

Material flow analysis as a strategic planning tool for regional waste water and solid waste management

Hasan Belevi

Department of Water & Sanitation in Developing Countries (SANDEC),
Swiss Federal Institute for Environmental Science and Technology (EAWAG), Duebendorf

Abstract

The main purpose of this paper is to familiarize the reader with the material flow analysis method using a case study. Organic material and waste fluxes in the City of Kumasi, Ghana are chosen for this purpose. The annual nitrogen and phosphorus fluxes are determined in urban¹ and peri-urban agriculture², in industry, households, fecal sludge treatment, and in solid waste management. The data obtained reveal that the key process contributing to the organic material fluxes are private households, as they are characterized by a large turnover of materials and a large waste production. Therefore, measures taken at the household level and an appropriate household waste management could greatly enhance resource recovery and environmental protection in Kumasi. The results also show that the nitrogen and phosphorus demands of about 30 % of the urban and peri-urban agriculture could be covered theoretically by co-composting fecal sludge together with solid waste currently disposed of in landfills. However, only a higher collection and treatment of excreta from private households could significantly reduce soil, surface water and groundwater pollution.

1. Introduction

To achieve a sustainable development of urban regions it is essential to manage the resource consumption and to leave unpolluted ecosystems to future generations. Officials and planners aiming at sustainable development have to adapt the management objectives of resources and waste to the regional requirements. The method "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. It analyzes the flux of different materials through a defined space and within a certain time. In industrialized countries, MFA proved to be a suitable instrument for early recognition of environmental problems and development of solutions to these problems. It is possible to combine data from market research with data from urban waste management, in order to observe the metabolism of urban regions [1].

¹ In this paper, the urban agriculture refers to the area within the administrative boundary of the City Kumasi.

² In this paper, the peri-urban agriculture refers to the area between the administrative boundary of the City Kumasi and a circle with a radius of 40 km from the city center [20].

The main purpose of this paper is to familiarize the reader with the material flow analysis tool using a case study. Organic material fluxes including hypothetical co-composting of a part of organic waste in the City of Kumasi, Ghana is chosen for this purpose. Co-composting is one option to treat human and organic solid waste prior to their use in agriculture. The main objectives of composting are to decompose potentially putrescible organic matter into a stable state and to produce a material for use as soil improvement by reducing runoff and erosion. Compost provides additionally various nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium. A considerable volume of the commercial and household waste and fecal sludge is amenable to composting. Since compost from urban organics can be used on urban and peri-urban agricultural plots, urban and peri-urban food production can be associated with urban waste management.

Currently, no specific data is known about the demand and supply of compost produced in the City of Kumasi, the capital town of Ashanti region, Ghana. Its population numbers 982,000 inhabitants spread on a total area of 254 km², of which 38 % is open land [19]. Breweries, saw-mills, poultry farms are important industries regarding organic material fluxes. The available sanitation systems are: unsewered public toilets, bucket latrines, pit latrines, WC/septic tank systems, sewerage. Open defecation is also being practiced. Part of the fecal sludge produced in the unsewered system is collected and treated in a pond system in Kaasi near Kumasi. The Municipal Waste Management Department is responsible for municipal waste collection and landfill disposal. The peri-urban area covers an area of 40 km from the city center beyond the administrative boundaries of the city and numbers about 740,000 inhabitants [20].

Material flow analysis allows to link production and supply of organic material with the collection, production and treatment of urban waste. The urban waste referred to in this paper comprises the streams of municipal solid waste and human excreta. Focus is placed on the organic material and waste fluxes in the City of Kumasi. Mass fluxes of goods (fertilizer, food, municipal solid waste, compost, etc.) and the mass fluxes of the elements nitrogen and phosphorus are presented. Economic, political and social issues are not dealt with in this paper. The following specific questions are formulated:

- Which are the key processes in organic material and nutrient fluxes in the City of Kumasi?
- To what extent can the nutrient demand of urban and peri-urban agriculture be met by organic waste reuse?
- To what extent can emissions to water and soil be reduced by collecting and treating municipal solid waste and fecal sludge?

2. Method

The development of a regional material flux analysis starts with a system analysis [1]:

- Which goods and processes are to be included?
- Where are the system borders?
- Which time span is to be considered?

In material flow analysis, materials or material mixtures with functions valued by man are defined as “goods”. Materials are chemical elements and their compounds. The term “process” denotes the transport, transformation or storage of materials and goods. While in most cases transport does not change the chemical composition of goods, it requires energy and involves other goods and materials. The same applies to storage. Through transformation, goods are changed into new products with new qualities and usually new chemical composition. In system analysis it is convenient to link goods and processes. Each good has one origin and one destination process. Consequently, each process is linked to other processes by means of goods. A particular good, which flows from process A to process B is called an output good for process A, and an input good for process B. An import good is defined as a good entering the system, and an export good a good leaving the system. The same terminology applies to material flux.

A material flow analysis comprises:

- 1) A system analysis comprising goods and processes
- 2) Determination of the mass fluxes of all the goods per unit of time
- 3) Determination of the concentrations of the selected elements in these goods
- 4) Calculation of the mass and element fluxes from the mass fluxes of goods and element concentrations in these goods
- 5) Interpretation and presentation of the results

Figure 1 illustrates system analysis of the organic material streams including the hypothetical process “co-composting” in the City of Kumasi . The system comprises 8 processes within the system border, the fluxes between these processes as well as the import and export fluxes to and from the system. The administrative boundary of the City of Kumasi is chosen as the system border. The process peri-urban agriculture is also included into the system. The environmental compartments “atmosphere”, “groundwater and surface waters”, and “soil” are sinks for the residual fluxes. They are placed outside the system border and have not been investigated here.

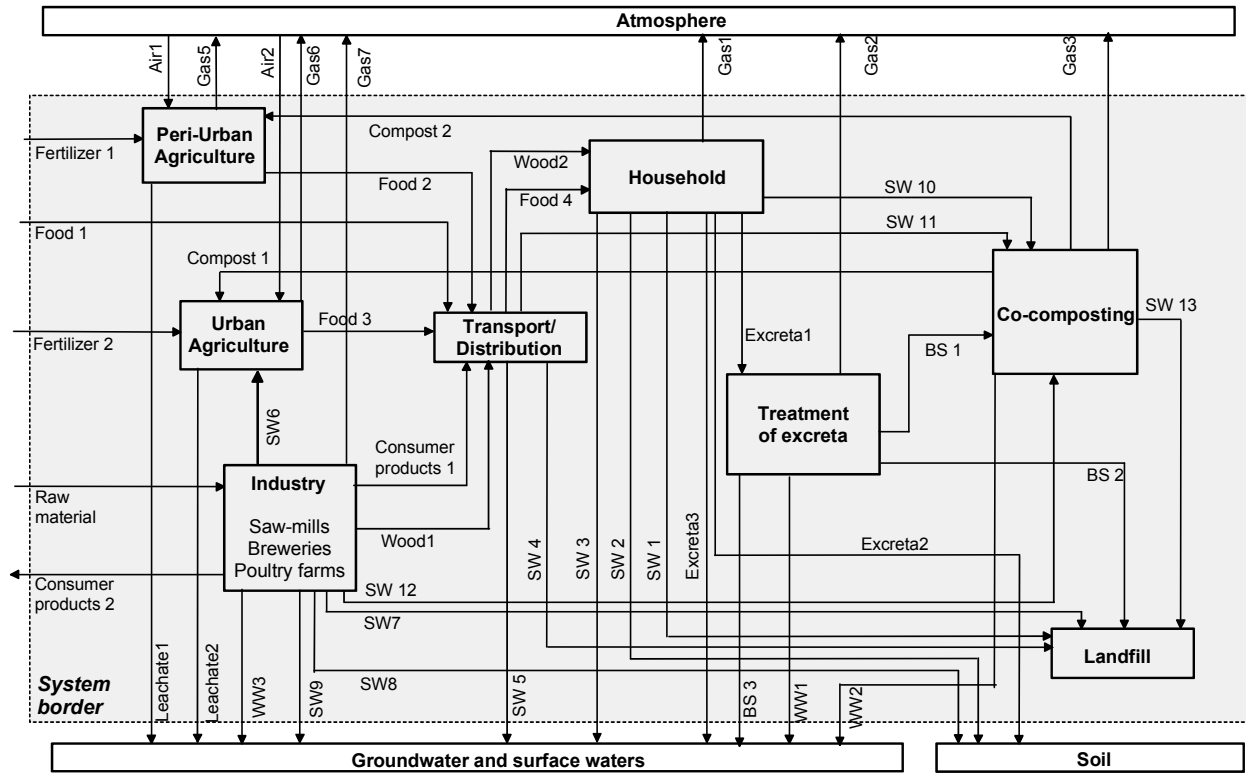


Figure 1: System analysis of the organic material streams in the City of Kumasi

SW: solid waste BS: biosolids WW: waste water

The processes themselves can be viewed as black boxes. Material transfers from input goods to output goods are expressed as transfer coefficients. Transfer coefficients are defined by the following equation [1]:

$$k_{i,j} = \frac{A_{i,j}}{A_{i,w}}$$

where

- $k_{i,j}$ stands for the transfer coefficient of the total mass or of the element i and describes the relative amount of the total input into the process transferred to the output good j .
- $A_{i,j}$ stands for the total mass or for the element flow of the element i to the output good j .
- $A_{i,w}$ corresponds to the total mass or element input of the element i into the process.

Transfer coefficients describe the input mass distribution amongst the various products. For example, if co-composting process is considered, a high transfer coefficient of an element to the compost (Compost 1 and Compost 2 in Figure 1) indicates that this element is mainly transferred to the compost. A high transfer coefficient of an element to the gas (Gas 3) indicates that this element is volatilized during composting.

Table 1: Determination methods of mass and element fluxes

Good	Origin Process	Destination Process	Determination Method
Fertilizer1	Outside the system border	Peri-urban Agriculture	Literature data [3]
Food1	Outside the system border	Transport/ Distribution	Measurements and literature data [4,5]
Fertilizer 2	Outside the system border	Urban agriculture	Literature data [6]
Raw material	Outside the system border	Industry	Available company information and literature data [5,7]
Air1	Atmosphere	Peri-urban agriculture.	Literature data [3]
Air2	Atmosphere	Urban agriculture	Literature data [6]
Food2	Peri-urban agriculture	Transport/ Distribution	Measurements and literature data [4, 5, 8]
Leachate1	Peri-urban agriculture.	Groundwater and surface waters	Literature data [3, 9]
Gas5	Peri-urban agriculture	Atmosphere	Literature data [5]
Food3	Urban agriculture	Transport/ Distribution	Literature data [6]
Leachate2	Urban agriculture	Groundwater and surface waters	Literature data [6]
Gas6	Urban agriculture	Atmosphere	Literature data [6]
Consumer Products1	Industry	Transport/ Distribution.	Available company information and literature data [5,7]
Consumer Products2	Industry	Outside the system border	Available company information and literature data [5]
Wood1	Industry	Transport/ Distribution	Available company information and literature data [5]
SW6	Industry	Urban agriculture	Available company information and literature data [5,7, 10]
SW12	Industry	Co-composting	Theoretical values according to future scenarios
SW7	Industry	Landfill	Mass balance by assuming that 25% of poultry waste are landfilled
SW8	Industry	Soil	Mass balance by assuming that 50% of wood are disposed of on soil in a unregulated manner
SW9	Industry	Groundwater and surface waters	Mass balance by assuming that 20% of wood and 50% of poultry waste are disposed of in surface waters in a unregulated manner
WW3	Industry	Groundwater and surface waters	Mass balance
Gas7	Industry	Atmosphere	Mass balance by assuming that 30% of wood waste are combusted and literature data [10]

Table 1: (continuing)

Good	Origin Process	Destination Process	Method of Determination
Food4	Transport/ Distribution	Household	Measurement and literature data [4,5]
Wood2	Transport/ Distribution	Household	Measurement and literature data [5]
SW11	Transport/ Distribution	Co-composting	Theoretical values according to future scenarios
SW4	Transport/ Distribution	Landfill	Mass balance by using available data and literature data [11]
SW5	Transport/ Distribution	Groundwater and surface waters	Mass balances by using available data
Gas1	Household	Atmosphere	Mass balances by using literature data [12]
SW10	Household	Co-composting	Theoretical values according to future scenarios
BS1	Household	Co-composting	Theoretical values according to future scenarios
Excreta 1	Household	Treatment of excreta	Literature data [13,14]
Excreta 2	Household	Soil	Mass balance by using literature data [13]
Excreta 3	Household	Groundwater and surface waters	Measurements and literature data [14]
SW1	Household	Landfill	Measurement and literature data [15]
SW2	Household	Soil	Mass balances by assuming that 50% of MSW which cannot be collected are littered
SW3	Household	Groundwater and surface waters	Mass balances by assuming that 50% of MSW which cannot be collected are disposed of in surface waters
Gas2	Treatment of excreta	Atmosphere	Mass balance and literature data [16]
BS2	Treatment of excreta	Landfill	Literature data [13]
BS3	Treatment of excreta	Groundwater and surface waters	Literature data [13]
WW1	Treatment of excreta	Groundwater and surface waters	Literature data [13]
Compost 2	Co-composting	Peri-urban agriculture	Mass balance and literature data [17, 18]
Compost1	Co-composting	Urban agriculture	Mass balance and literature data [17, 18]
Gas3	Co-composting	Atmosphere	Mass balance and literature data [17, 18]
SW13	Co-composting	Landfill	Mass balance and literature data [17, 18]
WW2	Co-composting	Groundwater and surface waters	Mass balance and literature data [17, 18]

SW: solid waste

BS: biosolids

WW: waste water

There are several ways of determining mass and element fluxes. They can either be assessed by literature data (existing information), determined by field measurements, calculated by mass balances over a process or process chains, or through a combination of all these methods.

Table 1 lists the goods, their origin and destination processes, and the method for determining mass fluxes (mass fluxes of goods) as well as nitrogen and phosphorus fluxes (mass fluxes of elements nitrogen and phosphorus). Assessment and measurement procedure are elucidated elsewhere [2].

3. Results and Discussion

Figure 2 illustrates the annual mass fluxes.

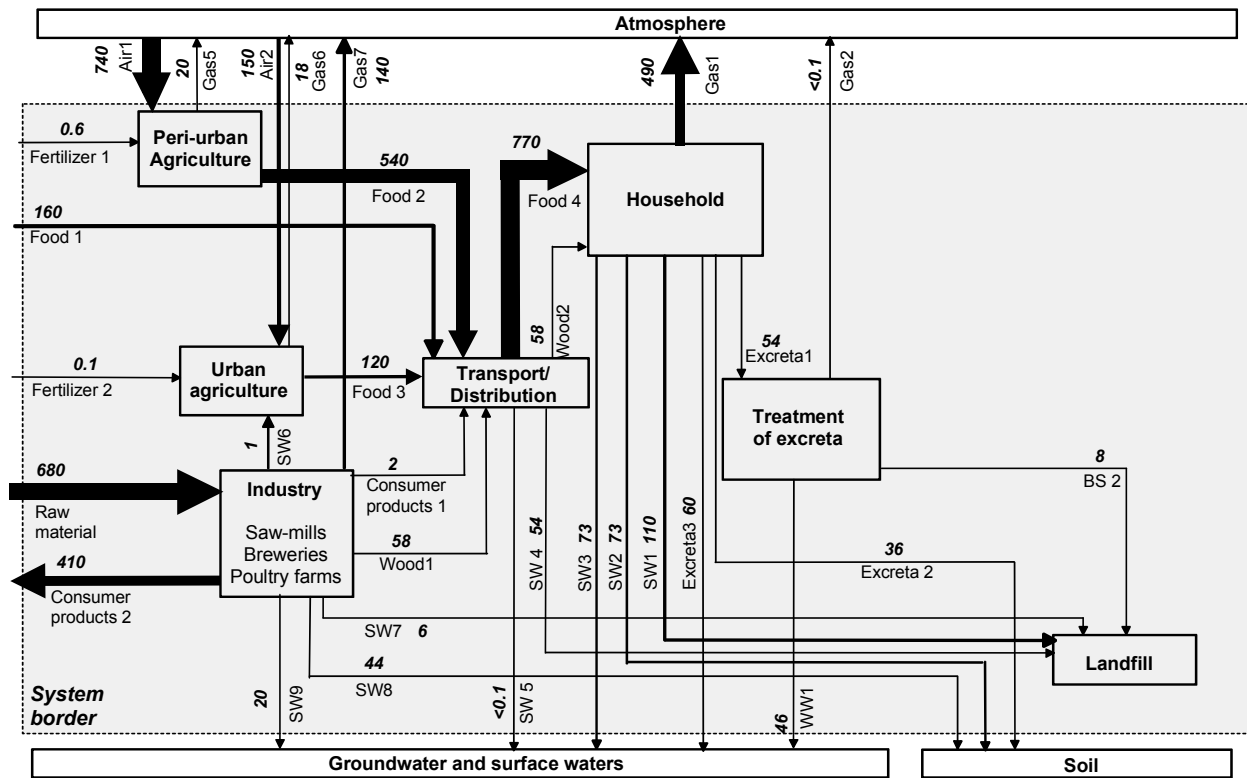


Figure 2: Annual mass fluxes in $\text{kg} \cdot \text{capita}^{-1} \cdot \text{year}^{-1}$
Fluxes are estimated with a 20-50% error margin

An “average” person consumes annually 770 kg of food³ in the City of Kumasi. This value is estimated with an error margin of about 20% and does not include food production for own consumption. Peri-urban agriculture supplies about 66% of the household food requirements. About 14% is covered by urban agriculture. About 20% of the household food demand is met by import. There is a high turnover of organic material in the local industry, i.e. saw-mills,

³ The data for the consumption of for different food products such as vegetables, cereals, sugar, meat, fish, and the nitrogen and phosphorus concentrations in these products are given elsewhere [2].

breweries and poultry farms. The raw material for this industrial production is imported into the system and an important part of the products are exported out of the system.

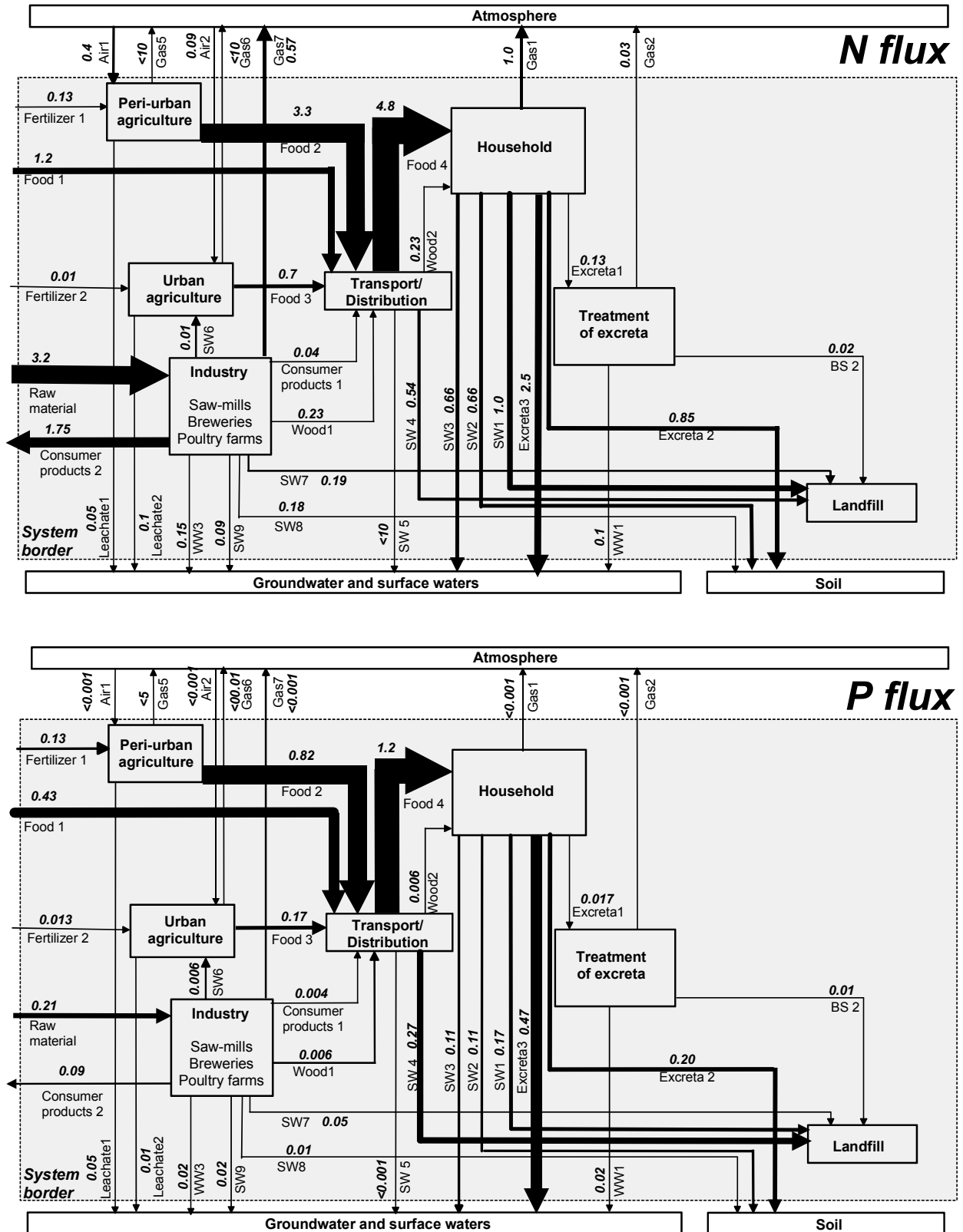


Figure 3: Annual nitrogen and phosphorus fluxes in kg·capita⁻¹·year⁻¹ .

Fluxes are estimated with a 20-50% error margin.

Figure 3 illustrates the annual nitrogen and phosphorus fluxes. Industry is responsible for a significant nitrogen flux amounting to an import of $3.2 \text{ kg} \cdot \text{capita}^{-1} \cdot \text{year}^{-1}$. About 54% of the nitrogen is exported and only 9% is transported to the households from the industry. The rest is either landfilled or transferred to the air, water or soil. The industrial contribution to the phosphorus flux is not high.

Transport and distribution of goods constitutes a major transport process. Households are however the most significant transformation process. About 80% of the nitrogen and about 90% of the phosphorus, transferred to air, water, soil, and landfill, flow through the households. Households contribute 87% of the nitrogen, 82% of the phosphorus emissions to groundwater and surface waters, as well as 90% of the nitrogen and 97% phosphorus emissions to the soil. Households are also responsible for 58% of the nitrogen and 34% of the phosphorus fluxes to the landfill. Consequently, households are the key processes. Measures taken at the household level would significantly contribute to saving resources and to environmental protection in Kumasi.

Groundwater and surface waters receive 47 % of the total nitrogen and 54 % of the total phosphorus outputs from households. About 22% of the nitrogen and 29% of the phosphorus are emitted to soil. About 15 % of the nitrogen and 16% of the phosphorus are landfilled. Fecal sludge treatment plant receives less than 2% of the nitrogen and phosphorus. About 15 % of the nitrogen is transferred to the atmosphere from the households.

The total fluxes in the system can be calculated by multiplying the fluxes per capita and year with the number of inhabitants in Kumasi. Hence, the nutrient deficiencies in agriculture can be calculated by the differences between output and input fluxes. The annual nitrogen and phosphorus deficiencies in urban agriculture seems to amount to 690 t/year and 160 t/year, respectively. In peri-urban agriculture, soils lack 2700 tons of nitrogen and 720 tons of phosphorus every year. These values seem not to be plausible. Therefore, the assessment and measurement procedure for the fluxes in the urban and peri-urban agriculture has to be reviewed before drawing any conclusions.

About 1700 tons of nitrogen and 500 tons of phosphorus are disposed of annually in landfills through different types of waste. Additionally, about 3600 tons of nitrogen and 690 tons of phosphorus are discharged into surface waters and about 1700 tons of nitrogen and 310 tons of phosphorus reach the soil. Seen from a technical and content perspective, part of these nitrogen and phosphorus fluxes could be recycled by co-composting fecal sludge and municipal

solid waste and by using the finished compost as soil conditioner and fertilizer. This could also reduce soil, groundwater and surface water pollution, and save landfill space. The fluxes to be collected and treated are dependent on numerous technical, social and economical criteria. Material flow analysis could be applied to combine the fluxes according to selected criteria and to optimize the entire system. For this purpose, the transfer behavior of the process co-composting has to be known, i.e., the mass transfer coefficients and the transfer coefficients of the elements nitrogen and phosphorus have to be determined. Table 2 lists the transfer coefficients in a composting plant for garden and kitchen wastes [17, 18].

Table 2: Transfer coefficients in a composting plant for garden and kitchen wastes [17, 18]

	Mass	Carbon	Nitrogen	Phosphorus
Gas	0.36	0.52	0.30	<0.001
Compost	0.61	0.45	0.69	0.99
Leachate	0.03	0.03	0.01	0.01

The carbon fluxes are not presented in this paper, but have also been determined to optimize the C:N ratio in the feedstock. Therefore, the transfer coefficients of carbon are also listed in Table 2. About 61% of the mass and 45% of the carbon are transferred to the compost in a composting process. About 30% of the nitrogen volatilize and 99 % of the phosphorus remains in the compost product.

The transfer coefficients of the hypothetical co-composting plant are assumed to be the same as the ones measured in the aforementioned composting plant. Only two scenarios for nitrogen and phosphorus recovery are presented in this paper, i.e., a “realistic” and an “optimistic” scenario. In the “realistic” scenario (Scenario 1), only the waste fluxes currently transported by truck to the landfill are considered. These solid waste originate from industry (SW7), market places (SW4), and from households (SW1) and the biosolids from fecal sludge treatment plant (BS2) transported to the landfill. In the “optimistic” scenario (Scenario 2), the entire solid waste in the system except the timber processing waste, which is disposed of in surface waters, is collected and composted. According to this scenario, the waste fluxes SW1, SW2, SW3, SW4, SW5, SW7, SW8, and BS2 are delivered to a co-composting plant. These scenarios have been chosen to illustrate the material flow analysis. However, depending on the different objectives, there are many other possible scenarios.

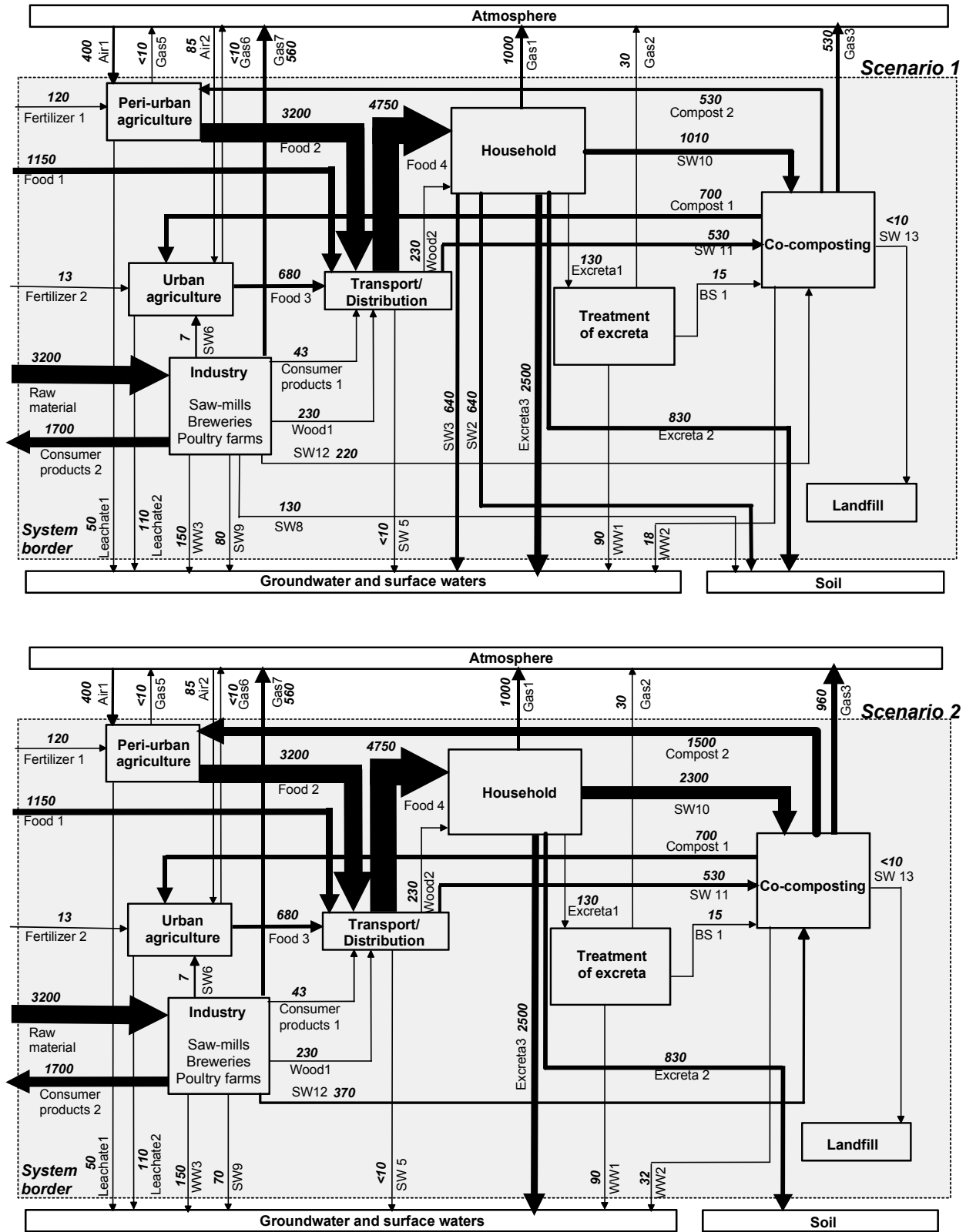


Figure 4: Annual nitrogen fluxes according to Scenarios 1 and 2 in t/year.

Figure 4 illustrates the nitrogen fluxes in Scenarios 1 and 2. The reduction in the nitrogen and phosphorus emissions to soil and surface waters is negligible in Scenario 1. The nitrogen loads to groundwater and surface waters are reduced by about 17%, and to soil by about 50% in Scenario 2. The corresponding values for phosphorus are 16% and 38%. Higher reductions can be reached by treating higher amounts of fecal sludge and using them as a compost feedstock, since the most significant nitrogen and phosphorus fluxes to soil, surface waters and groundwater occur via feces and urine transfers from households to these environmental compartments. The collected and treated amount of excreta is currently much lower than the amount transferred to the soil, groundwater and surface waters. Additionally, a high part of nutrients are anyhow transferred after fecal treatment to groundwater and surface waters. Consequently, a higher collection ratio for feces and urine and their co-composting could decrease the nitrogen and phosphorus loads to the environment.

As aforementioned, co-composting not only contributes to environmental protection, but also to resource recovery. How far can the nutrient demand of urban and peri-urban agriculture be covered by co-composting? According to the both scenarios, it is possible to cover the entire nutrient requirements of urban agriculture. In Scenario 1, 57% of the produced compost has to reach urban-agriculture and the rest peri-urban agriculture, in order to fulfill the requirements. In Scenario 2, only 32% of the produced compost will be sufficient to meet the nutrient demand of urban-agriculture. In Scenario 1, about 530 tons and in Scenario 2 about 1500 tons of the nitrogen can be delivered annually to peri-urban agriculture in the form of compost, and annually 210 tons and 490 tons of the phosphorus, respectively. This recycling would cover 18% of the nitrogen and 25% of the phosphorus needs of peri-urban agriculture in Scenario 1. In Scenario 2, 53 % of the nitrogen and 58% of the phosphorus requirements will be met.

Can the co-composting process be carried out with the input delivered to the co-composting plant is another important aspect. For this purpose, the C:N ratio and water content of the input material in the composting plant is assessed by material flow analysis. The optimum C:N ratio should amount to 30:1 and the optimum water content between 50% and 60%. The C:N ratios of the input material amount to 37:1 in Scenario 1, and 42:1 in Scenario 2. These values are slightly higher than the optimum ratio. The water content of the input amount 51% in Scenario 1, and 48% in Scenario 2. These values are within the optimum range.

However, the scenarios do not consider one of the most important concerns pertaining to use and marketability of the compost; the heavy metal content of the compost. Material flow analysis can also be used to assess the heavy metal content in the compost, as the level of heavy metal concentrations in compost is dependent on the feedstock entering the co-

composting plant. Therefore, the heavy metal content of input fluxes has to be determined, but has not been carried out in this study. The transfer coefficients of heavy metals in the composting process can be either measured or assessed by literature data. A theoretical compost product with acceptable heavy metal concentrations can be obtained by reaching an optimum combination of mass and element fluxes in the system.

4. Conclusions

- Material flow analysis allows planners and decision makers to identify the key processes for environmental protection and resource recovery in a region. This method allows to assess the critical emissions to air, water and soil, and an early detection of possible hazards. Based on this information, most effective measures and strategies can be chosen. An optimum resource recovery system can be designed by using a combination of relevant mass and material fluxes.
- In the City of Kumasi, the key process for organic material and nutrient fluxes are private households. They are characterized by a large turnover of materials and a large waste production. Measures taken at the household level and an appropriate household waste management could greatly enhance resource recovery and environmental protection in Kumasi.
- The nitrogen and phosphorus demands of about 30 % of the urban and peri-urban agriculture could be covered theoretically by co-composting fecal sludge together with solid waste currently disposed of in landfills. Only a collection and treatment of excreta in co-composting plants, however, attain a significant reduction in soil, surface water and groundwater pollution.

5. Literature Cited

- [1] Baccini P. & Brunner P.; 1991, "Metabolism of the Anthroposphere", Springer-Verlag, Berlin.
- [2] Leitzinger Ch.; 2000, "Ist eine Co-compostierung aus stofflicher Sicht in Kumasi/Ghana sinnvoll?", Diploma Thesis, ETH Zurich.
- [3] IFDC; 1995, "Ghana Fertilizer Privatizations Scheme; Private sector roles and public sector responsibilities in meeting needs of farmers"; International Fertilizer Development Center – Africa; Lomé, Togo.
- [4] Stoorvogel J.J., Smaling E.M.A.; 1990, "Assessment of soil nutrient depletion in Sub-Saharan Africa: 1983 – 2000", Volume III: Literature review and description of Land Use Systems; Instituut voor onderzoek van het Landelijk Gebied; Report Nr. 28; Wageningen, The Netherlands.
- [5] Müller D., Oehler D., Baccini P.; 1995, "Regionale Bewirtschaftung von Biomasse, eine stoffliche und energetische Beurteilung der Nutzung von Agrarflächen mit Energiepflanzen"; vdf Hochschulverlag an der ETH Zurich, Switzerland.

- [6] MOFA; 1999, "Production of Major Crops in the Ashanti – Region 1998"; Ministry of Food and Agriculture; Regional Office Kumasi, Ghana.
- [7] Bessei W.; 1988, "Bäuerliche Hühnerhaltung, Junghennen, Legehennen", Mast; Verlag Eugen Ulmer; Stuttgart, Germany.
- [8] Nketiah K. S., Hagan E. B., Addo S. T.; 1988, "The Charcoal Cycle in Ghana", A Baseline Study; United Nations Development Programme and National Energy Board, Ghana.
- [9] Mauderli A. F.; 1998, „Erhaltung der Bodenfruchtbarkeit, Bekämpfung der Bodenerosion, pflanzenbauliche Massnahmen“; Lecture notes , ETH Zurich, Switzerland.
- [10] Frenken A.; 1989, "Stickstoffverlust aus verschiedenen Stickstoffverbindungen des Legehennenkotes während der Lagerung in unterschiedlichen Haltungssystemen"; Dissertation an der Rheinischen Friedrich – Wilhelms – Universität; Bonn, Germany.
- [11] Mensah A.; 1999, "Deputy Director Kumasi Metropolitan Assembly (KMA) – Waste Management Department (WMD); personal communications.
- [12] Koller E.A.; 1996, "Einführung in die Atmungsphysik", 24. erweiterte Auflage; Lecture notes , ETH Zürich, Switzerland.
- [13] Leitzinger C. und Adwedaa D.; 1999, "Field Monitoring of the Faecal Sludge Treatment" – Plant in Kaasi, Kumasi / Ghana 1999; Report EAWAG / SANDEC.
- [14] Heinss U., Larmie S. A., Strauss M.; 1998, "Solid Separation and Pond Systems for the Treatment of Faecal Sludges in the Tropics"; SANDEC Report 5/98; EAWAG; Duebendorf, Switzerland.
- [15] Salifu L.; 1990, "An Overview of Solid Waste Management in the Kumasi Metropolitan Area; Urban Sanitation Management Series No. USMS 3.
- [16] Montangero A.; 1999, personal communications; SANDEC, EAWAG, Duebendorf, Switzerland.
- [17] Obrist W., Baccini P.; 1986, "Auswahlkriterien für Kompostierbare Abfälle"; Wasser, Energie, Luft, 78 (11/12), 290 – 294.
- [18] Belevi H., Baccini P.; 1997, "Verfahrenstechnik in Entsorgungssystemen", Lecture notes , ETH Zurich, Switzerland.
- [19] Kumasi Metropolitan Assembly; 1996, Development Plan for Kumasi 1996 – 2000; Part II, District Profile
- [20] Blake B., Kasanga K.; 1997, Kumasi Natural Resource Management Research Project, Inception Report; NRI, Natural Resources Institute, The University of Greenwich, UK and University of Science and Technology, Kumasi, Ghana