practice was limited in Hue Citadel. In addition, the presence of wastewater treatment plants in the cities of Hefei and Chaohu could transform a huge percentage of phosphorus from wastewater into sludge (*i.e.*, 85% in Hefei (Li *et al.*, 2010)), which helps reduce the phosphorus loading to water bodies in these cities.

Thus, reducing the phosphorous loading derived from the sewer system can be crucial in reducing the overall phosphorus loading discharged into water bodies. As the city of Hue plans to establish a centralized wastewater treatment plant, sewage treatment from the sewer system will contribute to the reduction. Moreover, as mentioned, effluent from on-site sanitation systems was the largest portion of the phosphorus loading to the sewer system, and also to the ground/groundwater. Improvement of on-site sanitation systems could also be crucial in mitigating the pollution. Furthermore, practices of phosphorus recovery from waste and wastewater should be encouraged, not only for the improvement of water quality, but also for the betterment of the material cycle in the area.

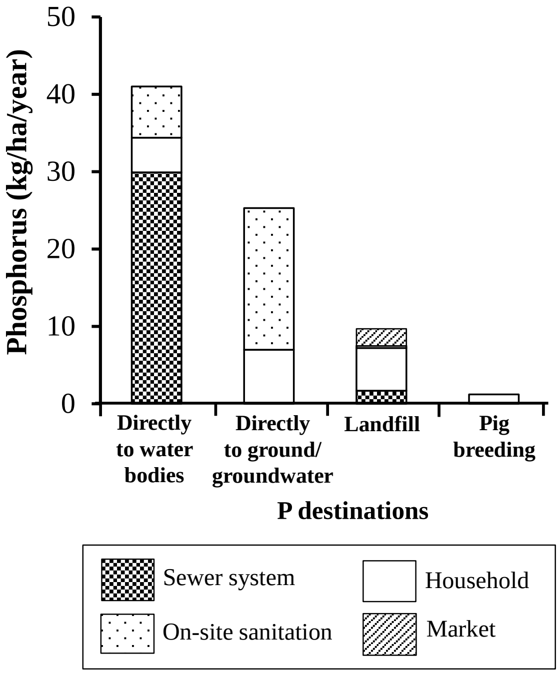

Figure 5. Phosphorus destinations

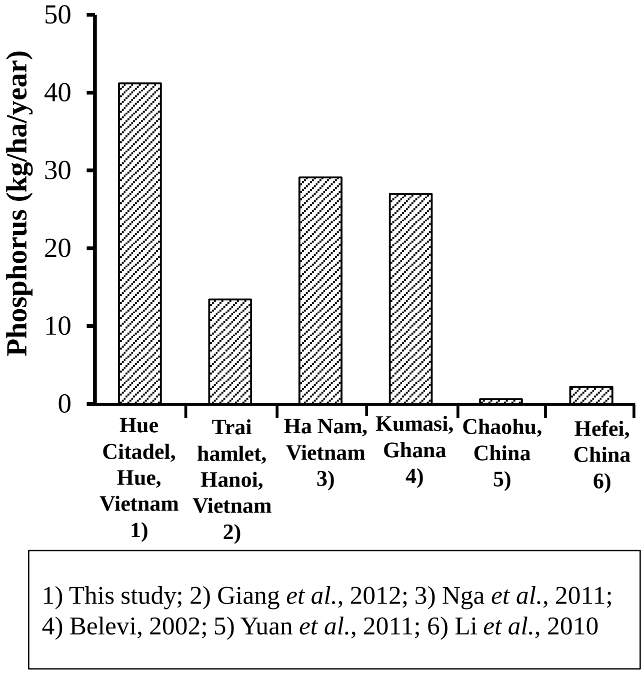

Figure 6. Phosphorus loading to water bodies in various areas

CONCLUSIONS

This study examined the characteristics of waste and wastewater management in Hue Citadel and a material flow model was developed to characterize the phosphorus flow in Hue Citadel in 2013. Due to the absence of a wastewater treatment plant and wastewater reuse practices, most wastewater generated in the Citadel was eventually discharged into water bodies and to the ground/groundwater. This discharge has led to alarmingly large levels of phosphorus released into water bodies (41.2 kg P/(ha·year)) and to the ground/groundwater (25.3 kg P/(ha·year)), which has become an issue in surface water and groundwater protection. The sewer system, which received various types of wastewater, contributed the greatest phosphorus loading to water bodies (72.6%), whereas a major part of phosphorus loading to the ground/groundwater was derived from effluent from on-site sanitation systems. To mitigate the phosphorus loading to surface water, it is crucial to reduce the phosphorus loading derived from the sewer system. In addition, an improvement of on-site sanitation systems together with proper fecal sludge treatment is essential both for the prevention of groundwater contamination and surface water pollution.

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