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# Assessing nutrient flows in septic tanks by eliciting expert judgement: A promising method in the context of developing countries

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ABSTRACT

Simple models based on the physical and biochemical processes occurring in septic tanks, pit and urine diversion latrines were developed to determine the nutrient flows in these systems. Nitrogen and phosphorus separation in different output materials from these on-site sanitation installations were thus determined. Moreover, nutrient separation in septic tanks was also assessed through literature values and by eliciting expert judgement. Use of formal expert elicitation technique proved to be effective, particularly in the context of developing countries where data is often scarce but expert judgement readily available. In Vietnam, only 5–14% and 11–27% of the nitrogen and phosphorus input, respectively, are removed from septic tanks with the faecal sludge. The remaining fraction leaves the tank via the liquid effluent. Unlike septic tanks, urine diversion latrines allow to immobilise most of the nutrients either in form of stored urine or dehydrated faecal matter. These latrines thus contribute to reducing the nutrient load in the environment and lowering consumption of energy and non-renewable resources for fertiliser production.

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## 1. Introduction

Nutrient management in the conventional sanitation system is not sustainable. Nutrients are discharged into surface water leading to eutrophication or are partly removed from wastewater through energy-intensive processes. On the other hand, production of artificial fertilisers requires a significant amount of energy and mines the limited phosphorus reserves. It is therefore important to find solutions to closing the nutrient flows.

The method of material flow analysis (MFA) studies the fluxes of resources 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 appropriate measures (Baccini and Brunner, 1991). It allows to simulate new environmental sanitation concepts, which can be evaluated by their nutrient load to the environment, nutrient saving or recovery (e.g. through urban waste reuse in agriculture). MFA is therefore a promising method that could contribute to the development of new environmental sanitation concepts. MFA has already been applied in the field of environmental sanitation in urban areas of developing countries (Binder, 1996; Belevi, 2002). However, information on how to deal with uncertain data in MFA studies is scarce. Danius (2002) identified data uncertainty in MFA as one barrier to a broader use of the method, particularly as a tool for policy decision. This issue is even more important in the context of

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**Nomenclature**

$A_{i,j}$ mass flow of substance *i* in good *j* ($g\,cap^{-1}\,day^{-1}$)
$A_j$ mass flow of good *j* ($g\,cap^{-1}\,day^{-1}$)
$\frac{A_{i,\ faeces\_part}}{A_{i,\ faeces}}$ Ratio between load of substance *i* in particulate form in faeces and total load of substance *i* in faeces (dimensionless)
$C_{i,j}$ concentration of substance *i* in good *j*
$C_{i,\ additives}$ concentration of substance *i* in additives (ash) ($g\,100\,g\,additive^{-1}$)
$C_{i,\ biomass}$ concentration of substance *i* in bacterial cell ($g\,g\,VSS^{-1}$)
$C_{i,fs}$ concentration of substance *i* in faecal sludge ($mg\,l^{-1}$)
$C_{i,fs\_liquid}$ concentration of substance *i* in the liquid fraction of faecal sludge ($mg\,l^{-1}$)
$C_{i,ST\_liquid}$ concentration of substance *i* in the clear zone of the septic tank ($mg\,l^{-1}$)
Kd endogenous respiration coefficient ($day^{-1}$)
$k_{i,j}$ transfer coefficient for substance *i* in output good *j* (dimensionless)
$M_i$ mass of substance *i* in a given process ($g\,cap^{-1}$)
$Q_j$ mass flow of good *j* ($l\,cap^{-1}\,day^{-1}$)
$r_{mis\_urine}$ proportion of misdiverted urine in urine diversion latrines (dimensionless)
$r_{i,\ excreta}$ amount of substance *i* in excreta per amount of food protein supplied ($g\,g^{-1}$)
$r_{N\_lossess\_faeces}$ proportion of nitrogen lost during faecal matter dehydration (dimensionless)
$r_{N\_losses\_urine}$ proportion of nitrogen lost during urine storage (dimensionless)
$RR_i$ removal efficiency of substance *i* in septic tanks (%)
$S_{COD}$ soluble COD concentration in the septic tank ($g\,m^{-3}$)
t time (days)
$X_v$ biomass concentration in the septic tank ($g\,m^{-3}$)
$V_{ST}$ septic tank volume ($m^3\,cap^{-1}$)
$Y_{obs}$ observed or net biomass yield coefficient ($gVSS\,gCOD^{-1}$)
$Y_{VSS}$ biomass yield coefficient ($gVSS\,gCOD^{-1}$)

developing countries where data availability and reliability is low, and resources for data collection are limited (available laboratory equipment, trained laboratory staff, financial and human resources).

This paper describes simple methods that can be used in the event of limited data to assess nutrient flows in common sanitation options in developing countries: septic tanks, pit latrines and urine diversion latrines. These methods will be used to develop and calibrate a broader model permitting to assess water and nutrient flows within the environmental sanitation system of Hanoi, Vietnam.

## 2. Background

### 2.1. *Assessment of expert judgement*

Assessment of expert judgement is a promising method where data is too scarce to achieving a reliable characterization of a process, but where expert understanding allows to describe well enough the phenomena occurring in the process. Expert knowledge can be translated into prior probability distributions. A posterior probability distribution can be obtained by combining the prior probability distribution with additional knowledge gained subsequently (Morgan and Henrion, 1990; Clemen and Reilly, 2001). In the “subjective assessment”, probability of an event describes the degree of a person’s belief in an event to occur, based on the relevant information currently known to that person. Meyer and Booker (1991) describe biases that can occur when conducting expert judgement assessment and ways to counteract them. Adoption of the probabilistic approach improves understanding and communication of predictive uncertainty (Borsuk and Stow, 2000).

### 2.2. *Nutrient behaviour in septic tanks*

A septic tank is a single or multi-chambered watertight vault. Portions of suspended solids settle at the bottom, grease and floatables rise to the surface and are thus retained while wastewater flows through the tank. Moreover, organic matter is partly decomposed by anaerobic microorganisms.

About 10–20% of the nitrogen and 20–50% of the phosphorus consumed through food will be transferred to the faecal fraction, while the remaining fraction reaches the urine (Jönsson et al., 2004). In raw wastewater, nitrogen enters the septic tank as a complex organic molecular form of the proteinaceous matter in faeces and urea in urine (Seabloom et al., 2004). Compared to urine, exhibiting water-soluble nutrients, the faeces contain both water-soluble and insoluble nutrients combined in larger particles. Still, some 50% of the nitrogen in faeces are water-soluble. In the presence of urease, urea is quickly biodegraded to ammonium (Jönsson et al., 2004). Part of the proteins is degraded during anaerobic decomposition and nitrogen released in the inorganic form ($NH_4^+$) (Kelderman, 2003). Since the pH in septic tanks ranges around 7, ammonia is almost entirely found as $NH_4^+$. $NH_3$ volatilization is therefore not likely to occur.

Phosphorus is commonly found in wastewater as orthophosphate, polyphosphate and organic phosphate. Orthophosphate is available for biological metabolism. Polyphosphate slowly undergoes hydrolysis in aqueous solutions and reverts to its orthophosphate form (von Sperling and Chernicharo, 2005). The phosphorus in urine is almost entirely (95–100%) inorganic and excreted as phosphate ions. Phosphorus in faeces is mainly found as calcium phosphate particles with only a slow water-soluble capacity (Jönsson et al., 2004).

The main removal mechanisms for nitrogen and phosphorus comprise their settling in particulate and only partly biodegradable form (thus, only partly converted into soluble

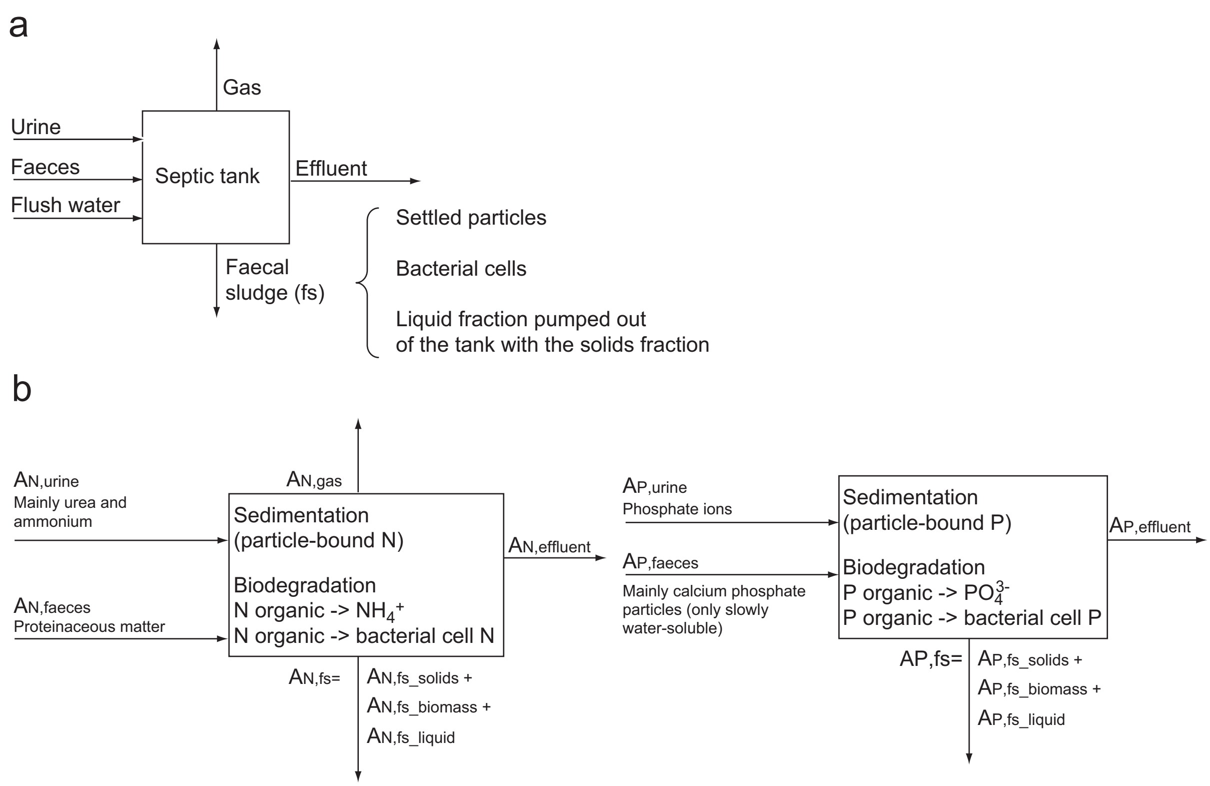


**Fig. 1 – (a) Input and output goods flowing to and from septic tanks, (b) nitrogen and phosphorus flows to and from septic tanks and mechanisms determining their separation.**

form), as well as nutrient uptake in cell material during anaerobic decomposition of organic matter (Fig. 1).

### 2.3. *Nutrient behaviour in urine diversion latrines*

The double vault latrine with urine diversion comprises two “faeces” chambers used alternatively, a squatting slab for urine diversion and a pot for collecting urine. The faeces storage in the unused chamber allows to reduce the number of pathogens and, thus, to decrease the health risks if faecal matter is reused in agriculture. Urine is applied as fertiliser. Double vault urine diversion latrines were widely used in rural areas of North Vietnam.

Several factors affect the separation of nutrients into gas, faecal matter and urine, e.g. amount of misdiverted urine (urine flowing into the faeces compartment), type of urine storage tank, length of the urine storage period and temperature. The high pH of the urine in the collection vessel, normally 9–9.3, coupled with its high ammonium concentration, reveals a risk of N loss in the form of ammonia. Additives, such as plant ash, lime and dried soil are added to the faeces to decrease the risk of odour and flies. The additives increase the dry matter content of the faeces/additives mixture and provide different nutrients. Due to the high pH of ash and lime and rapid decrease in moisture level of the faeces, conditions for anaerobic degradation in the faeces compartment are not optimal. Thus, losses of organic matter through biodegradation are likely to be small. In the drying process, all nutrients except N and most of the organic matter are conserved. Some N is lost as ammonia.

## 3. Methodology

### 3.1. *Determining transfer coefficients in septic tanks*

#### 3.1.1. *Expert judgement elicitation*

The expert elicitation technique was applied to determine prior probability distributions for nitrogen and phosphorus transfer coefficients in septic tanks—one of the most common on-site sanitation systems in developing countries. Transfer coefficients describe the partitioning of a substance in a process. They illustrate the proportion of the total input of a substance transferred to a specific output material (faecal sludge, effluent and gas in the case of septic tanks). Since septic tanks were designed to reduce solids and organic matter loads in the wastewater and not to remove nutrients, it is not surprising that information on nutrient removal in septic tanks is scarce.

Experts were selected on the basis of their theoretical knowledge on wastewater treatment techniques and research experience related to septic tanks. Three experts participated in the expert elicitation study on nitrogen and phosphorus partitioning, and an additional one supported the study with his knowledge on nitrogen behaviour. The selected experts are expected to provide estimates covering the entire range of realistic values. Morgan and Henrion (1990) state that there is no rule related to the appropriate number of experts. However, enough experts are required to illustrate the main views.

Experts were first introduced to the project and to the principles of subjective probability assessment. They examined the results of a literature review on septic tanks and were given the opportunity to correct or add information. They were then asked to generally describe the qualitative mechanisms occurring in a septic tank and, in particular, the ones influencing nutrient separation in faecal sludge, effluent and gas.

In a second step, points on the cumulative distribution function were assessed by assigning a transfer coefficient value to a given cumulative probability. To avoid anchoring, extreme points, i.e. transfer coefficient values corresponding to cumulative probabilities of 95% and 5% were first assessed. Anchoring occurs when an individual fails to adjust sufficiently from his/her first impression (Meyer and Booker, 1991). After having assessed the largest and smallest values, intermediate cumulative probabilities and their corresponding transfer coefficient values were determined. Experts were asked to explain the rationale for their assessment. The cumulative distribution functions were then fitted through the points (non-linear regression) using the *Palisade's DecisionTools* software (Clemen and Reilly, 2001) and assuming that transfer coefficients follow a lognormal distribution (non-negative, positively skewed, appropriate to represent large uncertainties). The cumulative distribution functions were then converted to probability density functions (derivation of the cumulative distribution functions). Experts were invited to review the results of their interviews. The resulting probability density functions were averaged by attaching the same weight to the results obtained by each expert.

### 3.1.2. *Mathematical model*

The type of septic tanks described here receives only blackwater (wastewater from toilets). Greywater (kitchen, bath and laundry wastewater) in Hanoi is usually discharged directly to the drainage system. Faecal sludge (fs) characterizes the solids (sludge and scum) accumulating in a septic tank and removed occasionally. As the dry matter content of faecal sludge is low (1–5%), it is important to consider not only the nutrients contained in the accumulated solids, but also the ones contained in the liquid fraction removed from the septic tank with the solids. The spatial boundary of the system considered is the septic tank, and the temporal boundary the period between two desludgings. The mass balance is calculated for an entire operation period (sludge accumulation and desludging). The following equations describe nitrogen and phosphorus flows in septic tanks (see Fig. 1):

$$\partial M_N/\partial t = A_{N,\ excreta} - A_{N,\ fs} - A_{N,\ effluent} - A_{N,\ gas},$$
$$\partial M_P/\partial t = A_{P,\ excreta} - A_{P,\ fs} - A_{P,\ effluent} - A_{P,\ gas},$$
(balance equations), (1)

where $A_{N,\ excreta} = A_{N,\ urine} + A_{N,\ faeces}$ and $A_{P,\ excreta} = A_{P,\ urine} + A_{P,\ faeces}$. The left side of the equation describes the stock change rate of nitrogen/phosphorus in the septic tank. The right side describes the difference between input and output nitrogen/phosphorus flows.

When considering an entire operation period (sludge accumulation and desludging):

$$\partial M_N/\partial t = 0, \quad \partial M_P/\partial t = 0. \tag{2}$$

Therefore, Eq. (1) can be reformulated as

$$A_{N,\ excreta} = A_{N,\ fs} + A_{N,\ effluent} + A_{N,\ gas},$$
$$A_{P,\ excreta} = A_{P,\ fs} + A_{P,\ effluent} + A_{P,\ gas}. \tag{3}$$

Output flows can be described as functions of input flows and transfer coefficients:

$$A_{N,\ fs} = k_{N,\ fs}\, A_{N,\ excreta}, \quad A_{P,\ fs} = k_{P,\ fs}\, A_{P,\ excreta}, \tag{4}$$

$$A_{N,\ effluent} = k_{N,\ effluent}\, A_{N,\ excreta},$$
$$A_{P,\ effluent} = k_{P,\ effluent}\, A_{P,\ excreta}, \tag{5}$$

$$A_{N,\ gas} = k_{N,\ gas}\, A_{N,\ excreta}, \quad A_{P,gas} = k_{P,\ gas}\, A_{P,\ excreta}. \tag{6}$$

Relationships were established between the amount of total food protein (TFP) and vegetable food protein (VFP) supplied to the population and excretion of nitrogen and phosphorus:

$$A_{N,\ excreta} = r_{N,\ excreta}\, A_{TFP,\ food},$$
$$A_{P,\ excreta} = r_{P,\ excreta}\, (A_{TFP,\ food} + A_{VFP,\ food}),$$
Jönsson et al. (2004). (7)

Consequently, nitrogen and phosphorus output flows can be determined by assessing the transfer coefficients using equations describing the physical and biochemical processes in septic tanks as shown below.

According to Eq. (4) and Fig. 1,

$$k_{N,\ fs} = A_{N,\ fs}/A_{N,\ excreta}$$
$$= (A_{N,\ fs\_biomass} + A_{N,\ fs\_solids} + A_{N,\ fs\_liquid})/A_{N,\ excreta},$$
$$k_{P,\ fs} = A_{P,\ fs}/A_{P,\ excreta}$$
$$= (A_{P,\ fs\_biomass} + A_{P,\ fs\_solids} + A_{P,\ fs\_liquid})/A_{P,\ excreta}. \tag{8}$$

Nitrogen and phosphorus accumulated in the biomass and removed with the faecal sludge can be determined by Eqs. (9) and (10):

$$A_{N,fs\_biomass} = \partial X_v/\partial t\, V_{ST}\, C_{N,biomass},$$
$$A_{P,fs\_biomass} = \partial X_v/\partial t\, V_{ST}\, C_{P,biomass}, \tag{9}$$

$$\partial X_v/\partial t = Y_{VSS}\, \partial S_{COD}/\partial t - Kd\, X_v,$$
von Sperling and Chernicharo (2005), (10)

where VSS designates volatile suspended solids and COD chemical oxygen demand. Eq. (10) describes the net biomass production (total biomass production minus biomass reduction due to endogenous respiration). Assuming finite time conditions within the steady-state hypothesis, Eq. (10) can be rewritten as

$$\Delta X_v/\Delta t\, V_{ST} = Y_{obs}/Y_{VSS}\, Y_{VSS}\, \frac{RR_{COD}}{100}\, A_{COD,\ excreta}. \tag{11}$$

Nitrogen and phosphorus accumulated in the settled, not biodegraded solids removed with the faecal sludge can be determined by Eq. (12):

$$A_{N,\,fs\_solids} = A_{N,\,excreta}(A_{N,\,faeces}/A_{N,\,excreta}) \times (A_{N,\,faeces\_part}/A_{N,\,faeces})\frac{RR_{TSS}}{100}\left(1-\frac{RR_{BOD}}{100}\right),$$
$$A_{P,\,fs\_solids} = A_{P,\,excreta}(A_{P,\,faeces}/A_{P,\,excreta}) \times (A_{P,\,faeces\_part}/A_{P,\,faeces})\frac{RR_{TSS}}{100}\left(1-\frac{RR_{BOD}}{100}\right), \quad (12)$$

where TSS designates total suspended solids and BOD biochemical oxygen demand.

Nitrogen and phosphorus contained in the liquid fraction of the faecal sludge can be approximated by

$$A_{N,fs\_liquid} = Q_{fs\_liquid}\, C_{N,\,fs\_liquid},$$
$$Q_{fs\_liquid} \cong Q_{fs}, \quad C_{N,\,fs\_liquid} \cong C_{N,\,ST\_liquid},$$
$$C_{N,\,ST\_liquid} = A_{N,\,liquid}/Q_{influent},$$
$$A_{N,fs\_liquid} \cong Q_{fs}((1-A_{N,\,faeces}/A_{N,\,excreta})A_{N,\,excreta} + (1-A_{N,\,faeces\_part}/A_{N,\,faeces})\,A_{N,\,faeces})/Q_{influent},$$
$$A_{P,fs\_liquid} \cong Q_{fs}((1-A_{P,\,faeces}/A_{P,\,excreta})A_{P,\,excreta} + (1-A_{P,\,faeces\_part}/A_{P,\,faeces})\,A_{P,\,faeces}/Q_{influent} \quad (13)$$

As aforementioned, gaseous nitrogen losses are likely to be negligible. Besides, there are no gaseous phosphorus losses:

$$A_{N,\,gas} \approx 0, \quad A_{P,\,gas} = 0. \quad (14)$$

Nitrogen and phosphorous flows in the effluent can be determined by mass balance (Eq. (3)).

#### 3.1.3. *Literature values*

Transfer coefficients were also calculated on the basis of literature values for faecal sludge generation rate ($Q_{fs}$) and *N* and *P* concentrations ($C_{N,\,fs}$, $C_{P,\,fs}$) by Eq. (15). $A_{N,\,excreta}$ and $A_{P,\,excreta}$ were determined by Eq. (7):

$$k_{N,\,fs} = A_{N,\,fs}/A_{N,\,excreta} = Q_{fs}\, C_{N,\,fs}/A_{N,\,excreta},$$
$$k_{P,\,fs} = A_{P,\,fs}/A_{P,\,excreta} = Q_{fs}\, C_{P,\,fs}/A_{P,\,excreta}. \quad (15)$$

As nitrogen and phosphorus gaseous losses are neglected, the fractions of nitrogen and phosphorus removed during treatment in septic tanks correspond to the transfer coefficients in faecal sludge. Therefore, data on nitrogen and phosphorus removal efficiencies in septic tanks have also been used as an estimate of the *N* and *P* transfer coefficients in faecal sludge based on

$$k_{N,\,fs} \approx RR_N, \quad k_{P,\,fs} = RR_P. \quad (16)$$

### 3.2. *Determining transfer coefficients in pit latrines*

A single pit latrine is generally composed of a single unsealed pit. The liquid fraction of the excreta infiltrates the ground through the bottom and the solids are retained and accumulate in the pit. The accumulated faecal sludge should be emptied regularly. Even though solids removal mechanisms in septic tanks and pit latrines differ (settling and floating in septic tanks, filtration in a pit latrine), solids removal and biodegradation are the phenomena steering nutrient partitioning in both systems. The septic tank model has therefore also been used to assess nutrient transfer coefficients in pit latrines and the model parameter values adapted.

### 3.3. *Determining transfer coefficients in urine diversion latrines*

The following equations are proposed to model nitrogen and phosphorus flows in urine diversion latrines:

$$\partial M_P/\partial t = A_{P,\,excreta} + A_{P,\,additives} - A_{P,\,faecal\_matter} - A_{P,\,urine} - A_{P,\,gas},$$
$$\partial M_N/\partial t = A_{N,\,excreta} + A_{N,\,additives} - A_{N,\,faecal\_matter} - A_{N,\,urine} - A_{N,\,gas} \quad \text{(balance equations)}. \quad (17)$$

The left side of the equation describes the nitrogen/phosphorus stock change rate in the urine diversion latrine. The right side corresponds to the difference between nitrogen/phosphorus input and output flows.

By assuming that latrines are desludged when full and based on an entire filling-emptying cycle:

$$\partial M_N/\partial t = 0, \quad \partial M_P/\partial t = 0. \quad (18)$$

There is no phosphorus in the gas flow:

$$A_{P,\,gas} = 0. \quad (19)$$

Therefore, Eq. (17) can be reformulated as:

$$A_{N,\,excreta} + A_{N,\,additives} = A_{N,\,faecal\_matter} + A_{N,\,urine} + A_{N,\,gas},$$
$$A_{P,\,excreta} + A_{P,\,additives} = A_{P,\,faecal\_matter} + A_{P,\,urine}. \quad (20)$$

Nutrient flows in the additives are estimated on the basis of the quantity of additives used, as well as on the nitrogen and phosphorus concentrations of the additives:

$$A_{N,\,additives} = A_{additives}\, C_{N,\,additives}/100,$$
$$A_{P,\,additives} = A_{additives}\, C_{P,\,additives}/100. \quad (21)$$

Nutrient output flows in the dehydrated faecal matter are calculated as the sum of nutrient flows in faeces, nutrient flows in the urine fraction that is misdiverted and thus ends up in the faeces chamber, and nutrient flows in the additives. Loss of some of the nitrogen contained in faeces and urine as ammonia during the dehydration process should be taken into account:

$$A_{N,faecal\_matter} = \left[\left(A_{N,excreta}\frac{A_{N,\,faeces}}{A_{N,\,excreta}}\right) + \left(A_{N,\,excreta}\frac{A_{N,\,urine}}{A_{N,\,excreta}}\, r_{mis\_urine}\right)\right] \times (1 - r_{N,\,losses\_faeces}) + A_{N,\,additives},$$
$$A_{P,faecal\_matter} = \left(A_{P,\,excreta}\frac{A_{P,\,faeces}}{A_{P,\,excreta}}\right) + \left(A_{P,\,excreta}\frac{A_{P,urine}}{A_{P,\,excreta}}\, r_{mis\_urine}\right) + A_{P,\,additives}. \quad (22)$$

Nitrogen output flow in the stored urine is calculated as the nitrogen flow in the urine, taking urine misdiversion and nitrogen losses during urine storage into account:

$$A_{N,\,urine} = \left(A_{N,\,excreta}\frac{A_{N,\,urine}}{A_{N,\,excreta}}\right)(1 - r_{mis\_urine}) \times (1 - r_{N,\,losses\_urine}). \quad (23)$$

Phosphorus output flow in the stored urine and nitrogen output flow in gas can be determined by the mass balance (Eq. (20)).

Output flows can be described as functions of input flows and transfer coefficients:

$$A_{N,\ faecal\_matter} = k_{N,\ faecal\_matter}(A_{N,\ excreta} + A_{N,\ additives}),$$
$$A_{P,\ faecal\_matter} = k_{P,\ faecal\_matter}(A_{P,\ excreta} + A_{P,\ additives}), \quad (24)$$

$$A_{N,\ urine} = k_{N,\ urine}\,(A_{N,\ excreta} + A_{N,\ additives}),$$
$$A_{P,\ urine} = k_{P,\ urine}\,(A_{P,\ excreta} + A_{P,\ additives}), \quad (25)$$

$$A_{N,\ gas} = k_{N,\ gas}\,(A_{N,\ excreta} + A_{N,\ additives}). \quad (26)$$

### 3.4. *Uncertainty and sensitivity of transfer coefficients*

The Monte Carlo simulation was used to determine transfer coefficients uncertainty for septic tanks, pit and urine diversion latrines on the basis of parameter uncertainty. Moreover, a sensitivity analysis was conducted based on the change in transfer coefficient value for a 10% parameter increase.

## 4. Results and discussion

### 4.1. *Transfer coefficients in septic tanks*

#### 4.1.1. *Expert judgement elicitation*

Figs. 2 and 3 illustrate the cumulative distribution and probability density functions for nitrogen and phosphorus transfer coefficients in faecal sludge from septic tanks. The points on the cumulative distribution were assessed by the experts.

Probability density functions for nitrogen transfer coefficient in faecal sludge as assessed by experts 1, 3 and 4 are similar (Fig. 2). The three functions comprise a narrow range of probable values averaging 0.02, 0.03 and 0.06. The probability density function fitted through the points assessed by expert 2 is broader, corresponding to a wider uncertainty. Moreover, its average value is higher (0.22). Probability density functions for phosphorus transfer coeffi-

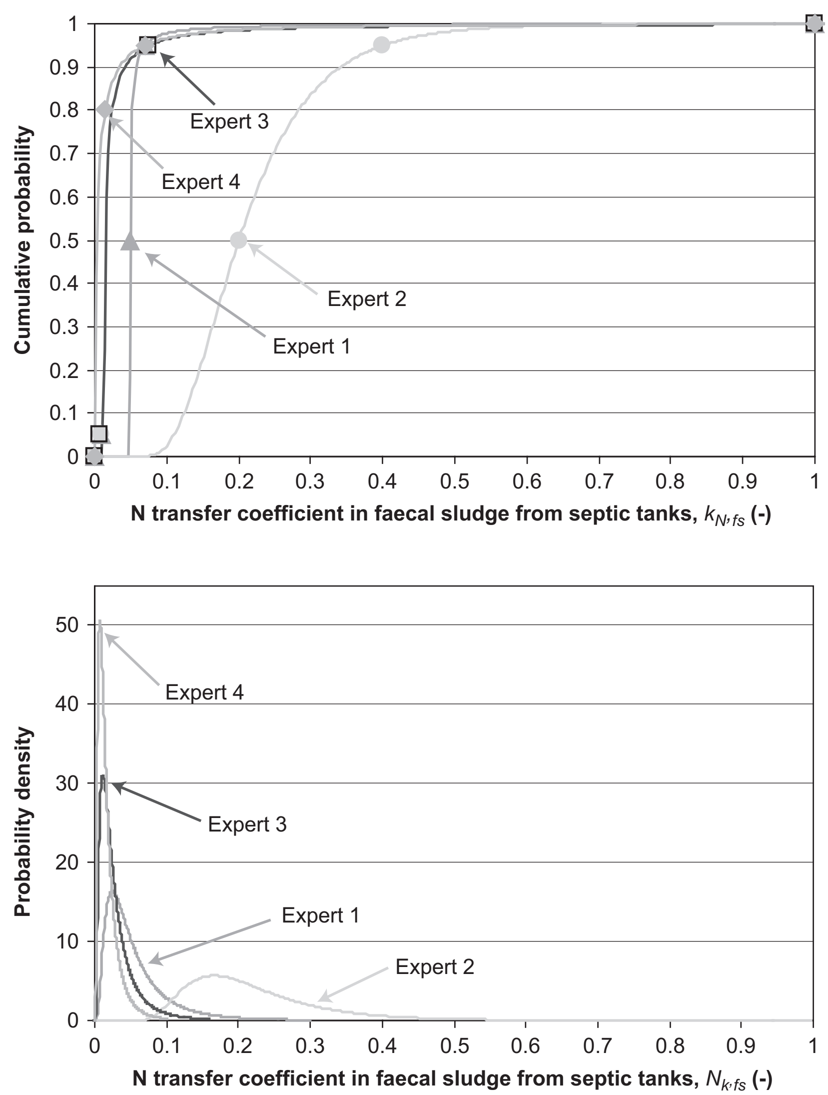


**Fig. 2 – Cumulative distribution and probability density functions for N transfer coefficient in faecal sludge (results from expert assessment).**

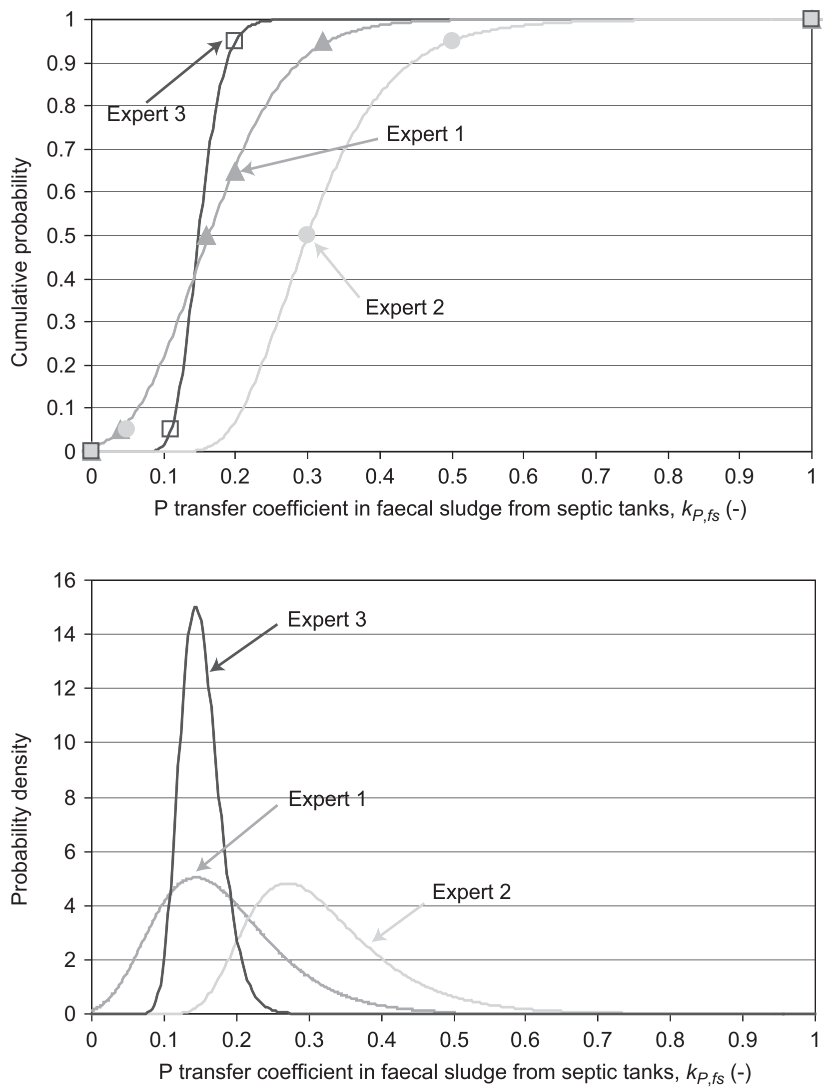


**Fig. 3 – Cumulative distribution and probability density functions for P transfer coefficient in faecal sludge (results from expert assessment).**

cient in sludge as assessed by experts 1 and 3 are similar (0.17 and 0.15), however, the range of probable values described by expert 3 is narrower (Fig. 3). The average value of expert 2 is again higher (0.32). Average prior probability distributions for nitrogen and phosphorus transfer coefficients are plotted in Fig. 4.

### 4.1.2. *Mathematical model*

Table 1 contains the parameter values for Vietnam determined on the basis of a literature review. These values are representative of average septic tank emptying frequencies (1–3 years). The transfer coefficient for nitrogen ranges from 0.05 to 0.14 and averages 0.09 and for phosphorus ranges from 0.11 to 0.27 and averages 0.18 (Figs. 4 and 5). Ranges correspond to the 90% confidence interval. Model results compare well with the results obtained from the experts' interviews. The most sensitive parameters with regard to P transfer coefficient are: the ratio between the phosphorus load in faeces and that in excreta, ratio between phosphorus load in particulate form in faeces and total phosphorus load in faeces, as well as TSS removal efficiency. Removal of particle-bound phosphorus thus significantly influences the ratio of phosphorus transferred to faecal sludge. The different model parameters have a similar influence on the N transfer coefficient.

### 4.1.3. *Literature values*

Results from several studies have been used to calculate the transfer coefficients by Eq. (15). Data collated from these studies are summarized in Tables 2 and 3. Transfer coefficient values amount to 0.11 (0.02–0.31) for nitrogen and 0.17 (0.03–0.49) for phosphorus (Fig. 4). They are in the same order of magnitude than the values determined by the expert assessment and the model, however they vary within a wide range. This can be explained by the large variability of faecal sludge characteristics.

Table 4 summarizes data on septic tank removal efficiencies collated from different sources. According to Eq. (16), transfer

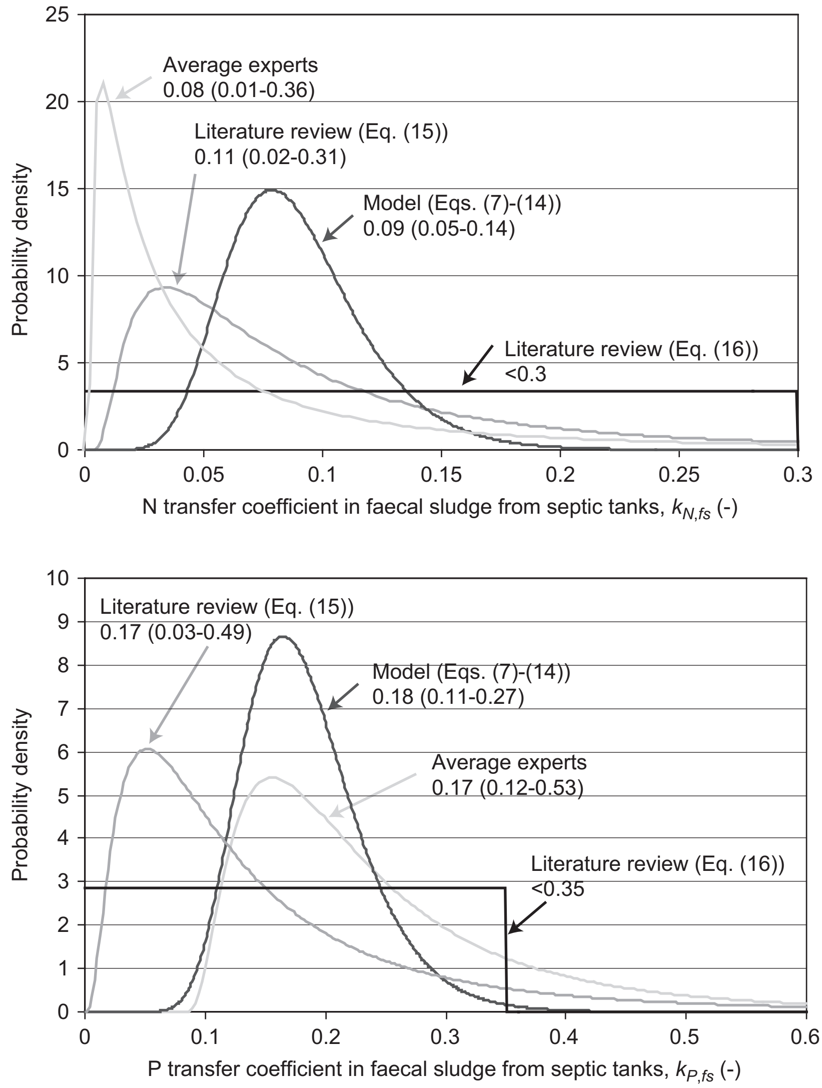


**Fig. 4 – Comparison of N and P transfer coefficients in faecal sludge from septic tanks determined through eliciting expert judgement, by applying the model and via literature values. Average values and ranges (90% confidence interval) are also indicated.**

coefficients are below 0.3 and 0.35 for nitrogen and phosphorus, respectively (Fig. 4).

#### 4.1.4. *Comparison of transfer coefficients obtained by eliciting expert judgement, applying the model and using literature values*

The results reveal that only a minor nutrient fraction is removed from septic tanks via faecal sludge. The main fraction is transferred to the liquid effluent and either infiltrates the ground or is discharged into surface water through sewerage or drainage channels.

The transfer coefficient values for septic tanks obtained through expert judgement, by model application and via literature values as described above are compared in Fig. 4. Average values for nitrogen transfer coefficient determined by expert elicitation and through the model are similar (0.08 and 0.09). The average value obtained from the literature values is slightly higher (0.11). The ranges of values determined by expert elicitation and literature review are very wide. This can be attributed to the fact that one of the experts assessed higher transfer coefficient values with a larger uncertainty than the other experts. The wide range of values obtained through the literature review can be explained by the large variability of faecal sludge characteristics.

Average phosphorus transfer coefficient values determined by expert elicitation, model application and literature review are similar (0.17; 0.18; 0.17). The ranges obtained through expert elicitation and literature review are wider than the one resulting from model application.

Transfer coefficients values determined by expert elicitation were used as parameter estimates in a broader model describing nutrient flows within Hanoi's environmental sanitation system. Costly experimental determination of these parameter values could thus be avoided.

**Table 1 – Parameter values to calculate N and P transfer coefficients in faecal sludge from septic tanks and pit latrines**

| Parameter | Distribution: mean; standard deviation (septic tank/pit latrine) | Unit | Source (septic tank/pit latrine) |
|---|---|---|---|
| $A_{TFP,\ food}$ | Normal: 62.3; 5 | $g\,cap^{-1}\,day^{-1}$ | FAOSTAT, 2004 |
| $A_{VFP,\ food}$ | Normal: 46.2; 4 | $g\,cap^{-1}\,day^{-1}$ | FAOSTAT, 2004 |
| $r_{N,\ excreta}$ | Normal: 0.13; 0.03 | $gN\,g^{-1}$ | Jönsson et al., 2004 |
| $r_{P,\ excreta}$ | Normal: 0.011; 0.002 | $gP\,g^{-1}$ | Jönsson et al., 2004 |
| $A_{COD,\ excreta}$ | Normal: 48; 8 | $g\,cap^{-1}\,day^{-1}$ | GHD, 2003 |
| $RR_{TSS}$ | Normal: 55; 10/ Normal: 80; 10 | % | Table 4/assuming higher solids retention in pit latrines than in septic tanks |
| $RR_{COD}$ | Normal: 27; 5 | % | Table 4 |
| $RR_{BOD}$ | Normal: 40; 10 | % | Table 4 |
| $Y_{VSS}$ | Normal: 0.18; 0.02 | $gVSS\,gCOD^{-1}$ | von Sperling and de Lemos Chernicharo, 2005 |
| $Y_{obs}/Y_{VSS}$ | Normal: 0.9; 0.05 | — | $Y_{obs}/Y_{VSS}$ for activated sludge treatment $\approx 0.85$: von Sperling and de Lemos Chernicharo, 2005, and assuming a slower decay for anaerobic bacteria |
| $C_{N,\ biomass}$ | Normal: 0.12; 0.01 | $gN\,gVSS^{-1}$ | von Sperling and de Lemos Chernicharo, 2005 |
| $C_{P,\ biomass}$ | Normal: 0.02; 0.002 | $gP\,gVSS^{-1}$ | von Sperling and de Lemos Chernicharo, 2005 |
| $A_{N,\ faeces}/A_{N,\ excreta}$ | Normal: 0.19; 0.08 | — | Table 2 |
| $A_{P,\ faeces}/A_{P,\ excreta}$ | Normal: 0.42; 0.11 | — | Table 2 |
| $A_{N,\ faeces\_part}/A_{N,\ faeces}$ | Normal: 0.5; 0.1 | — | Assumption, after Jönsson et al., 2004 |
| $A_{P,\ faeces\_part}/A_{P,\ faeces}$ | Normal: 0.92; 0.03 | — | Assumption, after Jönsson et al., 2004 |
| $Q_{fs}$ | Lognormal: 1; 1/Lognormal: 0.175; 0.1 | $l\,cap^{-1}\,day^{-1}$ | Heinss et al., 1998 |
| $Q_{input}$ | Lognormal: 40; 10/Lognormal: 2; 0.5 | $l\,cap^{-1}\,day^{-1}$ | Assumption (only blackwater) |

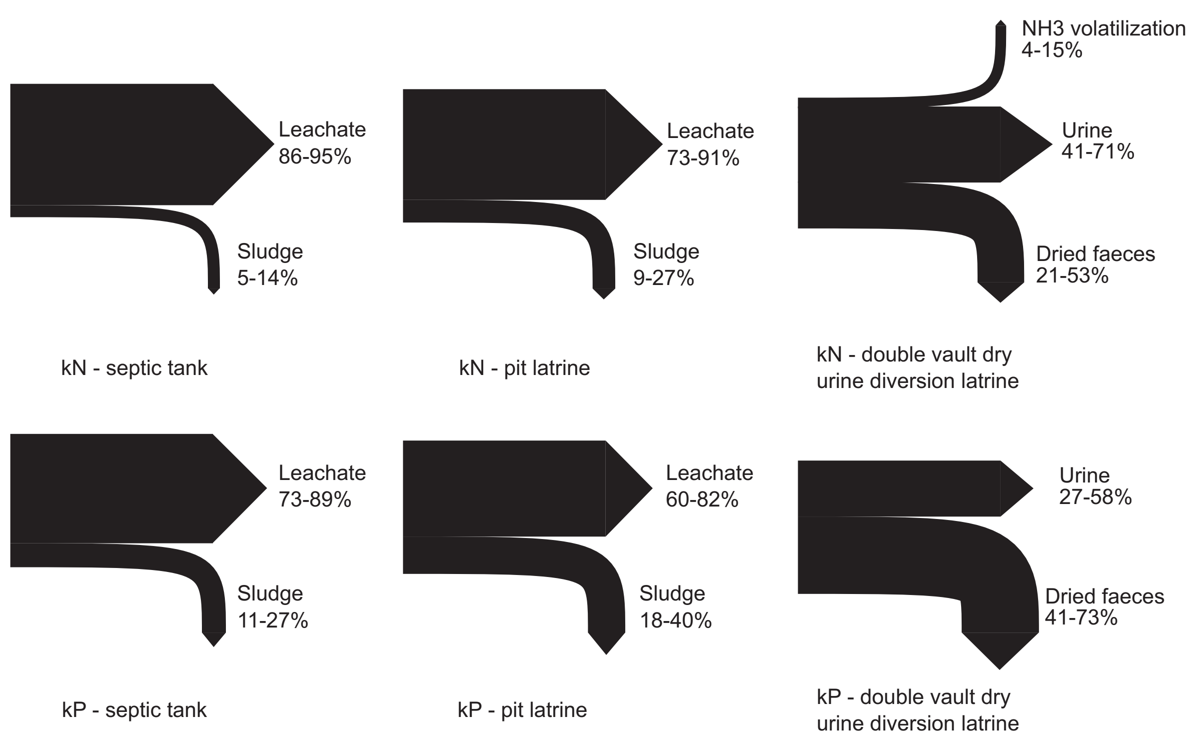


**Fig. 5 – Nitrogen and phosphorus transfer coefficients in different on-site sanitation systems in Vietnam determined by applying the models. Indicated ranges correspond to the 90% confidence interval.**

**Table 2 – Nitrogen and phosphorus loads in excreta, urine and faeces (g $cap^{-1}$ $day^{-1}$)**

| Reference | $A_{N, excreta}$ | $A_{N, faeces}$ | $A_{N, urine}$ | $A_{P, excreta}$ | $A_{P, faeces}$ | $A_{P, urine}$ |
|---|---|---|---|---|---|---|
| a | 7.9±1 | | | 1.6±0.2 | | |
| b | 10 | | | | | |
| c | 12.1 | | | 1.4 | | |
| d | | 1.2 (1–2) | 10 (3.6–16) | | 0.5 (0.1–1.7) | 1 (0.4–2.5) |
| e | | | | | | 0.4–0.6 |
| f | 11.4 | | | | | |
| b, g | 3.9–11.2 | | | 0.7–1.5 | | |
| b, h | 5.3–9.7 | | | 1–1.3 | | |
| b, i | 4.6–10.4 | | | 0.8–1.4 | | |
| b, j | 4.5–10.3 | | | 0.8–1.4 | | |
| b, k | 4.9–9.6 | | | 0.9–1.3 | | |
| a, b | 6–8 | | | 1.1 | | |
| b | 9.9–13.2 | 2–3.5 | 7–9 | 1.8 | 0.9 | 0.8 |
| b, d | 10.3–13.7 | 1.8–3.1 (1.2–4.2) | 6.2–7.9 (4.2–10.8) | 1.9 | 0.8 (0.5–1.1) | 0.7 (0.5–1) |
| b, l | | 2.5–3.5 | 7.5–9.5 | | 0.7–1.2 | 0.6–1.1 |
| d, l | | 2.2–3.1 (1.5–4.2) | 6.6–8.4 (4.5–11.4) | | 0.6–1 (0.4–1.4) | 0.5–1 (0.3–1.3 |
| b, g, l | | 0.8–2.9 | 4.6–15.1 | | 0.3–0.7 | 0.5–1.4 |
| b, k, l | | 0.7–8.4 | 3.4–15.1 | | 0.3–2.1 | 0.4–1.4 |
| b, l | | 1.5–5.3 | 6.7–15.1 | | 0.7–1.3 | 0.8–1.4 |
| b, l, m | | 0.8–10.9 | 6.7–15.1 | | 0.3–2.7 | 0.8–1.4 |
| b, d, l | | 1.1–3.8 | 6.7–15.1 | | 0.5–0.9 | 0.8–1.4 |
| n | 8.1 | | | 1.2 | | |
| o | 7.4 | | | 1.0 | | |
| p | 10.6 | | | 1.4 | | |
| q | 7.3 | | | 1.0 | | |
| r | | 1.4 | 11 | | 0.5 | 1.1 |

[a] Schouw et al., 2002. Southern Thailand.
[b] Heinss et al., 1998.
[c] Jönsson et al., 2004.
[d] GHD, 2003. Developed countries.
[e] Gumbo and Savenije, 2002. Zimbabwe.
[f] WASTE, 2004. Tingloy/Philippines.
[g] Polprasert et al., 1981. Vietnam.
[h] Schouw et al., 2002. Denmark.
[i] Schouw et al., 2002. Prik/Thailand.
[j] Schouw et al., 2002. Phattalung/Thailand.
[k] Schouw et al., 2002. Kuan Lang/Thailand.
[l] Polprasert, 1996.
[m] Feachem et al., 1983. Developing countries.
[n] FAOSTAT, 2004; Jönsson et al., 2004. Vietnam.
[o] FAOSTAT, 2004; Jönsson et al., 2004. Thailand.
[p] FAOSTAT, 2004; Jönsson et al., 2004. China.
[q] FAOSTAT, 2004; Jönsson et al., 2004. Philippines.
[r] Drangert, 1998.

### 4.2. *Transfer coefficients in pit latrines*

Nitrogen and phosphorus transfer coefficients in faecal sludge from pit latrines were assessed by the septic tank equations (Eqs. (7)–(14)) and adapted parameter values for solids removal efficiency, faecal sludge generation and influent flow rate (Table 1). Transfer coefficients amount to 0.17 (0.09–0.27) for nitrogen and 0.28 (0.18–0.40) for phosphorus. Pit latrines are therefore about 1.5–2 times more efficient in retaining nutrients than septic tanks. The results obtained are illustrated in Fig. 5.

### 4.3. *Transfer coefficients in urine diversion latrines*

Eqs. (20)–(26) were used to determine the transfer coefficients in urine diversion latrines. Table 5 contains the parameter values. Transfer coefficients for nitrogen amount to 0.35 (0.21–0.53) in dehydrated faecal matter, 0.57 (0.41–0.71) in stored urine and 0.08 (0.04–0.15) in gas. Transfer coefficients for phosphorus amount to 0.58 (0.41–0.73) in dehydrated faecal matter and 0.42 (0.27–0.58) in stored urine (Fig. 5).

The results of the sensitivity analysis reveal that the most sensitive parameters for the nitrogen and phosphorus transfer coefficients in faecal matter and urine are the ratio

Table 3 – Concentrations in faecal sludge from septic tanks ($mg\,l^{-1}$)

| $C_{TS,\,fs}$[a] | $C_{TVS,\,fs}$[b] | $C_{TSS,\,fs}$ | $C_{BOD,\,fs}$ | $C_{COD,\,fs}$ | $C_{TKN,\,fs}$[c] | $C_{NH3-N,\,fs}$ | $C_{p,\,fs}$ | |
|---|---|---|---|---|---|---|---|---|
| | | 7000–100,000 | 2000–30,000 | 6000–90,000 | 200–1500 | 50–150 | 40–300 | Lens et al., 2001 |
| 34,106 | 23,100 | 12,862 | 6480 | 31,900 | 588 | 97 | 210 | Polprasert, 1996 |
| (1132–130,475) | (353–71,402) | (310–93,378) | (440–78,600) | (1500–703,000) | (66–1060) | (3–116) | (20–760) | |
| 25,000–32,000 | | 18,000–24,000 | 4000–12,000 | 8000–15,000 | 3500–7500 | | 800–1200 | Polprasert, 1996. Japan |
| 5000–25,400 | 3300–19,300 | 3700–24,100 | 800–4000 | 5000–32,000 | | 250–340 | | Polprasert, 1996. Bangkok, Thailand |
| 15,647 | 11,476 | 12,898 | 2609 | 16,003 | 1002 | 396 | 863 | AIT/SANDEC, 2003. Thailand |
| (2202–67,200) | (848–52,362) | (980–43,633) | (630–5550) | (1108–76,075) | (344–4880) | (60–1200) | (0.4–1482) | |
| 11,000–39,000 | 8000–28,000 | 2000–21,000 | 3100–5900 | 16,000–60,000 | 410–820 | | | Strauss, 1995. US |
| 20,000–40,000 | | | | | | | | Strauss, 1995. Asia |
| 6,380–130,000 | | | | | 320–1900 | 40–150 | 20–310 | Strauss, 1995 |
| 40,000 | 25,000 | 15,000 | 7000 | 15,000 | 700 | 150 | 250 | Strauss, 1995. US |
| | | 2600 | 1600 | 5750 | | | | Strauss, 1995. Jordan |
| 47,000 | | | | 24,400 | 644 | | 54 | Strauss, 1995. Indonesia, Jakarta |
| 15,000–25,000 | | | 2500–3000 | 23,000 | 920 | | | Strauss, 1995. Bangkok/Thailand |
| | | | | (11,000–51,000) | (280–1500) | | | |
| 31,000 | 19,000 | | 5500 | 12,800 | | 209 | | Strauss, 1995. Philippines |
| 54,000 | 31,600 | 45,000 | 10,300 | 42,550 | 793 | 113 | 171 | Strauss, 1995. Norway |
| | | | 680 | 8100 | | | | Strauss, 1995. Ghana |

[a] TS: total solids.
[b] TVS: total volatile solids.
[c] TKN: total kjeldahl nitrogen.

between the nitrogen load in faeces and that in excreta, the ratio between the phosphorus load in faeces and that in excreta as well as the ratio of misdiverted urine. Furthermore, the transfer coefficient of nitrogen in urine is sensitive to the nitrogen ratio lost during urine storage. The nitrogen ratio lost during urine storage and during dehydration of faecal matter are the most sensitive parameters regarding the nitrogen transfer coefficient in gas.

### 4.4. *Comparison of transfer coefficients in septic tanks, pit latrines and urine diversion latrines*

Fig. 5 compares nitrogen and phosphorus transfer coefficients determined by the aforementioned models and parameter values in septic tanks, single pit latrines and double vault urine diversion latrines in Vietnam. Model results were selected for this comparison since expert elicitation was only conducted for septic tanks. In the case of pit latrines or septic tanks with soil infiltration system, the main nutrient fraction entering the tank is discharged into the ground. Consequently, it cannot be used as a fertilizer for crop production and may have a negative environmental impact. Urine diversion latrines allow to retain most of the nutrients either as stored urine or dehydrated faecal material, which may subsequently be used as fertilizer and soil conditioner.

This information was used to assess the nitrogen and phosphorus flows in Hanoi's environmental sanitation system and impact of different measures. By replacing septic tanks with urine diversion latrines for example, phosphorus load into surface water could be reduced by 42% from $1572 \pm 601$ to $905 \pm 557\,\text{ton}\,\text{year}^{-1}$ (Montangero and Belevi, submitted).

## 5. Conclusions

The proposed mathematical models can be used to assess nutrient flows in on-site sanitation installations. Assessment of parameter values, however, requires resources not likely to be available in developing countries. Use of the eliciting expert judgement technique seems a very promising alternative to obtaining fairly accurate parameter values.

According to the results obtained, only 5–14% and 11–27% of the nitrogen and phosphorus inputs are removed from septic tanks with the faecal sludge. The remaining fraction leaves the tank with the liquid effluent and usually ends up in rivers and lakes. Unlike septic tanks, urine diversion latrines allow to immobilize most of the nutrients either in form of stored urine or dehydrated faecal matter. These products could be reused as fertilizer and soil conditioner in peri-urban agriculture. This would not only reduce consumption of fertilizer and hence raw material and energy, but also decrease nutrient loads into the environment.

The described submodels will be used in Hanoi, Vietnam as part of a broader water and nutrient flow model simulating the impact of different environmental sanitation options on resource recovery and environmental protection.

Table 4 – TSS, BOD, COD, N, and P removal efficiencies in septic tanks (%)

| $RR_{TSS}$ | $RR_{BOD}$ | $RR_{COD}$ | $RR_N$ | $RR_P$ | |
|---|---|---|---|---|---|
| 55–65 | 30–35 | 25–35 | <30 | <35 | von Sperling and de Lemos Chernicharo, 2005 |
| 60–80 | 50–60 | | 10–30 | | Seabloom et al., 2004 |
| | | | 9 | | Chulalongkorn University, 2003. Thailand |
| | 30–50 | | | | US EPA, 2002 |
| 31–50 | 52–63 | 54–70 | | | Rahman et al., 1999. Dhaka, Bangladesh |

Table 5 – Parameter values for calculating nitrogen and phosphorus transfer coefficients in urine diversion latrine products

| Parameter | Value | Unit | Source |
|---|---|---|---|
| $A_{TFP,\ food}$ | Normal: 62.3; 5 | $g\,cap^{-1}\,day^{-1}$ | FAOSTAT, 2004 |
| $A_{VFP,\ food}$ | Normal: 46.2; 4 | $g\,cap^{-1}\,day^{-1}$ | FAOSTAT, 2004 |
| $r_{N,\ excreta}$ | Normal: 0.13; 0.03 | $gN\,g^{-1}$ | Jönsson et al., 2004 |
| $r_{P,\ excreta}$ | Normal: 0.011; 0.002 | $gP\,g^{-1}$ | Jönsson et al., 2004 |
| $A_{additives}$ | Normal: 120; 30 | $g\,cap^{-1}\,day^{-1}$ | Nghien and Calvert, 2000 (100–300 ml defecation$^{-1}$) and assuming a wood ash density of 600 g/l |
| $C_{N,\ additives}$ | Lognormal: 0.15; 0.1 | $g\,100\,g^{-1}$ | Pasquini and Alexander, 2004 |
| $C_{P,\ additives}$ | Lognormal: 0.084; 0.05 | $g\,100\,g^{-1}$ | Pasquini and Alexander, 2004 |
| $A_{N,\ faeces}/A_{N,\ excreta}$ | Normal: 0.19; 0.08 | — | Table 2 |
| $A_{P,\ faeces}/A_{P,\ excreta}$ | Normal: 0.42; 0.11 | — | Table 2 |
| $r_{mis\_urine}$ | Lognormal: 0.2; 0.1 | — | Jönsson and Vinnerås, 2003 |
| $r_{N\_losses\_urine}$ | Lognormal: 0.1; 0.05 | — | Jönsson et al., 1998 |
| $r_{N\_losses\_faeces}$ | Lognormal: 0.05; 0.02 | — | Assumption |

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