Application of the material flow analysis method for evaluating Strategic Sanitation Plan in Sub-Saharan Africa: the case of Fada N’Gourma–Burkina Faso

Lydie Yiougo, Halidou Koanda, Christoph Luethi and Joseph Wéthé

ABSTRACT

In the context of rapid urbanization across Sub-Saharan Africa there is a critical need for more robust decision-making between different ways of providing sanitation services in existing and new peri-urban areas. In several countries, authorities tried to find solutions by developing strategies to address sanitation problems in the form of Strategic Sanitation Plans. In Burkina, Strategic Sanitation Plans have been elaborated and implemented since the 1990s. Fada N’Gourma, a secondary city in Burkina, also adopted a Strategic Plan for wastewater and excreta management in 2006. In this study we use material flow analysis as a decision making tool to verify technology options of the Plan. A model was developed and data was collected in order to assess material and nitrogen flows. The status quo situation was compared to scenario based on the proposals made in the Sanitation Plan. Results show that the technology options which were recommended improved human health in the short term. However, the options led to groundwater pollution in the medium term. Compared to the current situation, matter and nitrogen flows would increase by 7% and 7.4% respectively in groundwater. It is thus concluded that the proposed options will not achieve the Plan’s stated objectives of environmental protection.

Key words | environmental sanitation, groundwater, health, material flow analysis, nitrogen, sanitation planning

INTRODUCTION

According to Kauffmann (2007), it will be difficult for Africa to reach the Millennium Development Goals in the sanitation field. In the past decades, developing countries did not give the priority to sanitation. Since 1970, sanitation coverage rates remained constant at about one third of the population. In secondary cities where rapid urbanization takes place, the situation is worse. Local administrations have insufficient political powers and lack human resources and the skills needed to make an appropriate development plan that tackles sanitation as an urgently required service (Drewsky & Kunzmann 1991). In Burkina Faso, local authorities of secondary cities are responsible for the sanitation of their cities. However, they do not have sufficient human, material, technical and financial resources to address sanitation challenges. Fada N’Gourma is a secondary city of 40,000 inhabitants located in the eastern part of Burkina Faso in West Africa. The average rainfall is 875 mm per year. The city is divided into two parts by two dams (Anonymous 2006). The free groundwater level is between 25 and 7 m. But sometimes, it can reach 2 m in some part of the city (ONEA 2006). As far as sanitation is concerned, solid waste is collected door-to-door by local women NGOs and discharged in the environment without treatment. The rainwater is drained by few open channels and discharge in the water dams located in the city centre. For excreta management, 78% of households use simple pits, 5% septic tanks. About 10% of households practise open defaecation and 7% use their neighbourhood facilities. Households discharge their grey water into soak pits (20%) and streets (80%) (ONEA 2006). In the framework of the national millennium program for water and sanitation, the National Water and Sanitation Agency (Office Nationale de l’Eau et de l’Assainissement; ONEA) has developed for the municipality a Strategic Sanitation Plan for wastewater and excreta based on several technologies: ventilated improved pits, pour-flush latrines, soak pits and septic tanks. According to the Strategic Sanitation Plan (ONEA 2006), 78% of households will be equipped with ventilated improved pit (VIP), 8% with septic...
MATERIAL AND METHODS

Definition of MFA method

The principle of MFA is based on the law of matter conservation. MFA can be applied to have an overall view of water flow and substance in a defined system as sanitation in urban area. It can be used to make the early recognition of environmental impacts of human activities (Binder 1996). MFA is the investigation of physical flows of materials, typically on a geographic basis. In this way, MFA can help to understand how changes in land use, industrialization, consumption and population affect the cycles of specific chemicals in watershed (Gumbo 1999). MFA is a systematic assessment of flows and stocks of materials within a system defined in space and time (Brunner & Rechberger 2004; Montangero 2006). It can be used to design and to test different materials, management in order to compare the flows to the environment, or against some acceptance criteria for environmental loading. So, any strategy of materials management can be discussed through the results of an MFA system (Lu et al. 2007). This recommends MFA as a tool for decision making that allows comparing different sanitation technology options.

Background on MFA

The application of the MFA method consists in four steps (Binder et al. 1997): (i) definition of the system border and process, characterization of goods, choice of the indicator elements; (ii) formulation of the model equation by measuring mass fluxes of input and output through the different processes per unit of time and the concentration of the indicator elements; (iii) interpretation and validation of the determined material and element fluxes; (iv) development of scenarios and determination of monitoring activities.

MFA was used in industrialized countries to predict environmental problems due to technology choices and to develop some counter-measures. It was used to assess environmental policies (Baccini 1996; Binder 1996). The method of MFA was used to check process, waste management, nutrients management in agriculture, water quality and resource conservation and recovery.

In the context of developing countries, MFA was already used to develop and to attain early recognition concerning changes in water quality and quantity in Tunja, an urban region in Colombia, in spite of poor data quality and quantity (Binder et al. 1997). In 1999, this method was used to analyse phosphorus flows in the water management system in an urban area in Hararé, Zimbabwe (Gumbo 1999).

In Kumasi, Ghana, MFA made it possible to assess the solvency of nitrogen and phosphorus in peri-urban agriculture for compost production from household refuse and faecal sludge. The result showed that the nitrogen and phosphorus demands of about 50% of the urban and peri-urban agriculture could be theoretically covered and surface water and groundwater pollution significantly reduced in this way (Belevi 2000).

In Pak Kret, Thailand, MFA application showed that the use of chemical fertilizers did not bring micronutrients or organic matter to soil, and that if used for a long time it could cause soil damage. The reuse of household garbage organic matter and wastewater provided part of mineral requirement. This action led to reduction of the discharge of nitrogen into the environment. So, the installation of wastewater treatment plant and reusing the treated effluent to peri-urban agriculture led to reduced nitrogen (N) requirement from chemical fertilizer by around 57%. It could supply irrigation water to agriculture areas, while reducing pollution loading from wastewater by 31% (Sinsupan 2004).

In Vietnam, MFA was also used to compare two options of sanitation technology, that is, septic tank and urine diverted toilet, despite scarcity of data (Montangero 2006).

Recently, in Ethiopia, MFA was applied to assess resources and environmental impact of different sanitation scenarios. This tool did not only allow emphasizing the pollution due to uncontrolled disposal of waste, but also helped identifying solutions for sustainable sanitation (Meinzinger et al. 2009).

System boundary, process and goods

The system border for the present study is the geographic limit of the city of Fada (755.4 ha). The indicator element is Nitrogen (N), a pollutant linked to sanitation problems and used in agriculture as fertilizer. It is also one of the causes of surface water eutrophication. The major sources of nitrogen in urban...
aquifers are related to wastewater disposal and solid waste disposal (Wakida & Lerner 2005). The system is composed by 12 processes and 52 flows, three environmental compartments (atmosphere, surface and groundwater) which interact with processes. The 12 processes are:

(1) Households: they consume water and food and eject excreta, wastewater, garbage, and biogas;
(2) On-site sanitation, which is represented by different types of technology such as simple pit latrines, septic tank, soakaway …
(3) Drainage channels and natural drainage receive wastewater, rain water with a part of household garbage and faecal sludge;
(4) Open dumps receive household and market waste partly used as organic manure in peri-urban agriculture;
(5) Water supply process concerns running water, water from fountain and from alternative resources such as wells, dams …

(6) Markets where foods, livestock and mineral fertilizers pass through;
(7) Industries, of which there are two: dairy enterprises and cotton ginneries;
(8) Stock of faecal sludge on the street: sludge removed from the pit is sometimes discharged on the street;
(9) Peri-urban agriculture, concerning market gardening, urban agriculture and urban livestock;
(10) Atmosphere;
(11) Surface water;
(12) Groundwater.

Formulation of model equation: quantification of mass of material and nitrogen flows

Mass of material and nitrogen was calculated with measured data, calculated or estimated data and data from bibliography (Table 1). Data and information were

<table>
<thead>
<tr>
<th>Description</th>
<th>Value (mean ± confidence interval or mean; standard deviation)</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of inhabitants</td>
<td>40,815</td>
<td>–</td>
<td>(INSD 2007)</td>
</tr>
<tr>
<td>Water consumption on private pipe</td>
<td>29</td>
<td>l/cap./day</td>
<td>ONEA</td>
</tr>
<tr>
<td>Water consumption on public stand pipe and other</td>
<td>17</td>
<td>l/cap./day</td>
<td>ONEA</td>
</tr>
<tr>
<td>Fraction of water poured (soak pit, on street …)</td>
<td>80%</td>
<td>–</td>
<td>ONEA</td>
</tr>
<tr>
<td>Fraction of households connected to private pipe</td>
<td>11%</td>
<td>–</td>
<td>survey, 2006</td>
</tr>
<tr>
<td>Fraction of households who used stand pipe</td>
<td>89%</td>
<td>–</td>
<td>survey, 2006</td>
</tr>
<tr>
<td>Food consumption (vegetables, meat and cereal)</td>
<td>768 ± 10.7</td>
<td>kg/cap./year</td>
<td>FAOSTAT (1993–2003)</td>
</tr>
<tr>
<td>Fraction of households who have flush toilet (septic tank)</td>
<td>5%</td>
<td>–</td>
<td>(ONEA 2006)</td>
</tr>
<tr>
<td>Per capita water consumption for toilet flushing (septic tank)</td>
<td>15</td>
<td>kg/cap./day</td>
<td>Assumption</td>
</tr>
<tr>
<td>Fraction of households who have soak away</td>
<td>20%</td>
<td>–</td>
<td>(ONEA 2006)</td>
</tr>
<tr>
<td>Fraction of households who don’t have toilet</td>
<td>10%</td>
<td>–</td>
<td>(ONEA 2006)</td>
</tr>
<tr>
<td>Production of fermentable garbage</td>
<td>65.33</td>
<td>kg/cap./year</td>
<td>(CAGEC 2006)</td>
</tr>
<tr>
<td>Biogas production</td>
<td>2</td>
<td>kg/cap./day</td>
<td>(Montangero 2006)</td>
</tr>
<tr>
<td>Excreta production</td>
<td>1.5</td>
<td>l/cap./day</td>
<td>(Heinss et al. 1998)</td>
</tr>
<tr>
<td>Faecal sludge density</td>
<td>1.34</td>
<td>kg/l</td>
<td></td>
</tr>
<tr>
<td>Faecal sludge production</td>
<td>0.30</td>
<td>l/cap./day</td>
<td>(Koanda 2006)</td>
</tr>
<tr>
<td>Average N content of the different food items</td>
<td>12.4; 1</td>
<td>gN/kg</td>
<td>(Montangero 2006)</td>
</tr>
<tr>
<td>N in excreta</td>
<td>7.9 ± 1</td>
<td>g/cap./day</td>
<td>(Schouw et al. 2002)</td>
</tr>
<tr>
<td>N in grey water on the street</td>
<td>0.5 ± 0.004</td>
<td>gN/l</td>
<td></td>
</tr>
<tr>
<td>N in grey water in soak away</td>
<td>0.22 ± 0.002</td>
<td>gN/l</td>
<td></td>
</tr>
<tr>
<td>N in septic tank faecal sludge</td>
<td>1.44 ± 0.01</td>
<td>gN/l</td>
<td></td>
</tr>
<tr>
<td>N in simple pit latrine faecal sludge</td>
<td>15.4 ± 0.32</td>
<td>gN/l</td>
<td></td>
</tr>
<tr>
<td>N transfer coefficient in leachate for the septic tanks</td>
<td>86–95%</td>
<td>–</td>
<td>(Montangero &amp; Belevi 2007)</td>
</tr>
<tr>
<td>N transfer coefficient in leachate for the pit latrines</td>
<td>86–95%</td>
<td>–</td>
<td>(Montangero &amp; Belevi 2007)</td>
</tr>
</tbody>
</table>
obtained through interviews with local stakeholders: public administration (mainly administration in charge of water resource, agriculture, and livestock), municipality, NGOs, and industries. The interviews had two objectives: (1) to validate the model framework, and (2) to collect data for the model. A survey among the population of Fada was carried out, and 165 households were interviewed based on the three kinds of household standards of living (high, average and low).

Nitrogen (N) values in faecal sludge and grey water are based on lab analysis results. Grab sampling was used to collect wastewater samples (40 samples) during two sampling campaigns. Samples of faecal sludge (16 samples) were taken during emptying operation of pit latrines or septic tanks. Sampling was done in polyethylene bottle containing nitric acid in order to have a pH < 2 and stored at approximately 4°C. N has been determined by Kjeldahl method according to Standard Methods for the Examination of Water and Wastewater (2005). Matter flow was expressed in kg/cap./year and nitrogen flow in g/cap./year.

The software Excel was used for mass flow calculation and software for substance flow analysis (STAN) was used for the graphic representation. It was produced by the Vienna University of Technology. It can be used as a base for modelling material flow for the assessment of the economic resource and environmental value of materials (Cencic & Rechberger 2008).

**Evaluated scenarios**

Two scenarios have been evaluated by using MFA model: the current status and the strategic sanitation options developed by ONEA (Table 2).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Current status</th>
<th>Strategic sanitation options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple pit latrines</td>
<td>78%</td>
<td>−</td>
</tr>
<tr>
<td>Simple pit latrines rehabilitated to VIP latrines</td>
<td>−</td>
<td>78%</td>
</tr>
<tr>
<td>Septic tank</td>
<td>5%</td>
<td>8%</td>
</tr>
<tr>
<td>Pour flush</td>
<td>−</td>
<td>9%</td>
</tr>
<tr>
<td>Open defaecation</td>
<td>10%</td>
<td>2%</td>
</tr>
<tr>
<td>Using neighbourhood facility (mainly simple pit latrine)</td>
<td>7%</td>
<td>3%</td>
</tr>
<tr>
<td>Soak pits (grey water)</td>
<td>20%</td>
<td>30%</td>
</tr>
</tbody>
</table>

**RESULTS AND DISCUSSION**

**Current situation analysis**

The principal matter flows are water consumption (6.7 m³/cap./year) and wastewater. Wastewater is poured into soak-aways where it infiltrates into the soil to reach groundwater, or on the street where it evaporates, infiltrates or streams to surface water. About 3.4 m³/cap./year of wastewater is infiltrating to groundwater. There was no wastewater reuse in the system, so water is used and poured. The organic solid waste in open dumps increased by about 55 kg/cap./year.

The most important nitrogen flows come from household food, kitchen waste and human excreta. The most part of excreta is collected in on-site sanitation systems with infiltration of 86–95% of nitrogen from septic tanks and 73–91% from pit latrines due to leachate (Montagnero & Belevi 2007). Per year, each inhabitant of Fada discharges about 5.7 kg of nitrogen toward surface water, soil and groundwater. The rate of N reused as peri-urban agriculture enrichment is about 11% (see Figure 1).

**Evaluation of Strategic Sanitation Plan**

The first impact of Strategic Sanitation Plan implementation is the increase of water consumption due to the proposed increase of septic tanks and pour-flush pit latrines. The simulation predicts the increase of water consumption by about 1.8 m³/cap./an. There is an increase of liquid matter flow for on-site sanitation in comparison to the current situation, because more households will have septic tanks and pour flush pits.

Table 3 summarizes the main differences between the current situation and the strategic plan. The technology options promoted by the Strategic Sanitation Plan due to their permeability increase the nitrogen flow which infiltrates to groundwater. More households will be equipped with VIP latrine, septic tanks and pour flush, and then a portion of wastewater and excreta will be moved from the street to sanitation facilities which are permeable. About 0.42 kg/cap./year will be moved from surface water to groundwater. The groundwater level can reach 2 m in some parts of Fada city and the average depth of VIP latrines and septic tanks is between 1.5 and 4 m. The options of this plan favour the transfer of pollutants from surface water to groundwater.
Constraints and shortcomings of MFA

MFA uses several parameters whose data is difficult to collect and determine in developing countries. MFA model is complex and difficult to use by every person. Each MFA model is specific to the system which it is studying. The equation formulation depends on the availability of data. For this reason, to simulate a scenario requires modifying parameter values and sometimes changing the equation formulation. It is therefore difficult if not impossible to apply the same model to another system. Another difficulty concerns errors or the propagation of uncertainties which are
important for this kind of model but complicated to estimate in the context of developing countries.

The model of MFA was applied for a defined system. In this case, the result is valid for the geographic limit of Fada city. One part of nitrogen contained in faecal sludge removed from pits was collected and discharged by trucks out of the city.

Last but not least, MFA method needs to be combined with social and economic analysis when designing sanitation plan. These parameters are important for sanitation technology choice.

CONCLUSIONS AND RECOMMENDATIONS

The standard process of sanitation planning in African cities by national authorities consists of six steps: (i) current status assessment, (ii) identification of problems, (iii) choice of technology, (iv) pilot project implementation, (v) monitoring, validation and (vi) large scale project implementation (McConville 2008). The program objectives are generally to improve human and environmental health. In the case of Fada, the sanitation strategies do not reach these objectives.

MFA results can be used as an environmental argument for the choice of sanitation solution in order to preserve natural resources. The methodology can be applied for the assessment of the current status and the selection of technology options for sanitation.

The results of the present MFA study allow having a critical view on urban system management. Solutions which are proposed by the Strategic Sanitation Plan of Fada move matter and nitrogen flows from surface water to groundwater. The implementation of the Strategic Sanitation Plan will increase water consumption and the pollution of groundwater. There is no efficient treatment of pollution, and nutrients cannot be reused. Based on the results of the MFA study in Fada, recommendations for improvement and sustainability are:

- Flush water systems should be avoided due to water shortages, and wastewater reuse should be promoted;
- The promotion of sanitation technologies with permeable pits and tanks is not appropriate in areas where groundwater levels are high; instead watertight lined pits and tanks should be promoted;
- Considering the high concentration of nutrients (nitrogen) in urine and faecal sludge, it is recommended to introduce urine diverted toilets and co-composting of faecal sludge with organic waste as main sustainable option for the strategic plan.

To be more efficient and to become common use in developing countries, MFA studies should focus on the key and challenging processes and flows. MFA models should be simple, in order to be easier to apply by local sanitation experts. MFA should ideally be combined with an economic analysis – like service costs including capital and operational expenditures, and households’ ability and willingness to pay, in order to allow informed choices for sustainable sanitation options.

In the next stage of this study, the MFA model will be used to evaluate more sustainable sanitation options such as urine diverted toilets and co-composting.

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REFERENCES


Binder, C. 1996 The Early Recognition of Environmental Impacts of Human Activities in Developing Countries. Abhandlung zur Erlangung des Titels Doktorin der Naturwissenschaften der ETHZ. Eidg. Technische Hochschule Zürich, Switzerland.


ONEA 2006 Plan Stratégique d’assainissement des Eaux Usées et Excrétas de la ville de Fada N’Gourma (Wastewater and excreta management plan in Fada N’Gourma city). Mairie de Fada N’Gourma, Burkina Faso.

