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Optimising water and phosphorus management in the urban environmental sanitation system of Hanoi, Vietnam

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Abstract

Many areas in the world face clean water scarcity problems and phosphorus reserves are likely to be depleted in the near future. Still, a large amount of clean water is used to transport excreta through sewer systems. Most of the wastewater generated worldwide is discharged untreated into aquatic systems and leads to water pollution and loss of valuable nutrients. In Hanoi, Vietnam's capital city, high population and economic growth as well as industrialisation have led to a decrease in groundwater level and to serious river and lake pollution. A probabilistic model, simulating the impact of measures on groundwater abstraction and nutrient recovery, was used to determine the impact of policy changes in Hanoi. The results obtained reveal that harmonising environmental sanitation and agricultural systems with one another will considerably increase nutrient recovery for food production, lower expenditure for artificial fertilisers and reduce the nutrient load into the environment. The model can be applied in urban areas of developing countries to assist in the design of environmental sanitation concepts.

Keywords: Environmental sanitation; Material flow analysis; Phosphorus; Nutrient recovery; Hanoi; Developing countries

1. Introduction

Water, nutrient and energy management practices of the conventional sanitation system are unsustainable. For example, large quantities of clean, potable water carry excreta through sewer systems. The world's drinking water resources decreased from 17,000 m^3 $capita^{-1}$ in 1950 to 7000 m^3 $capita^{-1}$ in the 1990s (UNDP, 1998) as a result of decreasing freshwater quantity and a near doubling of the world's population (Berndtsson and Hyvönen, 2002). Besides, some 90% of the wastewater generated worldwide are discharged untreated into receiving water bodies (GTZ, 2006). Excessive nutrient loads in aquatic systems stimulate plant growth and reduce dissolved oxygen in the water (eutrophication). Moreover, valuable nutrients contained in human excreta are therefore lost. Faeces and urine contain about 4.5 kg nitrogen, 0.55 kg phosphorus and 1.3 kg potassium per person and year. This is theoretically

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sufficient to cover the annual wheat and maize requirement of one person (Esrey, 1998). Since most of these nutrients are released with wastewater into the environment, artificial fertilisers must cover the agricultural nutrient demand. Production of artificial nitrogen fertiliser is energy-intensive and phosphate rocks are mined for the production of phosphorus fertilisers. However, phosphorus reserves are likely to be depleted within 50–100 years (Cordell, 2005). To secure water and phosphorus reserves for future generations, new environmental sanitation[1] concepts must be developed in compliance with the principles of "closed loop" resource management.

Hanoi and many other cities in developing countries with their high population growth, industrialisation and economic development are facing increased resource consumption and environmental degradation. Peri-urban agriculture is of key importance in the supply of food and provision of income to the poorest section of the population. However, rapid urbanisation also creates pressure on peri-urban land. Farmers tend to use more fertilisers in an attempt to enhance yield and benefit from their decreasing land area. An improved balance between water and nutrient supply in urban waste products, and water and nutrient demand in peri-urban food production could be the key to reducing resource consumption and environmental pollution.

The material flow analysis (MFA) method studies the resource fluxes used and transformed as they flow through a region. In industrialised countries, MFA proved to be a suitable instrument for the early recognition of environmental problems and development of countermeasures (Baccini and Brunner, 1991). It can be applied to analyse resource flows in a city, particularly to evaluate the impact of changes in consumption patterns, solid waste and wastewater treatment infrastructure, peri-urban agricultural production, including waste and wastewater reuse practices on resource consumption and environmental pollution. It provides useful information for planners and decision-makers and could help improve resource management of Hanoi's environmental sanitation system and other cities in developing countries. However, limited data availability, reliability and data collection means (available laboratory equipment, trained laboratory staff, financial and human resources) are common problems faced by developing countries and restrain the use of MFA as a policy-making tool.

Based on the method of material flow analysis, a tool assisting planners to optimise the environmental sanitation system with limited data availability was developed and tested in Hanoi (Montangero, 2006). This paper presents an application of this tool comprising an assessment of the impact of changes in Hanoi's environmental sanitation and agricultural practices on groundwater abstraction and phosphorus recovery in peri-urban agriculture.

2. Methodology

2.1. Description of the study area

Hanoi, capital and second largest city of Vietnam, comprises seven inner districts and five suburban districts with a registered population of 2.8 million (HSO, 2002). Formerly, the suburban districts were agricultural areas supplying food to the capital. Currently, new factories as well as industrial and export processing zones are being established in these districts. The most important changes in Vietnam's political economy began with the *Doi Moi* (Renovation policy) reforms in 1986 (Quang and Kammeier, 2002) leading to an opening of the economy to foreign capital. This boosted the urbanisation process, especially in Ho Chi Minh City and Hanoi, which experienced the greatest economic growth. Between 1991 and 1999, Hanoi's provincial population grew by 590,700, 319,000 of which were migrants and the remainder was natural population growth. These figures do not include the many unregistered immigrants living in Hanoi temporarily or permanently (van den Berg et al., 2003). Hanoi's population is steadily increasing at a high rate, with an expected population in the urban agglomeration of more than five million inhabitants by 2015 (UN, 2004). Rapid urbanisation poses a real challenge to Hanoi's authorities as far as ensuring water supply, solid waste and wastewater management services. It further creates significant pressure on the environment and on resource consumption.

Groundwater is Hanoi's main water supply source, however, the city's water demand is already reaching the aquifer's recharge rate. The groundwater level is lowered by overexploitation and some urban sectors are experiencing land subsidence. Nitrogen ammonia pollution of some deep wells within the inner city and of many peri-urban shallow wells is of growing concern. Septic tanks are the most common urban on-site sanitation option in Hanoi. Septic tank effluents are mainly discharged into the sewerage and drainage network. All the wastewater is discharged untreated into the aquatic system draining into the Nhue and Red Rivers, aside from the toilet wastewater pretreated in septic tanks and a limited amount of industrial and

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[1] Environmental sanitation comprises water supply, excreta, wastewater and solid waste management as well as drainage.

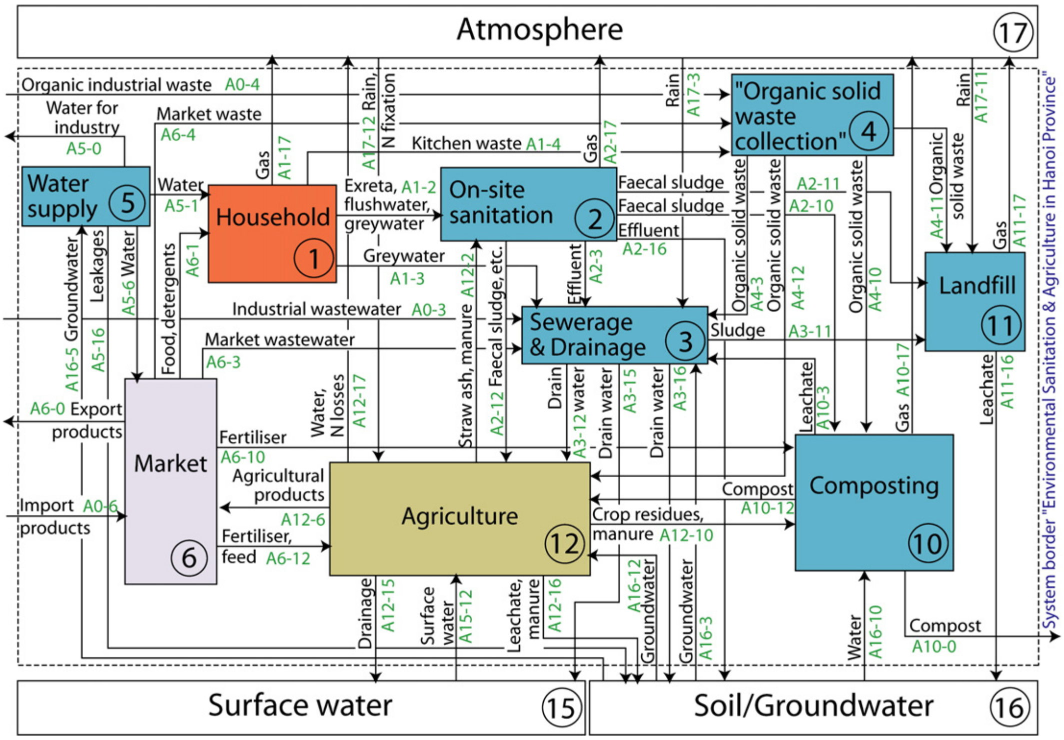

Fig. 1. System analysis of "environmental sanitation and agriculture in Hanoi province, Vietnam". Some process numbers are missing, as the figure does not include all the processes.

hospital wastewater, which is subjected to preliminary treatment (Viet Anh et al., 2004). The collected sludge from septic tanks in the urban centre is usually landfilled and a small fraction is co-composted with solid waste. In peri-urban areas, latrines are generally emptied by individuals and their content reused as fertiliser in agriculture or aquaculture either directly of after on-farm composting with other waste. About 70% of the solid waste generated in the urban districts are collected and landfilled; a small portion is co-composted with faecal sludge. The uncollected waste is either discharged on open dumps or in drainage channels, burnt in the open or recycled. Lakes, ponds and canals in Hanoi are seriously affected by untreated domestic and industrial wastewater. In Thanh Tri district located downstream of Hanoi, farmers use urban and industrial effluents as fertiliser and fish food (van den Berg et al., 2003). Although this practice has reportedly led to higher yields and greater financial benefits, it is also associated with health risks.

With regard to water and nutrient management, the following key issues have been identified:

- Excessive groundwater abstraction
- Serious surface water pollution
- Increased fertiliser consumption in peri-urban agriculture

Section 3 discusses the impact of different measures on groundwater consumption and nutrient recovery.

2.2. Assessing material flows despite limited data

In a material flow analysis (Baccini and Brunner, 1991), a system analysis is first conducted defining system border, goods, indicators, and processes relevant to selected key issues. Goods are materials or material mixtures with functions valued by man such as water, human excreta and wastewater. Indicator substances are chemical elements and their compounds such as water and phosphorus. Processes describe the transformation, transport or storage of goods and substances (e.g. household, wastewater treatment plant and landfill). In a next step, a mathematical model describing material flows as functions of different parameters is developed and calibrated. Finally, the status quo is analysed and different scenarios are simulated and evaluated. These different steps are described in more detail in Sections 2.3–3.2.

A probabilistic model was developed describing material flows in the environmental sanitation and agricultural

Table 1
Probability distributions of model parameters used to calculate groundwater consumption in Hanoi province

Model parameters	Uncertainty distribution	Reference
Number of inhabitants [1000 inhabitants]	Normal (3100; 400)	HSO (2002)) and assuming 15% unregistered inhabitants
Household water consumption [l cap^{-1} day^{-1}]	Normal (120; 10)	(CERWASS, 2004; Büsser, 2006)
Industrial water consumption [1000 m^3 year^{-1}]	Lognormal (17,000; 5000)	Osterwalder (2006)
Market wastewater generation [l m^{-2} day^{-1}]	Lognormal (70; 20)	Sinsupan (2004)
Market surface area [m^2]	Normal (610,000; 15,000)	Hanoi City PC (2005)
Evaporation [mm year^{-1}]	Normal (1262; 126)	Müller (1983)
Ratio of leakage losses related to total water flow [−]	Normal (0.25; 0.05)	WHO (2001)

Means and standard deviations are provided in parenthesis.

system of Hanoi province (Montangero, 2006). To assist model users in dealing with scarce data, the number of parameters was minimised. Parameters difficult to quantify were replaced by others more easily assessed or measured. Model parameters are expressed as probability distributions. Variables uncertainty is assessed by Monte Carlo simulation. Parameter values were first evaluated from a literature review and by eliciting expert judgement. The latter method enables to gain a greater understanding of specific system parts and prior probability distributions for unknown model parameters. Where parameter values or calculated variables were not plausible, parameter values were reassessed more accurately. Sensitivity analysis was performed to identify parameters requiring a more accurate assessment. Sensitive parameters were reassessed by conducting a more differentiated literature review, surveys and measuring campaigns.

2.3. System analysis

Fig. 1 illustrates the system forming the basis of the model. The boxes designate processes and the arrows represent the flows. The system is divided into four main parts:

- The households as water, detergent and food consumer as well as excreta, wastewater and organic waste producer.
- The urban environmental sanitation sector: water supply, on-site sanitation, sewerage and drainage network, solid waste collection, landfill and open dumps as well as composting.
- The peri-urban food production sector: crop production, livestock production and aquaculture.
- The environment as water supply source (groundwater, surface water, and atmosphere) as well as nutrient supplier (nitrogen fixation, nutrient deposition from the atmosphere) and receiver (surface water, groundwater and atmosphere).

The process “market” is a platform for the exchange of goods produced in Hanoi and distributed to the households in and outside Hanoi province, and where imported products such as food and agricultural inputs (fertiliser) are distributed to the households and agricultural processes. The process “industry” has been left outside the system border as the model focuses on the household water and environmental sanitation as well as agricultural sectors. Nevertheless, input and output flows to and from the process “industry” have been taken into account to include the overall water use as well as wastewater and solid waste flows into the environment.

Nitrogen and phosphorus have been selected as indicators. The system allows analysis of the impact of changes (household consumption patterns, type of sanitation infrastructure, crop and livestock categories, waste and wastewater reuse practices) on groundwater and fertiliser consumption, nutrient load discharged into the environment and nutrient recovery in peri-urban agriculture.

2.4. Modelling approach

As aforementioned, a model was developed describing mass flows of goods, nitrogen and phosphorus in the environmental sanitation and agricultural system of Hanoi province. Each flow is a variable expressed as a function of parameters. There are two types of equations,

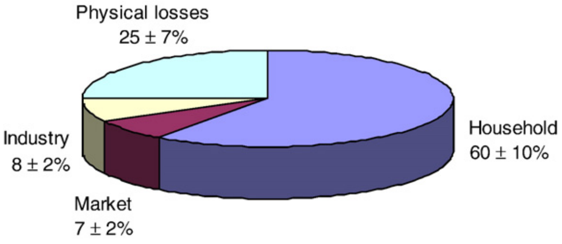

Fig. 2. Groundwater consumers and their relative importance.

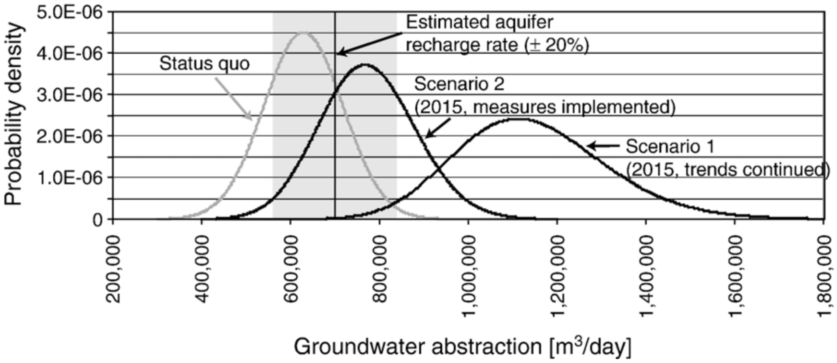

Fig. 3. Current groundwater abstraction today, in 2015 if current trends remain unchanged (Scenario 1), if leakage is reduced, if greywater is reused for toilet flushing and if industrial water consumption is reduced (Scenario 2). The estimated aquifer recharge rate is also illustrated with an assumed uncertainty interval of ±20%.

i.e. balance and model equation. The law of mass conservation allows to formulate a balance equation (Eq. (1)) for each process. Model equations are based on scientific and expert knowledge and express how different parameters determine the flows (variables) in the system.

$$\partial M_i^{(j)}/\partial t = \sum_r A_{i,r\text{–}j} - \sum_s A_{i,j\text{–}s} (\text{balance equation}) \qquad (1)$$

where i expresses the indicator substance, j the process number, $M_i^{(j)}$ the stock of substance i in process j, t the time, r the source process, s the destination process, $A_{i,r\text{–}j}$ the input flow of substance i from the source process r to the process j, and $A_{i,j\text{–}s}$ the output flow of substance i from the process j to the destination process s. The left side of the equation represents the stock change rate of substance i within the process j; the right side expresses the difference between input and output flows of substance i to and from process j.

2.5. Parameter assessment

Probability distribution type (normal, lognormal or uniform) and characteristics (mean and standard deviation or minimum and maximum) were determined for each parameter. Parameters were first assessed on the basis of a literature review and an expert elicitation study. Since some of the calculated flows from the first rough parameter value assessment were not plausible, sensitive parameters were reassessed by conducting a more differentiated literature review and measurement campaigns.

Given the limited data for each parameter, the type of probability distribution could not be determined from existing data but had to be assumed on the basis of the parameter type. According to Morgan and Henrion (1990), the lognormal distribution is appropriate to represent physical quantities that are constrained to being non-negative and positively skewed, such as pollutant concentrations and stream flows. Moreover, the lognormal distribution is particularly suitable to represent large uncertainties. Standard deviation was assumed based on parameter type and information source. Probability distributions of the parameters used to calculate groundwater abstraction and phosphorus recovery for food production are characterised in Section 3.

3. Results and discussion

The calibrated model was applied to simulate the impact of different measures on groundwater consumption and phosphorus recovery for food production in Hanoi.

3.1. Groundwater abstraction

3.1.1. Parameter values

Table 1 contains probability distributions of the parameters used to calculate groundwater abstraction in Hanoi and derived from a literature review. Water consumption of most inhabitants is assumed to lie within the same range with fewer people consuming a lot less or a lot more than the assumed mean. Consequently, water consumption is assumed to follow a normal distribution. Similarly, the number of inhabitants, market surface area, evaporation, and percentage of leakage losses in the water distribution network were also assumed to be normally distributed. The market wastewater generation rate was assumed to be lognormally distributed, as rain events may cause much larger peak flows than average flows. Distribution is therefore likely to be positively skewed. Industrial water

Table 2
Probability distributions of the main model parameters used to calculate the phosphorus load in waste products and P load reused in agriculture in Hanoi province

Model parameters	Uncertainty distribution	Reference
Number of inhabitants [1000 inhabitants]	Normal (3100; 400)	HSO (2002) and assuming 15% unregistered inhabitants
Ratio of inhabitants equipped with septic tank (WC flush) related to total no. of inhabitants [−]	Normal (0.15; 0.02)	(Hanoi URENCO, 2000; CERWASS, 2004)
Ratio of inhabitants equipped with septic tank (pour flush) related to total no. of inhabitants [−]	Normal (0.48; 0.07)	(Hanoi URENCO, 2000; CERWASS, 2004)
Ratio of inhabitants equipped with septic tanks or biogas latrines receiving pig slurry related to total no. of inhabitants [−]	Normal (0.05; 0.001)	(Hanoi URENCO, 2000; CERWASS, 2004)
Ratio of inhabitants equipped with pour flush infiltration latrines related to total no. of inhabitants [−]	Normal (0.01; 0.001)	(Hanoi URENCO, 2000; CERWASS, 2004)
Ratio of inhabitants equipped with dry single pit latrines related to total no. of inhabitants [−]	Normal (0.13; 0.02)	(Hanoi URENCO, 2000; CERWASS, 2004)
Ratio of inhabitants equipped with dry double pit latrines with urine diversion related to total no. of inhabitants [−]	Normal (0.16; 0.04)	(Hanoi URENCO, 2000; CERWASS, 2004)
Ratio of inhabitants equipped with bucket latrines related to total no. of inhabitants [−]	Normal (0.02; 0.01)	(Hanoi URENCO, 2000; CERWASS, 2004)
Total food protein in food supply [g cap^{-1} day^{-1}]	Normal (62.3; 5)	FAOSTAT (2004)
Vegetable food protein in food supply [g cap^{-1}day^{-1}]	Normal (46.2; 4)	FAOSTAT (2004)
Ratio between phosphorus load in excreta and total + vegetable food protein supply [−]	Normal (0.011; 0.0025)	Jönsson et al. (2004)
Septic tank emptying frequency factor[a] [−]	Lognormal (5; 2)	Assumption
Phosphorus transfer coefficient in faecal sludge from septic tanks [−]	Lognormal (0.2; 0.05)	Montangero and Belevi (2007)
Phosphorus transfer coefficient in faecal sludge from biogas latrines [−]	Lognormal (0.2; 0.05)	Assumption (see septic tanks)
Phosphorus transfer coefficient in faecal sludge from pit latrines [−]	Lognormal (0.3; 0.1)	Montangero and Belevi (2007)
Phosphorus load in greywater [g P cap^{-1} day^{-1}]	Lognormal (0.5; 0.2)	Büsser (2006)
Ratio of greywater discharged into septic tanks related to total greywater [−]	Lognormal (0.1; 0.1)	Assumption
Ratio of septic tank effluent discharged into drainage related to total septic tank effluent [−]	Normal (0.9; 0.05)	Assumption
Ratio between phosphorus load in urine and phosphorus load in excreta [−]	Lognormal (0.55; 0.08)	(Polprasert, 1996; Drangert, 1998; Heinss et al., 1998; Schouw et al., 2002a; GHD, 2003)
Ratio of misdiverted urine related to total urine [−]	Lognormal (0.2; 0.05)	Jönsson and Vinnerås (2003)
Straw ash added to pit latrines [kg cap^{-1} day^{-1}]	Normal (0.12; 0.03)	Nghien and Calvert (2000) and assuming an ash density of 600 g/l
Phosphorus content in ash [mg P 100 g^{-1}]	Lognormal (84; 25)	Pasquini and Alexander (2004)
Phosphorus load in kitchen waste [g P cap^{-1} day^{-1}]	Lognormal (0.2; 0.1)	(Diaz et al., 1996; Rytz, 2001; Schouw et al., 2002b; Strauss et al., 2003; Sinsupan, 2004)
Market surface area [m^2]	Normal (610,000; 15,000)	Hanoi City PC (2005)
Generation rate of organic market solid waste [kg m^{-2} day^{-1}]	Normal (0.7; 0.15)	Sinsupan (2004)
Moisture content of organic solid waste [%]	Lognormal (76; 5)	(Schouw et al., 2002b; Sinsupan, 2004)
Phosphorus content in organic solid waste [%TS]	Lognormal (0.5; 0.2)	(Schouw et al., 2002b; Sinsupan, 2004)
Phosphorus load in industrial organic waste [tonnes of P year^{-1}]	Lognormal (70; 21)	Osterwalder (2006)
Number of piglets per sow per year[b] [piglets sow^{-1} year^{-1}]	Normal (21; 3)	Ruettimann and Menzi (2001)
Number of breeding sows [sows]	Normal (36,706; 3,000)	HSO (2004)
Phosphorus load in fattening pig manure [kg P fattener^{-1} cycle^{-1}]	Normal (1.5; 0.25)	Ruettimann and Menzi (2001)
Phosphorus load in sow manure (including piglets) [kg P sow^{-1} year^{-1}]	Normal (10.5; 1)	Ruettimann and Menzi (2001)

Table 2 (*continued*)

Model parameters	Uncertainty distribution	Reference
No. of fatteners:total no. of pigs ratio [−]	Normal (0.9; 0.02)	HSO (2004)
Sown area of spring paddy[b] [ha]	Normal (24,260; 1000)	HSO (2004)
Sown area of summer paddy [ha]	Normal (26,484; 1000)	HSO (2004)
Yield from spring paddy [tonnes ha^{-1} year^{-1}]	Normal (4.45; 0.25)	HSO (2004)
Yield from summer paddy [tonnes ha^{-1} year^{-1}]	Normal (3.6; 0.25)	HSO (2004)
Phosphorus uptake in rice straw [kg P t grain^{-1}]	Normal (0.6; 0.1)	IFA (2006)
Irrigation water requirement (rice) [mm period^{-1}]	Normal (97; 7)	CROPWAT (2002)
Water input in fish ponds [m^{3} ha^{-1} day^{-1}]	Lognormal (30; 15)	FAO (1992)
Fish pond area [ha]	Normal (3260; 50)	HSO (2004)
Drainage water ratio in irrigation water [−]	Lognormal (0.07; 0.05)	Assumption
Phosphorus concentration in urban drainage water [mg P l^{-1}]	Lognormal (1.2; 1)	Assumption
Organic fertiliser application rate (rice) [tonnes ha^{-1}]	Normal (8; 2.5)	(Ha et al., 2001; HSO, 2004)
Phosphorus content in organic fertiliser [kg P t^{-1}]	Lognormal (0.4; 0.1)	Ha et al. (2001)
Weight gain per fattener [kg cycle^{-1}]	Normal (70; 5)	Ruettimann and Menzi (2001)
Feed conversion ratio of fattener [kg kg^{-1}]	Normal (3.8; 0.5)	Ruettimann and Menzi (2001)
Feed per sow [kg sow^{-1} year^{-1}]	Normal (550; 50)	Ruettimann and Menzi (2001)
Food waste:total feed pig ratio [−]	Lognormal (0.15; 0.03)	Assumption

Means and standard deviations are provided in parenthesis.

[a] The septic tank emptying frequency factor is a correction factor used if septic tank emptying frequency is below or above average. A factor 5 is selected here as septic tanks are reportedly emptied every 5–10 years instead of every 1–2 years.

[b] Only the major crops grown and livestock reared in Hanoi are listed here, i.e. rice and pigs, respectively. However, the model also considers other crop and livestock categories.

consumption was assumed to have a symmetrical distribution. However, since uncertainty is very high, a lognormal distribution was chosen to avoid negative values when applying Monte Carlo simulation. Given the limited uncertainty of the other parameters (coefficient of variation less than 0.2), negative values will not be obtained even if they are assigned a normal distribution.

3.1.2. Impact of simulated measures

According to the model results, today's groundwater abstraction in Hanoi province totals 620,000±90,000 m^{3} day^{-1}, 60% of which are used for domestic consumption and a relatively large fraction (25%) is lost through leakage (Fig. 2). The groundwater withdrawal is of the same order of magnitude as the estimated aquifer recharge of about 700,000 m^{3} day^{-1} (Nga, 2005). Moreover, the abstraction rate is steadily increasing due to population growth, increase in per capita water use and industrialisation.

The model was applied to determine the impact of different measures on groundwater withdrawal. In the first scenario, groundwater abstraction, simulated for the year 2015, was based on unchanged current trends. In assuming an increase in population from 3.1 to 5 million, a rise in water consumption from 120 to 140 l cap^{-1} day^{-1}, a 10% market area increase and a doubling of industrial water consumption, water abstraction would almost double by 2015 and total 1,134,000±171,000 m^{3} day^{-1}. Since this amount exceeds by far the aquifer's recharge rate of 700,000 m^{3} day^{-1}, urgent measures are necessary to guarantee adequate water supply and avoid land subsidence problems in the future.

In the second scenario, the impact of three demand-management measures was simulated for the year 2015. The relative importance of the different water consumers (Fig. 2) provides first indications of the kind of measures likely to be effective. The first simulated measure consists in reusing a fraction of the greywater (kitchen, bath and laundry wastewater) for toilet flushing. This measure would lead to a decrease in mean water use from 140 to 113 l cap^{-1} day^{-1} and correspond to a 16% decrease in water abstraction. By improving the water distribution network and thus reducing leakage from 25 to 10%, a 17% reduction in water abstraction would be reached. A 30% decrease in industrial water use would result in a 4% reduction of groundwater abstraction. Implementation of all three measures would reduce water consumption by 33% to 762,000±106,000 m^{3} day^{-1}. Interventions such as information and awareness raising campaigns, as well as introduction of financial mechanisms (incentives and/or sanctions) are preconditions for successful implementation of the aforementioned measures. However, even if the groundwater abstraction rate were reduced by a third, it would still be in the same order of magnitude as the recommended maximum withdrawal rate (Fig. 3).

Use of river water as additional water supply source is currently being discussed in Hanoi. Water from the 70-km distant Da River is recently being piped to Hanoi. Less polluted surface water imported from other regions is likely to increase in the near future. Yet, this could

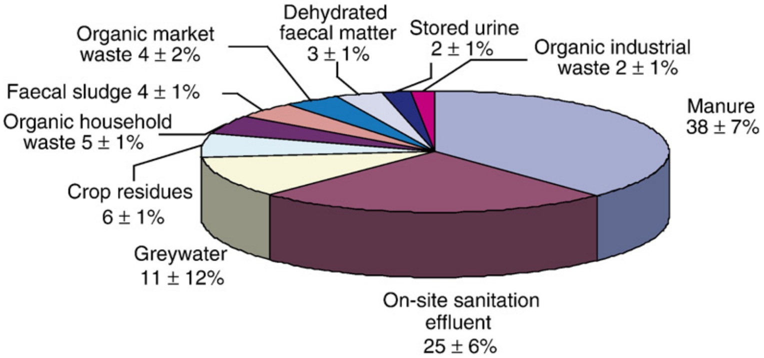

Fig. 4. Phosphorus load fractions in waste products.

lead to conflicts among consumers and increase water production costs. Improvement of surface water quality in and around Hanoi would render its use as water supply source more affordable. Furthermore, the increase of Hanoi's groundwater use could be limited by promoting the development of neighbouring small to medium-sized cities around Hanoi, as proposed by the Master Plan for Development of Hanoi (Hau, 2004).

3.2. Phosphorus recovery

3.2.1. Parameter values

The parameters described in Table 2 were used to calculate the amount of phosphorus contained in waste products and the one recovered in the form of irrigation water, organic fertiliser and animal feed. The generated waste products comprise greywater, faecal sludge and liquid effluent from on-site sanitation installations, industrial wastewater, organic solid waste (from households, markets and industries), animal manure, and crop residues. Most parameters were determined on the basis of a literature review. Prior probability distribution of the phosphorus transfer coefficient in faecal sludge from septic tanks was assessed from eliciting expert judgement (Montangero and Belevi, 2007). Since some of the flows, calculated on the basis of a preliminary assessment of parameter values, were not plausible, sensitive parameters were reassessed. Hanoi's per capita phosphorus load in greywater was for example determined more accurately by a differentiated literature review and a measurement campaign (Büsser, 2006).

3.2.2. Impact of simulated measures

The phosphorus quantity in waste products (generated in households, markets, industries, and peri-urban agriculture) amounts to 4400±790 tonnes of P year^{-1}. Fig. 4 illustrates the phosphorus distribution in different waste products. It is important to note that 44% of this load is contained in agricultural waste products (38% in manure and 6% in crop residues). Furthermore, 36% of the phosphorus load are contained in liquid waste products (effluent from on-site sanitation systems and greywater). Septic tank effluent is one of the main contributors of the phosphorus load. According to Montangero and Belevi (2007), 73–89% of the phosphorus entering the septic tank with urine and faeces leave the tank with the liquid effluent. Moreover, septic tank effluent in Hanoi is mainly discharged into the sewerage and drainage network instead of infiltrating into the ground through leaching pits or fields.

Currently, 1000±160 tonnes of P year^{-1} or 23% of the phosphorus load in waste products are recovered and used as organic fertiliser, irrigation water, livestock or fish feed. The remaining phosphorus-containing waste products are landfilled or discharged into the drainage network or on open grounds, leading not only to a loss of a valuable resource but also to environmental pollution. The phosphorus recovered corresponds to 18% of the total phosphorus actually used for food production in Hanoi province. The residual phosphorus demand is covered by artificial fertiliser and commercial livestock feed.

Food production within the urban and peri-urban area of the province covers about 44% of the food demand (Anh et al., 2004). "Phosphorus fertiliser use efficiency" was defined in this study as phosphorus uptake in crops (grain) per unit of phosphorus supplied as fertiliser. Similarly, "phosphorus livestock feed use efficiency" was defined as phosphorus uptake in livestock (meat) per unit of phosphorus supplied as feed. Mean "phosphorus fertiliser use efficiency" and "phosphorus livestock feed use efficiency" in Hanoi's peri-urban area were used to extrapolate the phosphorus amount necessary to produce food for the entire population of

Table 3
Description of the scenarios (mean values of the modified parameters)

Model parameters	Status quo	Scenario 1	Scenario 2	Scenario 3
Number of inhabitants [1000 inhabitants]	3100	5000	5000	5000
Ratio of inhabitants equipped with septic tanks (WC flush) related to total no. of inhabitants [−]	0.15	0.55	0	0
Ratio of inhabitants equipped with septic tanks (pour flush) related to total no. of inhabitants [−]	0.48	0.26	0.05	0.05
Ratio of inhabitants equipped with dry double pit latrines with urine diversion related to total no. of inhabitants [−]	0.16	0.05	0.8	0.8
Number of breeding sows [sows]	36,706	39,054	39,054	0
Sown spring paddy area [ha]	24,260	23,047	23,047	23,047
Sown summer paddy area [ha]	26,484	25,160	25,160	25,160
Fish pond area [ha]	3260	3422	3422	6844
Organic fertiliser application rate (rice) [tonnes ha^{-1}]	8	8	24	16
Drainage water ratio of irrigation water [−]	0.07	0.07	0.07	1
P load in organic industrial waste [tonnes of P year^{-1}]	70	84	84	84

Note: As in Table 2, only the parameters related to the main agricultural processes (pig and paddy production) are listed here. However, the model also considers other types of crops and livestock.

the province. Only 11% of this amount is currently covered by waste products generated in the province.

As aforementioned, a large fraction of the total phosphorus in waste products is contained in the effluent from on-site sanitation installations and in greywater. However, as rainwater covers most of the irrigation water requirement during the rainy season (May to October), only a small fraction of this wastewater can be recovered. A large amount of wastewater thus ends up in the river. Decreasing the amount of phosphorus in liquid waste in favour of solid or semi-liquid waste could reduce surface water pollution and increase the amount of organic fertiliser. If the organic fertiliser supply exceeds Hanoi's demand, it could be applied in neighbouring provinces or used for energy generation (biogas). The question is therefore whether the environmental sanitation system can be altered so as to produce a higher phosphorus fraction in waste products that could be applied as organic fertiliser.

The model was used to analyse the impact of changes in the environmental sanitation and agricultural system on phosphorus recovery. The following paragraphs first describe (Table 3) and then analyse the three simulated scenarios. Extreme scenarios were selected to clearly reveal the impact of policy changes.

Scenario 1 describes the situation for the year 2015 assuming unchanged current trends: persistent high population growth, continued shift from latrines to flush toilets with septic tanks, decrease in paddy fields and increase in fish pond and vegetable area as well as in the number of pigs. A persistent slight increase in mineral fertiliser application rate and in industrial production was also assumed.

Scenario 2 describes the situation for the year 2015 assuming that Hanoi's septic tanks are replaced by urine diversion latrines. Furthermore, an increase in organic fertiliser application rate and a decrease in commercial fertiliser use are also presupposed.

Scenario 3 describes the situation for the year 2015 assuming that Hanoi's population eliminates meat from its diet. Protein intake is compensated by a higher consumption of fish, vegetables, beans, soybean, and nuts. Organic fertiliser application rate is also higher than in the status quo, and only drainage water is used for irrigation. As in Scenario 2, septic tanks are assumed to be replaced by urine diversion latrines.

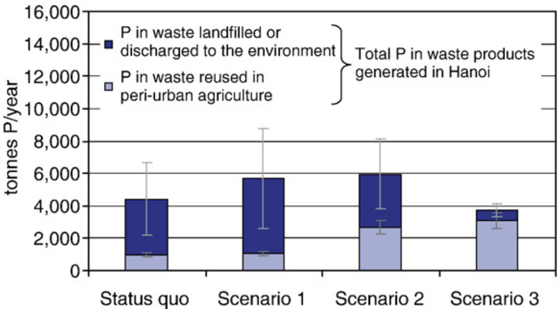

Fig. 5. Phosphorus load in waste products generated in Hanoi and reused in peri-urban agriculture (organic fertiliser, animal feed and irrigation water) as well as in waste products either landfilled, discharged into aquatic systems or on open grounds. The sum corresponds to the total amount of phosphorus in waste products generated by Hanoi's households, markets, industries, and agriculture. Error bars illustrate the standard deviation.

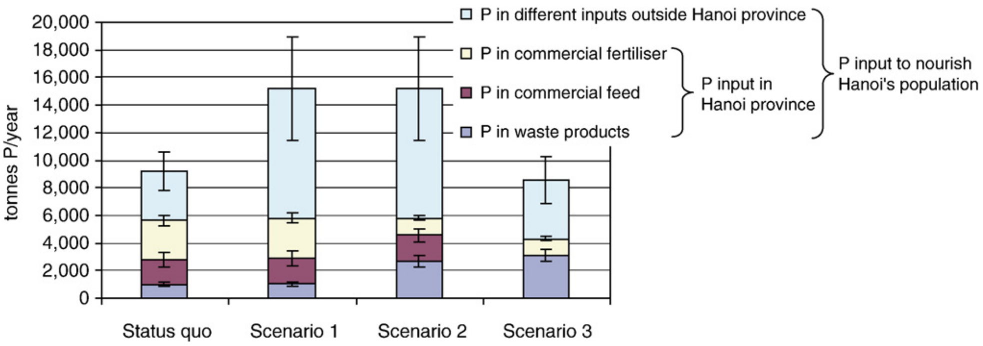

Fig. 6. Phosphorus load in waste products generated in Hanoi and reused in peri-urban agriculture, in Hanoi's commercial livestock and fish feed, in Hanoi's artificial fertiliser, and in different agricultural inputs applied outside Hanoi to produce food for Hanoi's population. Error bars illustrate the standard deviation.

Figs. 5 and 6 compare the results obtained from the status quo and from the three scenarios. The following three different indicators are analysed:

- fraction of total phosphorus in waste products recovered for food production in Hanoi's peri-urban agriculture (Fig. 5),
- fraction of total phosphorus demand in Hanoi's peri-urban agriculture covered by waste products (Fig. 6), and
- fraction of total phosphorus demand to nourish Hanoi's population (agricultural production in and outside Hanoi) covered by waste products generated in Hanoi (Fig. 6).

The agricultural system differs only slightly for the status quo and Scenario 1 (minor increase in number of pigs and minor decrease in paddy area); however, the number of inhabitants is increased significantly. Consequently, the phosphorus load in household waste and wastewater increases considerably while the amount of waste reused remains the same. The percentage of phosphorus in waste recovered decreases from 23 to 18%. In other words, a higher phosphorus load is landfilled or discharged into the environment. The fraction of phosphorus demand in Hanoi's peri-urban agriculture covered by secondary resources remains about the same. Moreover, the phosphorus demand for food production of the entire population increases substantially, and the percentage covered by waste products decreases from 11 to 7%.

If septic tanks are replaced by urine diversion latrines in Scenario 2, the total amount of phosphorus in waste products remains about the same as in Scenario 1. However, the phosphorus load increases in urine and in dehydrated faecal matter, but decreases in septic tank effluent. The percentage of phosphorus recovered increases from 18 to 45%, and the phosphorus load discharged into the environment is reduced since urine and faeces are being returned to the soil. The percentage of phosphorus demand in Hanoi's peri-urban agriculture covered by waste products increases from 17 to 46%. The total phosphorus demand to nourish Hanoi's population remains the same as in Scenario 1. Its percentage covered by waste products rises from 7 to 18%. An increased use of organic fertiliser leads to a reduced application of artificial fertiliser and, hence, to a decrease in phosphate rock mining.

Still, more than half of the phosphorus in waste products is not recovered and ends up in landfills or the environment. The agricultural system is altered considerably in Scenario 3. Since animal manure is no longer generated, the total amount of phosphorus in waste products decreases significantly. Crop production area increases, but the amount of organic fertiliser applied remains about the same due to the slightly reduced application rate (to match the supply). Moreover, drainage water used for irrigation increases. The percentage of phosphorus in reused waste products rises from 45 to 82%. Since meat production is far more nutrient-intensive than vegetable production, this scenario leads to a considerable reduction in total phosphorus demand. The phosphorus demand covered by waste products in peri-urban agriculture rises from 46 to 74%, and from 18 to 36% for food production of Hanoi's population (agriculture in and outside Hanoi). Changes simulated in this scenario thus lead to a decrease in phosphorus discharge into the environment and in phosphate rock mining.

4. Summary and conclusion

Application of the developed material flow model proved to be appropriate to simulate the impact of selected measures on groundwater abstraction and phosphorus recovery in Hanoi's province despite limited data availability. Use of the model enables to identify the most determining parameters. This not only enhances the design of effective measures, but also helps optimising measurement programmes. Moreover, Monte Carlo simulation allows to estimate variable uncertainty and, thus, to assess whether the impacts of different measures lie within the same range or if they differ significantly.

Groundwater abstraction could be reduced by a third, if the water distribution system is improved, greywater is reused for toilet flushing and if water efficiency of industrial processes is enhanced. Despite the aforementioned measures, the groundwater withdrawal rate still exceeds the aquifer recharge rate. Therefore, other strategies are necessary, in particular, protection of surface water to facilitate its treatment for domestic use.

By replacing septic tanks with urine diversion latrines, the percentage of phosphorus in waste products recovered for food production could be increased from 18 to 45%. Furthermore, replacing livestock production by a higher production of fish, vegetables, beans, soybean, and nuts could further increase recovery of phosphorus from 45 to 82%.

This paper describes the impact resulting from extreme scenarios to clearly reveal the impact of policy changes. However, the model can be used to assist in evaluating scenarios developed jointly by different stakeholders. Data supplied by the model can be combined with information on user's needs and demands, user's willingness to pay, costs, health impact, legal and institutional framework and, thus, contribute to the planning of sustainable environmental sanitation systems.

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