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PEOPLE-CENTRED APPROACHES TO WATER AND ENVIRONMENTAL SANITATION

Material flow analysis as a tool for environmental sanitation planning in Viet Tri, Vietnam

A. Montangero, Switzerland, T. Nguyen, Vietnam and H. Belevi, Austria

New environmental sanitation approaches must be developed in response to the need for more sustainable water and nutrient management. This paper illustrates how the method of Material Flow Analysis (MFA) can be applied to assess measures aiming at optimizing nitrogen recovery through improved excreta management in Viet Tri, Vietnam. The purpose of this paper is to identify how the application of MFA could be rendered more affordable for planners and decision-makers in developing countries confronted with poor data availability and quality. The analysis of the Viet Tri case indicates that a tool containing a database and assisting MFA users in determining which parameters should be determined with which accuracy (sensitivity analysis) would enable planners to optimise their data collection plan. This would help planners with limited means apply MFA as time requirement and cost for data collection would be reduced.

Introduction

Today's environmental sanitation practices do not enable to close the loop between food production on one hand and excreta and solid waste generation on the other hand. Most of the nutrients contained in excreta are discharged into the environment resulting in health hazards and the degradation of natural resources. Nutrients in excreta originate from food and hence mainly from agricultural soils. The discharge of faeces and urine into surface and groundwater therefore not only leads to environmental pollution but also to the depletion of nutrients and organic matter from the soil (Werner et al., 2003). The production of artificial nitrogen fertilizer is energy intensive, whereas limited, non-renewable raw materials are consumed for the production of artificial phosphorus fertilizer.

New environmental sanitation approaches must be developed - both in industrialised and in developing countries - in response to the need for more sustainable water and nutrient management. The method of material flow analysis (MFA) studies the fluxes of resources used and transformed as they flow through a region, through a single process or via a combination of various processes. In industrialized countries, MFA proved to be a suitable instrument for the early recognition of environmental problems and development of measures (Baccini and Brunner, 1991). One of the possible applications of the method is the quantification of urban waste and food flows and the corresponding nutrient flows in a given district or city. This quantification enables the identification of key processes and flows as well as the simulation of new environmental sanitation concepts or measures. These can be evaluated according to their impact on nutrient load into the environment as well as on nutrient saving or recovery (e.g. through urban waste reuse in agriculture).

MFA has already been applied in developing countries in the field of environmental sanitation (Binder et al., 1997; Belevi, 2001; Gumbo, et al., 2003). Binder et al. (1997) demonstrated that the method can be applied even with poor data quality and quantity. However, depending on the context (availability and reliability of data as well as means for further data collection: budget, laboratory equipment, etc.), the application of the method may not be affordable for planners in developing countries.

This paper describes the application of the method of MFA for a first estimation of nitrogen flows in Viet Tri, a city of 130,000 inhabitants located 80 km North-East of Hanoi. It further analyses the current situation and describes the impact of selected measures in the field of sanitation on nitrogen recovery in Viet Tri. The aim of this paper is to identify, based on the Viet Tri case, how the application of MFA could be rendered more affordable for environmental sanitation planners in developing countries where means for data collection may be limited.

Method

The method of MFA

The first step of the method consists in analysing the system. The system is defined by one or several processes, the interaction between the processes (fluxes of goods/substances) and the system boundary between these processes and other processes located outside the system border (Brunner and Rechberger, 2004). Goods are defined as substances or mixtures of several substances with functions valued by men (like solid waste, wastewater, food). A process is defined as the transformation, transport, or storage of substances or goods. Processes are, for example, private households where food is converted to excreta, solid waste and gaseous emissions. A wastewater treatment plant in which wastewater is transformed into treated wastewater, sewage sludge and gases is also a process.

Once the system is defined, mass flows of all goods and concentrations of the selected indicator substances in the goods are determined. Then indicator flows are calculated based on mass flows of goods and indicator concentrations. Mass flows or indicator flows are determined by using information obtained through literature review, field measurements (surveys, sampling and laboratory analysis) or calculated by mass balances over processes. Finally, results are interpreted and presented (Baccini and Brunner, 1991). The MFA procedure is iterative. In general, it is best to start with rough estimations and then to improve the system and data until the required certainty of data quality has been achieved (Brunner and Rechberger, 2004).

Application of MFA in Viet Tri

Step 1 System understanding and collection of information available in Viet Tri

Surveys (semi-structured interviews and questionnaires) as well as a review of documents were conducted in Vie Tri in order to define the system (relevant processes and goods) as well as gather quantitative information on mass, nitrogen and phosphorus flows. The Viet Tri Urban Environment Company (URENCO), the Director Board of Viet Tri Water Supply and Sanitation Project, workers of the co-composting plant, the centre for Disease Prevention in Viet Tri, farmers of the communities, the Department of Agricultural and Rural Development (DARD), the Department of Science, Technology and Environment (DOSTE), and the Department of Health (DOH) contributed to the surveys that were conducted by the Center for Environmental Engineering of Towns and Industrial Areas (CEETIA) at Hanoi University of Civil Engineering in Hanoi, Vietnam between November 2000 and June 2001 (Nguyen, 2001).

Step 2 Review of information on transfer coefficients (TC)

Transfer coefficients describe the partitioning of a substance in a process. They give the percentage of the total input of a substance transferred into a specific output good. They are defined for each output good of a process. They are substance-specific and process-specific values. They are not necessarily constant (Brunner and Rechberger, 2004). For example, the percentage of nitrogen that is volatilized during the process of windrow composting depends on the operational procedure (e.g. frequency of turning, covering the heaps), the climatic conditions, etc. TC are therefore defined for specific conditions (e.g. operational procedure, geographical location, etc.). The transfer coefficient for a substance S (e.g. nitrogen) through a process P (e.g. composting) into an output good O (e.g. compost) is defined as

$$\text{TC, S, P, O} = \frac{\text{Flow substance S in output good O}}{\text{Total input flow substance S in process P}}$$

Knowledge of transfer coefficients for the relevant processes in the system reduces the number of parameters that have to be quantified through field investigations. Some of the flows in the system were quantified by using transfer coefficients estimated based on information obtained through literature review (Table 1).

Step 3 Review of information on specific (per "unit") flows as well as on nutrient concentrations in relevant goods

Knowledge of per capita or per hectare flows – if they were determined in a comparable context! – can also reduce the number of parameters that have to be quantified through field investigations. In the case of Viet Tri, several flows (N and P flows in kitchen waste, food waste fed to animals, etc.) were estimated based on per capita flows determined in other cities in the region. Others were estimated based on per capita mass flows and N and P content in the goods (Table 1). Information on per capita and per hectare flows as well as on N and P concentrations in selected goods was obtained through literature review.

Step 4 Calculation of mass balances over processes

Many processes in the excreta management sector are only transport or transformation but not (or only to a limited extent) storage processes. For the processes in which no material is stored, selected flows were quantified by mass balance over the processes (Table 1). This again reduces the required means for data collection.

Step 5 Data analysis and interpretation

Once all flows were estimated, the plausibility of selected key flows was assessed. Weaknesses as well as potential of the current nitrogen management were analysed.

Step 6 Formulation of improvement measures and assessment of their impact

Based on the analysis of the current situation, measures aiming at improving nitrogen management in Viet Tri were formulated and their impact was quantified.

Results

System analysis and first estimation of nitrogen flows (status quo)

Viet Tri is situated in Phu Tho province in the Northern Uplands region of Vietnam. It consists of residential areas and industrial zones as well as intensively used agricultural lands. Rice, corn, tea, cassava, fruits and vegetables are the main crops cultivated in and around Viet Tri. Fishing (fish ponds) is an important activity. People are served by on-site sanitation systems such as septic tanks, bucket latrines, single pit latrines and double vault dry latrines. Some of these double vault dry latrines in the peri-urban area of Viet

Tri are equipped with a urine diversion channel and a collection bucket. Urine is used (sometimes after dilution) to water garden and fruit trees. Sludge from on-site sanitation

Table 1. Determination methods of N and P flows (see Figure 1 for a sketch of the system including the goods)

Good	Determination method
Food Households (Food HH)	Per capita N, P flows (Jönsson and Vinnerås, 2003; FAOSTAT data, 2003)
Excreta 1-5	Excreta management (Nguyen, 2001)
Sludge / effluent from bucket latrines, septic tanks and double vault dry (DVD) latrines	System description (Nguyen, 2001) and assumptions
Sludge and effluent from pit latrines	N, P in sludge/effluent (Jacks et al, 1999)
Sludge and effluent from DVD latrines with urine diversion	N, P in urine/faeces (Jönsson and Vinnerås, 2003) and assumptions
Sludge, effluent to fish ponds, to crops and to soil/surface water	System description (Nguyen, 2001) and assumptions
Urine to crops, urine losses to atmosphere	N, P in urine/faeces (Jönsson and Vinnerås, 2003). N losses (Jönsson et al.,1998)
Organic waste (Ow) 1-5	Solid waste management Viet Tri (Nguyen, 2001), per capita N&P flows in kitchen waste (Schouw et al., 2002)
Dump and landfill leachate	Transfer coefficients: assumptions
Compost, Gas	Transfer coefficients in compost, gas (Ritz, 2001; SKAT, 1996; Schouw et al., 2002)
Crops	List of cultivated crops, cultivated area for each crop (Nguyen, 2001), yield and N & P concentrations in crops: assumptions
Mineral fertilizers	List of crops, area, inputs, N & P in fertilisers (Nguyen, 2001) and assumptions
N fixation (agriculture)	List of crops, area (Nguyen, 2001). N fixation (Blasum, 1997)
N volatilization (agriculture)	List of crops, quantity of fertilizer used (Nguyen, 2001), assumptions
N, P losses from agriculture in soil/surface water/groundwater	Quantity of fertilizer used (Nguyen, 2001), assumptions
Manure storage losses, manure to fish ponds, to crops	Type of livestock, number of animals of each category (Nguyen, 2001), per head N, P flow in animal excreta (Swiss College of Agriculture, 2001)
Animal excreta to soil/surface water	Type of livestock, number of animals (Nguyen, 2001), assumptions
Meat, fish and eggs	Type of livestock, number of animals of each category (Nguyen, 2001). Weight/head, N and P concentrations, number of eggs/chicken: assumptions
Animal food	Assumptions
Effluent FP (fish ponds)	N balance over process “fish ponds”. N accumulation in fish ponds: assumptions
Food import, export	N balance over process “market”

systems is dumped without prior treatment into surface water, fish ponds or onto the soil. Most peri-urban families apply sludge from their on-site systems as organic fertilisers on their garden and vegetable fields. The effluent from septic tanks usually flows in open drainage channels and ends up in larger channels/rivers or in fish ponds. Half of the solid waste generated in Viet Tri is collected. After sorting, the organic fraction of the collected solid waste is composted; the rest is disposed of in the landfill. Most of the compost produced in Viet Tri is sold to the tea farms in the region. The uncollected solid waste is fed to the animals (pigs, etc.) or dumped on the soil or in surface water.

The visualisation of the N flows (Figure 1) shows that the N cycle between food production (crops production) and waste generation (households) is not closed. About 60% of the nitrogen delivered to households in form of food is discharged

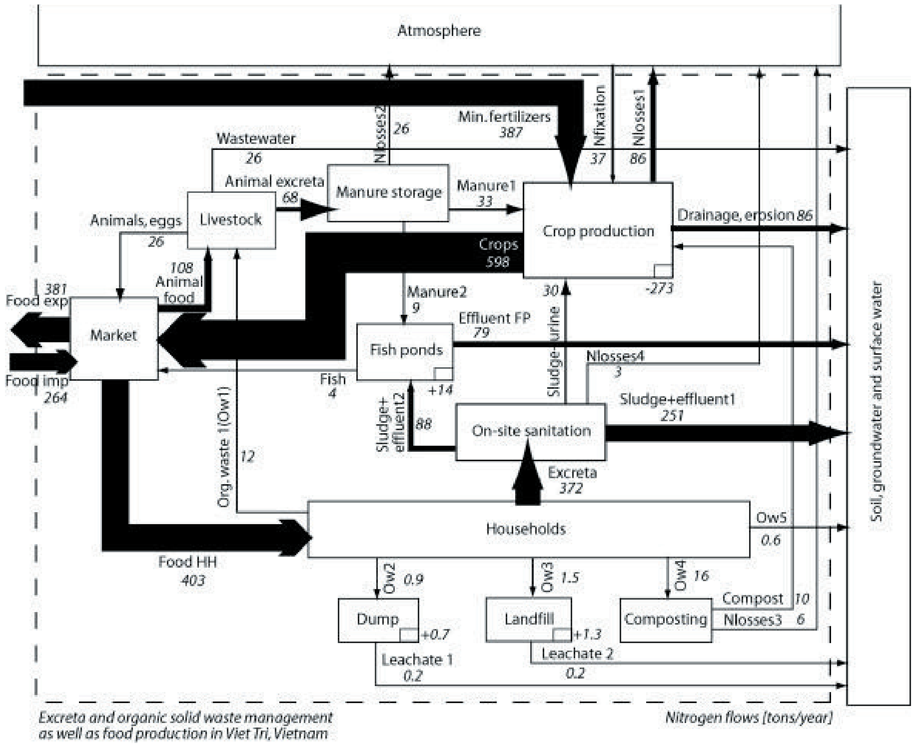

Figure 1. First estimation of nitrogen flows in the system "excreta and organic solid waste management as well as food production in Viet Tri", in tons /year
Processes are represented by boxes, flows by arrows, and the system boundary by a dashed line. The small rectangles within the processes represent stock changes in the processes

on the soil or in surface water. This leads to water pollution and eutrophication. 22% of the N input into the households (88 tons N/year) is directly discharged into fish ponds (total area ca. 100 ha). However, only a fraction of the discharged nutrients can be taken up by the fish. The remaining fraction leads to eutrophication and hence to competition for oxygen with fishes. Moreover, direct discharge of sludge and effluent from on-site sanitation systems in rivers and ponds is not only associated with nutrient but also with pathogens discharge. This in turn has a negative impact on health. Children, in particular, are reported to suffer from diarrhoea, cholera, and parasitic worms (Nguyen, 2001). Food waste management practices seem to be very efficient with regard to nutrient recovery. 51% of the nitrogen load in food waste is composted and 39% is fed to the animals.

Figure 1 shows that the N output from the process "crop production" is higher than the N input (273 tons N/year, corresponding to 35% of the N output). N is therefore depleted from the soils. However, the database is too scarce to confirm this result yet. At national level, N and P are reportedly supplied in sufficient quantity; only K is in deficit (Syers et al., 2002). However, soil characteristics are very variable in Vietnam. It is therefore difficult to draw conclusions based on national averages. According to Nguyen and Mutert (2001), most of the soil types in Vietnam are deficient in nutrient: more than 50% of soils types are poor in N, 87% are poor in P, and 80% are poor in K. Soils in the Phu Tho province are acid, poor in organic matter and in nutrients (Ho, 1999). It can be concluded that the first approximation of N flows in Viet Tri tends to indicate that urban waste could be applied in urban and peri-urban agriculture without overfertilizing the soil. Nevertheless, more accurate data are needed to refine the estimated flows and assess nitrogen as well as other nutrients demand in agriculture. This would allow the quantification of the additional nutrient load that could be applied on agricultural soils in form of hygienised excreta and solid waste.

Assessment of measures (scenario)

Socio-economic surveys conducted in urban areas of North Vietnam indicate that people are aware of the problems related to water pollution. Improving sanitation is an important concern for households with poor sanitation (Nguyen, 2001). The improvement measures assessed in this paper have been formulated according to the identified weaknesses in the current situation. The measures aim at reducing the nutrient discharge into the environment and increasing nutrient recovery. The main potential to improve nutrient management is to optimize excreta management as it contains most of the nutrients generated in households.

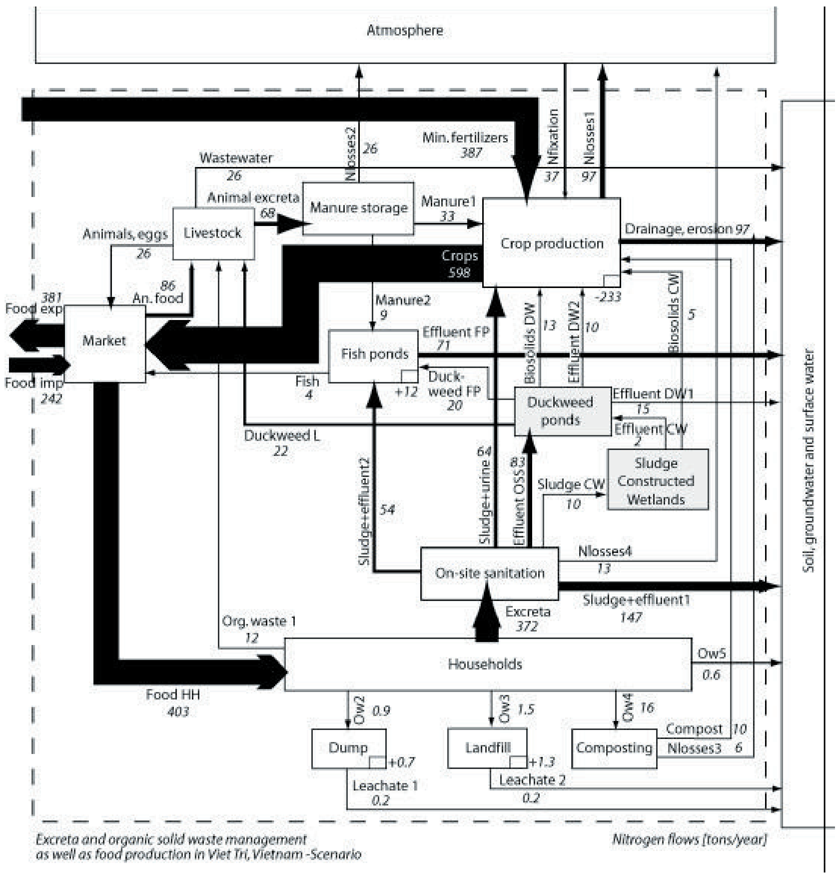

Figure 2. First estimation of nitrogen flows in the system "excreta and organic solid waste management as well as food production in Viet Tri" in tons /year according to the described scenario Simulated measures are the increase of the proportion of urine diverting toilets and the treatment of effluent and sludge from on-site sanitation systems

Estimation of N flows in the current situation demonstrated that urine diversion toilet is a promising option with regard to nutrient recovery. Most of the nutrients excreted from the human body are contained in the urine. Urine diversion toilets are already implemented by some households in Viet Tri. A pilot project conducted in Cam Duc Province (Vietnam) established that urine diverting toilets are well accepted by the population (Pham and Calvert, 2000) and that a 6-month storage period of the faeces allows the production of a hygienically safe product (Bui et al., 2002). The first measure selected for this example is therefore the increase of the number of people using double vault dry latrines with urine diversion from 10% to 50% of the population living in the peri-urban area of Viet Tri, corresponding to approximately 25% of the total population in Viet Tri. The second measure consists in collecting the effluent of on-site sanitation systems and treating it in a duckweed pond system (Iqbal, 1999) prior to using part of the pond effluent for irrigation. Effluent will be collected from half of the urban area of Viet Tri, corresponding to approximately 25% of the population. The third measure is the collection of sludge from on-site systems generated in the same area and its treatment in constructed wetlands. Treated sludge (biosolids) will be reused as organic fertilizer on different kinds of crops and effluent will be treated in the duckweed ponds.

The proposed measures lead to a 30% reduction of the nitrogen load into soil and surface water (Figure 2). The nitrogen load into fish ponds is reduced by about 35%, which could lead to a reduction of health risks associated with water uses and limit the risk of oxygen competition in the fish ponds. Moreover, nitrogen load available for crop production (e.g. tree watering with effluent and urine, biosolids application for tee, rice, and corn production, etc.) increases by a factor 3. This increase is particularly due to the higher proportion of urine diversion toilets and hence the higher quantity of urine applied in agriculture. N depletion in soils can be reduced by 15-20%.

How to assist planners applying MFA?

This first estimation of nitrogen flows was possible thanks to information obtained in Viet Tri through surveys and through literature review. Information that could enable MFA users to estimate nutrient flows in other cities in Vietnam or in the region should be synthesized and structured in a database.

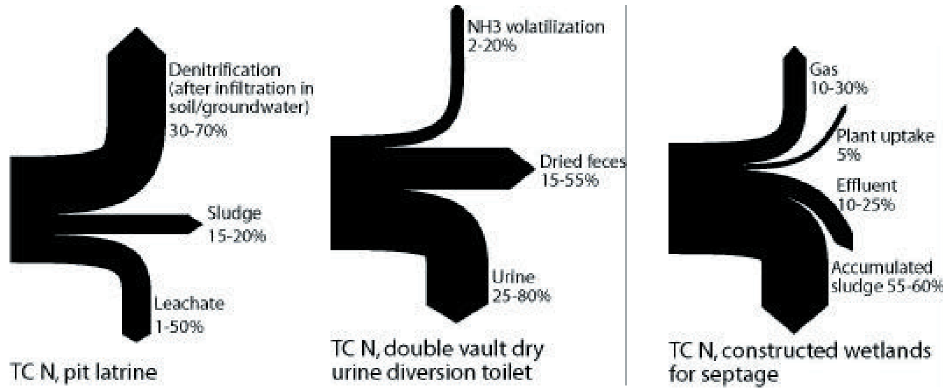

Figure 3. Examples of transfer coefficients (TC) for nitrogen TC were estimated based on Jacks et al. (1999) for the pit latrine, Jönsson and Vinnerås (2003) as well as Jönsson et al. (1998) for the urine diverting latrine, and Koottatep et al. (2002) for the sludge constructed wetlands

The database should contain information on transfer coefficients (Figure 3) for processes that are relevant in the field of environmental sanitation as well as food production. Specific flows (per capita or per hectare mass or nutrient flows) as well as typical nutrient concentrations in the relevant goods should also be contained in the database. It should not only contain average values but also ranges (standard deviations), and a detailed description of the context (geographical location, process description, etc.) so that users can assess whether the values can be applied in their specific context. Moreover, information contained in the database should enable planners to verify the plausibility of available data or of data estimated based on assumptions.

Sensitivity analysis aims at determining the impact of parameters (parameter variations) on system variables. The results of the sensitivity analysis enable to define which parameters have to be determined with a high accuracy (sensitive parameter) and which with a lower accuracy (Baccini and Bader, 1996). This is particularly useful in the context of low data availability and quality. Flows could first be estimated roughly in a first phase as in the example described in this paper. Then a sensitivity analysis could be conducted in order to determine which flows should be determined with a higher accuracy. These parameters could then be quantified more precisely in a second phase in order to refine the quantification of the flows. Conclusions could then be drawn from the refined flows and serve as basis for the identification of weaknesses and the simulation of scenarios.

The impact of changes in the proportion of the different types of on-site sanitation systems in Viet Tri on the nitrogen load to crop production is illustrated in Figure 4. It demonstrates that if the proportion of people owning septic tanks decreases from 50 to 40%, the change in nitrogen load available for crop production is low (10%). However, an increase in people using double vault dry (DVD) urine diverting latrines from 5 to 15% leads to a high increase in nitrogen load available for crop production (60%). The calculation

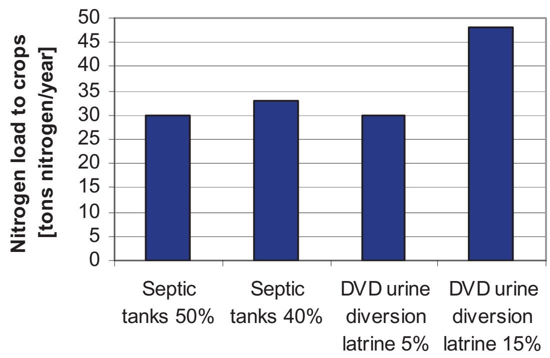

Figure 4. Sensitivity of nitrogen load to crop production. The figure illustrates the impact of changes in the proportion of on-site sanitation systems on the nitrogen load available for crop production

is based on the assumption that the changes (decrease of the proportion of septic tanks and increase of the proportion of urine diverting toilets, respectively) are compensated by an increase and a decrease in the proportion of people using DVD latrines without urine diversion, respectively. The results indicate that the proportion of people using urine diverting latrines is a sensitive parameter that should be determined with a better accuracy than the proportion of people owning septic tanks.

Conclusion

The practical case study conducted in Viet Tri, Vietnam allowed a first estimation of nitrogen flows related to excreta and organic solid waste management as well as food supply in Viet Tri by applying the method of material flow analysis. The results indicate that 60% of the nitrogen delivered to the households in form of food is finally discharged with the excreta in surface water, fish ponds or on the soil, resulting in water pollution. The quantified flows further tend to indicate that current urban waste management and food production practices result in nitrogen depletion from agricultural soils. However, some of the flows, nitrogen flows in crops and in fertilisers in particular should be assessed more precisely in order to determine nitrogen demand in agriculture. Phosphorus, potassium and possibly other nutrient flows should also be quantified in order to assess nutrient demand. The efficiency of nitrogen recovery through food waste management is high (90%). Excreta management and reuse should be improved in order to enhance nitrogen cycling in Viet Tri.

The impact of potential measures consisting in increasing the proportion of households using urine diversion latrines from 5 to 25%, in treating 25% of the effluent from on-site sanitation systems in duckweed ponds and 25% of the sludge from on-site systems in constructed wetlands was quantified. The proposed measures lead to a 30% reduction of the nitrogen load into soil and surface water. The nitrogen load into fish ponds is reduced by about 30%. The proposed measures could therefore limit the risk of oxygen competition in the fish ponds and reduce health risks associated with the use of excreta contaminated surface water. Moreover, nitrogen load available for crop production (e.g. tree watering with effluent and urine, biosolids application for tee, rice and corn production) originating from excreta increases by 200%.

The method of material flow analysis can be applied for a first estimation of flows even though data availability and reliability is low. Nevertheless, depending on the quantity and quality of available data, the first approximation may need to be refined. There is a need for a tool that could assist MFA users (e.g. planners and decision-makers responsible for environmental sanitation planning in developing countries) in estimating flows, in determining the plausibility of estimated flows and in defining which flows should be determined with a higher accuracy. This could enable MFA users to design an optimal data collection plan that could be implemented in spite of limited means (finances, personnel, equipment and time). A database containing values (average and range) for transfer coefficients of relevant processes in the field of environmental sanitation and food production (e.g. proportion of the total nitrogen leaving a pit latrine in the liquid infiltrating into the soil), specific flows (e.g. nitrogen flows in kitchen waste per capita and day) and concentrations in the relevant goods was identified as one important element of such a tool. Additional information should complement the values (e.g. geographical location, process characteristics, etc.) so that users can determine whether the values can be applied in their particular context. Moreover, the tool should help users conduct a sensitivity analysis in order to determine which flows should be determined with which accuracy.

Environmental sanitation concepts or measures should be developed based on householder's perceptions, needs and acceptance for innovations. The potential concepts and measures should then be evaluated according to health, socio-economic and socio-cultural impact, their compatibility with actor's capacity and institutional and legal framework, and their impact on the environment and resource saving and recovery. The MFA tool could be used to assist planners and decision-makers evaluating potential options (environment and resource management aspects) in context of poor data availability and reliability.

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Contact address

Agnes Montangero
Programme officer
SANDEC/EAWAG
P.O. Box 611, CH-8600 Duebendorf, Switzerland

Thi Kim Thai Nguyen
Professor
CEETIA/HUCE
55 Giai Phong Road, Hanoi, Viet Nam

Hasan Belevi
Professor
University Innsbruck
Department of Environmental Engineering
Technikerstrasse 13, A-6020, Austria