Preliminary analysis of phosphorus flow in Hue Citadel
T. N. Q. Anh, H. Harada, S. Fujii, P. N. Anh, P. K. Lieu and S. Tanaka

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 the phosphorus output flowing 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.

Key words | 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. 2015; Montanero 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.

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 & 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 by 3.5 times (Giang et al. 2015). 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 value. 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 (namely 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 m² (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 of it illegally into waterways (AECOM International Development Inc. & Eawag-Sandec 2010). However, the exact number of private companies desludging and the collected amount of sludge are 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.

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 the 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 waste 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):

\[ n = N(1 + Ne^2) \]

where: \( n = \) sample size (number of interviewed households); \( N = \) population size (total number of households in Hue Citadel = 13,695); \( e = \) acceptable error (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 are shown in Table 1.

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.

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. (2015) (Figure 2). The system boundary is defined by the administrative boundary of four wards (Thuan Thanh, Thuan Loc, Thuan Hoa, and Tay Loc). The model has four components inside the system boundary, i.e. households (\( j = 1 \)), on-site sanitation systems (\( j = 2 \)), a sewer system (\( j = 3 \)), and markets (\( j = 4 \)), and five components outside the system boundary, i.e. water bodies (river and lakes) (\( j = 5 \)), ground/groundwater (\( j = 6 \)), landfill (\( j = 7 \)), atmosphere (\( j = 8 \)), and outside market (\( j = 9 \)).

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

\[ P_{i,j}(k) = \frac{(U_{i}(k) \times C_{i}(k) \times R_{j}(k))}{S} \]

where: \( U_{i}(k) = \) unit phosphorus discharge (transfer) rate of material \( k \) from component \( i \) (kg P/(unit amount-year));
The flows, which could not be calculated by unit value method, were calculated based on mass conservation law, which is as follows:

\[ \text{Total input to component } m \left( \sum_k \sum_i p_{i,m(k)} \right) = \text{Total output from component } m \left( \sum_k \sum_i p_{i,j(k)} \right) \]  

(3)

Details of each equation are shown in Table 3.

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

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**Table 2 | Secondary data**

<table>
<thead>
<tr>
<th>Contents</th>
<th>Unit</th>
<th>Value</th>
<th>Source</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population in 2013</td>
<td>people</td>
<td>60,106</td>
<td>a</td>
<td>P</td>
</tr>
<tr>
<td>Total Citadel area in 2013</td>
<td>ha</td>
<td>520</td>
<td>a</td>
<td>S</td>
</tr>
<tr>
<td>Average rainfall at Hue station in 2013</td>
<td>mm/year</td>
<td>2,730.7</td>
<td>b</td>
<td>C_{rain}</td>
</tr>
<tr>
<td>Unit phosphorus rate by human excreta</td>
<td>g/(cap day)</td>
<td>1.2</td>
<td>c</td>
<td>U_{1(he)}</td>
</tr>
<tr>
<td>Phosphorus transfer coefficient in fecal sludge from septic tank</td>
<td>–</td>
<td>0.18</td>
<td>c</td>
<td>U_{2(fs)}</td>
</tr>
<tr>
<td>Unit phosphorus rate by greywater</td>
<td>g/(cap day)</td>
<td>0.59</td>
<td>d</td>
<td>U_{1(gw)}</td>
</tr>
<tr>
<td>Unit phosphorus rate by market wastewater</td>
<td>g/(m² day)</td>
<td>0.064</td>
<td>d</td>
<td>U_{4(maw)}</td>
</tr>
<tr>
<td>Unit phosphorus rate by kitchen wastes</td>
<td>g/(cap day)</td>
<td>0.16</td>
<td>e</td>
<td>U_{1(hw)}</td>
</tr>
<tr>
<td>Unit phosphorus rate by rainwater</td>
<td>mg/L</td>
<td>0.0625</td>
<td>f</td>
<td>U_{1(hw)}</td>
</tr>
<tr>
<td>Unit phosphorus rate by sewer sludge</td>
<td>g/kg</td>
<td>2.84</td>
<td>g</td>
<td>U_{3(ss)}</td>
</tr>
<tr>
<td>Phosphorus ratio in market solid wastes</td>
<td>–</td>
<td>0.0022</td>
<td>h</td>
<td>U_{4(sw)}</td>
</tr>
<tr>
<td>Amount of market solid wastes</td>
<td>kg/year</td>
<td>521,286</td>
<td>i</td>
<td>C_{sw}</td>
</tr>
<tr>
<td>Amount of sewer sludge</td>
<td>kg/year</td>
<td>312,000</td>
<td>j</td>
<td>C_{sw}</td>
</tr>
<tr>
<td>Water surface area</td>
<td>m²</td>
<td>690,190</td>
<td>k</td>
<td>S_{wb}</td>
</tr>
<tr>
<td>Pervious surface area</td>
<td>m²</td>
<td>52,141</td>
<td>k</td>
<td>S_{pc}</td>
</tr>
<tr>
<td>Impervious surface area</td>
<td>m²</td>
<td>4,457,669</td>
<td>k</td>
<td>S_{im}</td>
</tr>
<tr>
<td>Market area</td>
<td>m²</td>
<td>17,969</td>
<td>k</td>
<td>S_{ma}</td>
</tr>
</tbody>
</table>

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*People’s Committee of Wards (2013).
*Thua Thien Hue Hydrometeorological Center (2013).
*Schouw et al. (2002).
*Yuang et al. (2007).
*Huy (2007).
*Karthikeyan et al. (2007).
*HEPCO (2013b).
*HEPCO (2013a).
*CIT (2013b).
were not connected to the sewer system discharged
the houses were connected to the combined sewer system
households are outlined in Table 5. Fifty-two percent of
Discharge locations of greywater from the interviewed
Greywater management
Discharge locations of greywater from the interviewed
Table 3 | Equations for the calculation of individual phosphorus flows (kg P/ha/year)

<table>
<thead>
<tr>
<th>Component (f) from-to</th>
<th>Material</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Households to on-site sanitation systems</td>
<td>Toilet waste (tw)</td>
<td>( P_{1,2(fw)} = \left( \frac{U_{1(fw)}}{C_{0,1(fw)}} \times P \times 365 \times 10^{-3} \right) / S ) (4)</td>
</tr>
<tr>
<td>Households to sewer system</td>
<td>Greywater (gw)</td>
<td>( P_{1,3(gw)} = \left( \frac{U_{1(gw)}}{C_{0,1(gw)}} \times P \times R_{gw} \times 365 \times 10^{-3} \right) / S ) (5)</td>
</tr>
<tr>
<td>Households to water bodies</td>
<td>Greywater (gw)</td>
<td>( P_{1,5(gw)} = \left( \frac{U_{1(gw)}}{C_{0,1(gw)}} \times P \times R_{gw} \times 365 \times 10^{-3} \right) / S ) (6)</td>
</tr>
<tr>
<td>Households to ground/groundwater</td>
<td>Greywater (gw)</td>
<td>( P_{1,6(gw)} = \left( \frac{U_{1(gw)}}{C_{0,1(gw)}} \times P \times R_{6gw} \times 365 \times 10^{-3} \right) / S ) (7)</td>
</tr>
<tr>
<td>Households to landfill</td>
<td>Kitchen waste (kw)</td>
<td>( P_{1,7(kw)} = \left( \frac{U_{1(kw)}}{C_{0,1(kw)}} \times P \times R_{kw} \times 365 \times 10^{-3} \right) / S ) (8)</td>
</tr>
<tr>
<td>Households to outside market</td>
<td>Kitchen waste (kw)</td>
<td>( P_{1,9(kw)} = \left( \frac{U_{1(kw)}}{C_{0,1(kw)}} \times P \times R_{6kw} \times 365 \times 10^{-3} \right) / S ) (9)</td>
</tr>
<tr>
<td>Markets to households</td>
<td>Food, detergent (fd)</td>
<td>( P_{1,1/60} = P_{1,9} + P_{1,7} + P_{1,2} + P_{1,3} + P_{1,6} + P_{1,5} ) (10)</td>
</tr>
<tr>
<td>On-site sanitation systems storage</td>
<td>Fecal sludge (fs)</td>
<td>( P_{2,2(fw)} = (P_{1,1(fw)} \times U_{2(fw)}) - P_{2,7} ) (11)</td>
</tr>
<tr>
<td>On-site sanitation systems to sewer system</td>
<td>Effluent (ef)</td>
<td>( P_{2,3(ef)} = [P_{1,2} - (P_{1,2} \times U_{2(fw)})] \times R_{3(ef)} ) (12)</td>
</tr>
<tr>
<td>On-site sanitation systems to water bodies</td>
<td>Effluent (ef)</td>
<td>( P_{2,5(ef)} = [P_{1,2} - (P_{1,2} \times U_{2(fw)})] \times R_{5(ef)} ) (13)</td>
</tr>
<tr>
<td>On-site sanitation systems to ground/groundwater</td>
<td>Effluent (ef)</td>
<td>( P_{2,6(ef)} = [P_{1,2} - (P_{1,2} \times U_{2(fw)})] \times R_{6(ef)} ) (14)</td>
</tr>
<tr>
<td>On-site sanitation systems to landfill</td>
<td>Fecal sludge (fs)</td>
<td>( P_{2,7(ef)} = [(P_{1,2} \times U_{2(fw)}) \times h_{w} \times 10^{-3}] / f_{fs} / S ) (15)</td>
</tr>
<tr>
<td>Sewer system to landfill</td>
<td>Sewer sludge (ss)</td>
<td>( P_{3,7(ef)} = \left( \frac{C_{as} \times U_{3(as)} \times 10^{-3}}{S} \right) / S ) (16)</td>
</tr>
<tr>
<td>Sewer system to water bodies</td>
<td>Sewage (sg)</td>
<td>( P_{3,5(ef)} = P_{1,3} + P_{2,3} + P_{3,7} ) (17)</td>
</tr>
<tr>
<td>Markets to sewer system</td>
<td>Wastewater (wae)</td>
<td>( P_{4,3(efw)} = \left( \frac{U_{4(efw)} \times S_{ma} \times 365 \times 10^{-3}}{S} \right) / S ) (18)</td>
</tr>
<tr>
<td>Markets to landfill</td>
<td>Solid waste (sw)</td>
<td>( P_{4,7(efw)} = \left( \frac{C_{as} \times U_{4(asw)}}{S} \right) / S ) (19)</td>
</tr>
<tr>
<td>Outside-market to markets</td>
<td>Food, detergent (fd)</td>
<td>( P_{10,4(efw)} = P_{1,4} + P_{4,3} + P_{4,7} ) (20)</td>
</tr>
<tr>
<td>Atmosphere to water bodies</td>
<td>Rainwater (rwe)</td>
<td>( P_{8,5(efw)} = \left( \frac{C_{as} \times U_{8(efw)} \times S_{sw} \times 10^{-4}}{S} \right) / S ) (21)</td>
</tr>
<tr>
<td>Atmosphere to sewer system</td>
<td>Rainwater (rwe)</td>
<td>( P_{8,3(efw)} = \left( \frac{C_{as} \times U_{8(efw)} \times S_{sm} \times 10^{-4}}{S} \right) / S ) (22)</td>
</tr>
<tr>
<td>Atmosphere to ground/groundwater</td>
<td>Rainwater (rwe)</td>
<td>( P_{8,6(efw)} = \left( \frac{C_{as} \times U_{8(efw)} \times S_{sw} \times 10^{-4}}{S} \right) / S ) (23)</td>
</tr>
</tbody>
</table>

Table 4 | Kitchen waste management (n = 100)

<table>
<thead>
<tr>
<th>Type of management</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public collection</td>
<td>82%</td>
</tr>
<tr>
<td>Collection by pig farmers</td>
<td>18%</td>
</tr>
</tbody>
</table>

Table 5 | Greywater management (n = 100)

<table>
<thead>
<tr>
<th>Discharge location</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharged to city sewer system</td>
<td>52%</td>
</tr>
<tr>
<td>Discharged to ground/groundwater</td>
<td>29%</td>
</tr>
<tr>
<td>Discharged to water bodies</td>
<td>19%</td>
</tr>
</tbody>
</table>

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 nutrient recovery.

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.

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. & Eawag-Sandec 2010). It was also found that 62% of septic tanks in this area had been desludged in the past, with desludging intervals of 14 ± 12 years (Avg. ± S.D.). According to a recommendation from the US Environmental Protection Agency (2000), a septic tank should be desludged every 2 to 5 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.

### 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

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

**Figure 4** | Phosphorus flow in 2013 (kg P/(ha year)).
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 Ngù 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 Ngù 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.

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. 2011) 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.
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 phosphorus 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.

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 for the prevention of both groundwater contamination and surface water pollution.

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