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In-depth analysis of nitrogen flow in urban system in Low Income Countries: The case of Yamoussoukro in Côte d'Ivoire

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ABSTRACT

In-depth analysis of nitrogen flows (NF) using Material Flow Analysis (MFA) was curried out to assess the impact of the current urban sanitation system in the city of Yamoussoukro in Côte d'Ivoire. The aim of the study was to develop resource recovery mitigating option for a sustainable management of the sanitation system. MFA simulations were improved by integrating R.3.0.1 and STAN 2.5 in the research framework. With a context of limited data, NF were efficiently assessed using Monte Carlo simulation in R with 1,000 iterations, based on probability distribution and statistics of input parameters. About 905 tons of nitrogen per year are discharged from the sanitation system including waste water, solid waste and faecal sludge. The discharged nitrogen degrades the urban environment and increases human exposure to health risk. To address sustainable mitigation measures, three resource recovery sanitation technology scenarios were developed. The first scenario integrates lagoons and composting plants while the second and third scenarios include unplanted and planted drying beds respectively together with co-composting. The first scenario allows potential reuse in agriculture, of 89.3% (808.6 tons) of total nitrogen produced per year which would otherwise be discharged to the environment. This scenario was thus found to be the most ecologically relevant and low-cost option. The study highlighted relevant statistical estimations, reduction of time and energy consumption in simulations, MFA potential for environmental risk mitigation and

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improved agriculture by nutrient recovery. This productive urban waste management option could be helpful for urban planners in developing cities.

Keywords: Material Flow Analysis; Nitrogen Flows; Urban Waste Management; Monte Carlo simulation, Côte d'Ivoire, Sensitivity analysis

INTRODUCTION

As with several developing urban regions, Côte d'Ivoire shows signs of excessive use of materials and resource consumption. Côte d'Ivoire, as one of the highly urbanized developing countries in the West African region, is trapped with inefficient use of resources especially in urban centres. Cities now consume resources and produce wastes in amounts that are incommensurate with the populations they contain. However, urban waste management, that addresses waste waters, solid wastes and excreta is still limited in developing countries and particularly in Sub-Sahara Africa (SSA) (Agassounan et al, 2012; Bassan et al., 2013; Gning et al, 2017).

Therefore, there is a need to develop measures for innovative intervention in order to improve the urban waste management in the developing countries (Cools et al., 2013). According to the Sustainable Development Goals (SDGs), it is projected that approximately 2.5 billion people should have access to proper sanitation, However, the existing practice of open defecation together with indiscriminate discharge of domestic and industrial wastes in most developing countries poses a major challenge (IWA, 2014). Therefore, water resources are being degraded due to increasing demand and continued contamination from untreated waste water and leachate originating from industrial and domestic sources (Soro et al., 2010; Nyawira et al., 2014). It is estimated that by 2025, the rate of solid wastes generation worldwide will likely increase to 1.42 kg/cap/day from the projected global population of 4.3 billion inhabitants (Hoornweg and Bhada-Tata, 2012). The poor management of wastes - as it is the case in most SSA cities and specifically in that of Côte d'Ivoire - causes enormous threats to the environment, water resources, human well-being and the economy (Weihs and Mertens, 2013). Urban wastes, mostly from anthropogenic activities, contain enormous quantities of chemicals such as nitrogen, phosphorus and heavy metals, which could potentially affect the environment and the ecosystem (Khatri et Tyagi, 2015). Nitrogen is essential for ecological development and human survival. It is, therefore, one of the main components of urban wastes (wastewater, solid wastes and excreta) and its removal processes requires knowledge and specific technologies which are not readily available in SSA including Côte d'Ivoire (Khan et al., 2013).

In Côte d'Ivoire the nutrient loading of nitrogen to aquifers from on-site sanitation systems is largely unknown (Nyenje et al., 2013). For instance, in the city of Yamoussoukro, it was recently reported that the level of nitrogen has increased in the lake waters due to anthropogenic activities (Kouamé et al., 2014). Generally, the solid waste sector is poorly managed and wastes are open dumped without any treatment or reuse options. Furthermore, untreated effluents from septic tanks are discharged to the environment including the lakes without any control (Kouamé et al., 2014). Lack of sanitation in Yamoussoukro has considerably affected the environment and human health (Arvidsson et al., 2013).

Many efforts have been carried out to improve waste management worldwide (Allegrini et al., 2014). Specifically, to overcome the loss of possible resources, MFA has been conducted to characterize the resource recovery potential in many contexts

(Montangero, 2007). Recently, the use of R software (Development Core, Austria) for substance flows simulation has been shown to give a new view of model development in MFA (López-Villarreal et al., 2014). Taking the case of Yamoussoukro in Côte d'Ivoire as representative of many African cities, the current study aims at assessing the existing urban sanitation system through an in-depth analysis of nitrogen flows in order to provide evidence for developing a resource recovery mitigating option for a sustainable urban waste management system.

MATERIALS AND METHODS

Study area

This study was conducted in the city of Yamoussoukro, the political and administrative capital of Côte d'Ivoire. It is located about 240 km from Abidjan, the economic capital city. The area involved comprises the formal administrative borders of the city, including urban and peri-urban neighbourhoods, covering approximately 27,000 ha (Figure 1). According to the National Institute of Statistics in Côte d'Ivoire, the population of Yamoussoukro was about 207,412 inhabitants in 2014 (INS, 2014).

Waste management is not well addressed in the city: (i) onsite sanitation facilities septic tanks-based are poorly used by about 90% of the population, (ii) the poor neighbourhoods, accounting for 5% of the population use dry latrines, (iii) effluents from septic tanks are illegally discharged on the ground or in the lakes (iv) only 8% of residential areas and administrative offices are connected to the sewerage networks (N'Guessan et al., 2011). The solid wastes sector is poorly managed; wastes are openly dumped without any reuse policy. Yamoussoukro has above ten artificial lakes for aesthetic and tourism purposes. All types of waste water and solid wastes from anthropogenic activities are discharged into these artificial lake waters without prior treatment. Lake waters and channel waste water are used for agriculture and for watering vegetables. This agriculture uses mainly chemicals fertilizers.

Research framework and data collection process

This research applied MFA method considering nitrogen as a relevant indicator to assess the environmental sanitation and to address subsequent impacts on lake water. Nitrogen is well known to be a pollution indicator because its high concentration in the environment is mainly dependent on the increasing anthropogenic activities (Erisman et al., 2011). To assess waste management in the city of Yamoussoukro, the material flow analysis approach considering the Nitrogen flows, which enables a systematic assessment of the flows and stocks of materials within a system defined in space and time was applied. This involves the use of R statistical programming facilities and that of STAN, a graph drawing model software. This approach allows the connection of sources, pathways, and the intermediate and final sinks of a material. It is known to be a relevant basic tool implemented in many fields, such as environmental management, economics, resource management, and waste management in many developed and recently in developing countries (Brunner and Rechberger, 2004). Recently, MFA was successfully conducted to reduce environmental sanitation problems linked to the use of nitrogen and phosphorus in Vietnam (Montangero, 2007; Do-Thu et al., 2011).

For the city of Yamoussoukro, the research framework integrated the status of mass and nitrogen flows linked to the urban waste management. Nitrogen flows from mass of wastewater, solid waste and faecal sludge, are used to show how much flows affected groundwater and Lake environment in this city. The methodological approach was based on an iterative process as described by Baccini and followed by Montangero (Baccini and Brunner, 1991). Figure 2 shows the four main steps of the implementation process in this study, which

are: (i) Problem statement and system analysis, (ii) Material flows assessment, (iii) System validation, and (iv)Mitigation scenarios development.

However, some specificities were considered in each step. Indeed, during the first step, we deeply analysed the environmental threats linked to waste management in the city of Yamoussoukro. Various dynamics enabling solid wastes, wastewaters and faecal sludge generation were analysed after literature reviews, field visits, and a participatory workshop involving various stakeholders including scientist, practitioners and beneficiaries. For example, the main implication patterns and knowledge about the waste and sanitation shortcomings were investigated during this first step. The second step comprised of a material flows assessment, by modelling key mass and nitrogen with mathematical models using available data. The third step consisted of the validation of the whole system after the success of uncertainty considerations. The last step was conducted to simulate scenarios enabling environmental threats reduction regardless lake waters and ground water pollution and strategies improving nitrogen management in Yamoussoukro through resources recovery.

The data collection process integrated literature review to provide information for relevant estimation, including national and international databases (Table 1), secondary data from previous studies, as well as published paper and scientific reports. For nitrogen components investigation focusing on NO_3^- and NO_2^-, both secondary data (e.g. FAO STAT and USEPA report and scientific articles) for some parameters and laboratory analyses conducted over six months including 3 months during raining season and 3 other months during dry season have been used.

MFA model development

The mathematical modelling background and literature reviews were required for the model development. This consists of determining "model equations" based on scientific and expert knowledge (Montangero, 2007). Model equations (Eq.1) represent the characteristic features of the system and express how different parameters determine the variables in the system.

$$Y_{(x)} = F(x_1, x_2, x_3\ldots., x_i) \quad \text{(Eq.1)}$$

where x_1, x_2,…x_i represent parameters from model of equations

The model equation was elaborated through a code written in R 3.0.1

Table 2 presents some equations developed for the process Household in which the equations link the process "Household" to the processes "Septic and Solid waste Collection". Model equations (Eq.2 Eq.3 and Eq.4) in Table 2 describe nitrogen flows (in wastewater, excreta and solid waste) produced by anthropogenic activities and released in sanitation system. For example, the Equation (Eq.3) determines the N flows associated with excreta production.

Parameters of this equation are the number of inhabitants, N content in excreta and the percentage of individual connected to the on-site sanitation system in the city of Yamoussoukro. Parameters of the mass and nitrogen flows are assessed according to available variables (data) collected through conventional sources (e.g. National or international database, literature review).

The material flows were computed with R for 1,000 iterations. This number of iterations was chosen because it ensured the stability of the results (Do-Thu et al., 2011) and the simulations were computed using the Graphic User Interfaces (GUI) of R to reduce the computation time and energy needed to run the Monte Carlo simulations.

There are many sources of uncertainties associated with calculated data. Several factors, such as variation in mass values or nutrient concentrations and possible inaccuracy of statistics, could affect the outcomes (Wright et al., 2014). In developing countries with limited data, uncertainties must be considered because of the issue of inaccuracy data used to assess parameter values (Montangero, 2007). Furthermore, during the implementation of MFA research in these countries, checking all model

parameters from the fieldwork is a real task and not cost effective.

To reduce the uncertainties in this study, the nitrogen flows were reassessed using the data reconciliation module of STAN 2.5 (Vienna University Technology Institute for Water Quality, Resource and Waste Management). Data reconciliation interface was performed to propagate the uncertainties in the MFA system to improve the accuracy of the measured data by reducing the effects of random errors. This is a data pre-processing technique, that explicitly makes use of redundant measured data and adjusts the redundant data according to their estimated standard deviations and to obtain estimates that satisfy system constraints (Jiang et al., 2014). In this study, the first information of material flows obtained through R software was reported in STAN to process the data reconciliation according to flow statistics (mean and standard deviation values).

A sensitivity analysis (SA) was then conducted to assess the effect of the main parameters in the system. The SA is used to assess the influence of individual input parameters on the model output variables, by showing the relative differences of the variables when changing the parameter values. This implementation used a mathematical model, comprising of independent variables, dependent variables, and relationships between these quantities, as described in previous statistics literature (Chapman, 2003). In the current study, R was used to implement the sensitivity analysis. The Sobol method was used to identify the influence of each parameter in the MFA system by assessing its effects on the model outputs (Eq. 5 & Eq. 6). Sobol is well integrated in R. Working within a probabilistic framework, Sobol method can deal with nonlinear responses, and can measure the effect of interactions in non-additive systems. In this process, the main parameters influencing the lake waters and groundwater pollution paths in the study area were rigorously analysed.

$$V_{(Y)} = \sum_{i=1}^{k} Vi + \sum_{i=1}^{k-1} + \sum_{j=i+1}^{k} + V_{ij} + \cdots + V_{12..k}$$

Eq. (5)

where $V_{(Y)}$ is the variance of the output function Y ; Vi is the partial variance, first order, corresponding of principal effect on outputs, and V_{ij} is the partial variance, second order, corresponding of the estimating of interactions between parameters.

$$S_i = \frac{V_{ij}}{V_{(Y)}} \qquad \text{(Eq.6)}$$

where S_i is the Sobol indices representing the sensitivity of variables linked to the variance of Y; V_{ij} represents variances of variables i and j; $V_{(Y)}$ is the model variance. In this study, the first order of Sobol indices was estimated.

Development of scenarios

Based on the calculation of the scenario status quo, the environmental threats mitigating scenarios were developed to address the targeted pollution paths, mainly the soil, groundwater and the lake water. The analysis of the environmental sanitation system of Yamoussoukro showed that the lake environment was the most affected by the poor sanitation and waste management (N'guessan et al., 2011). In the light of this analysis, after validating the basic MFA system and modelling equations, mass and nitrogen flows were calculated based on available data, following the law of conservation rule (Eq.7).

$$SC_{(x)} = f(p_1, p_2, p_3\ldots, p_i) \qquad \text{(Eq.7)}$$

where p_1, p_2,…p_i are parameters of model equations in the given scenario's system.

According to the importance of N flow (critical points) from some identified processes of the sanitation system, highlighted in the status quo system in which the current existing situation of the urban waste management is described, three different scenarios were developed for the study area. These scenarios focused on the reduction of environmental threats and resource recovery. This mitigation process enabled to reduce environmental contamination associated with solid waste,

wastewater and faecal sludge. The scenarios selected combine a group of sanitation facilities enabling sustainable waste management with existing technologies. The waste management facilities were chosen based on the adequacy of sanitation technologies and the local conditions in the study area, including low cost and easy management system as highlighted previous investigations in developing countries (Eawag/Sandec, 2014).

Material flows were simulated for the year 2020 and used for further scenario development. Then, the impacts of the system changes in the lake water contamination were assessed after the integration of sanitation technologies in the MFA system. The developed scenarios are based on the optimisation of nitrogen in the MFA system through the reuse of the part being loosed in the urban environment and which will participate to the degradation of this urban environment.

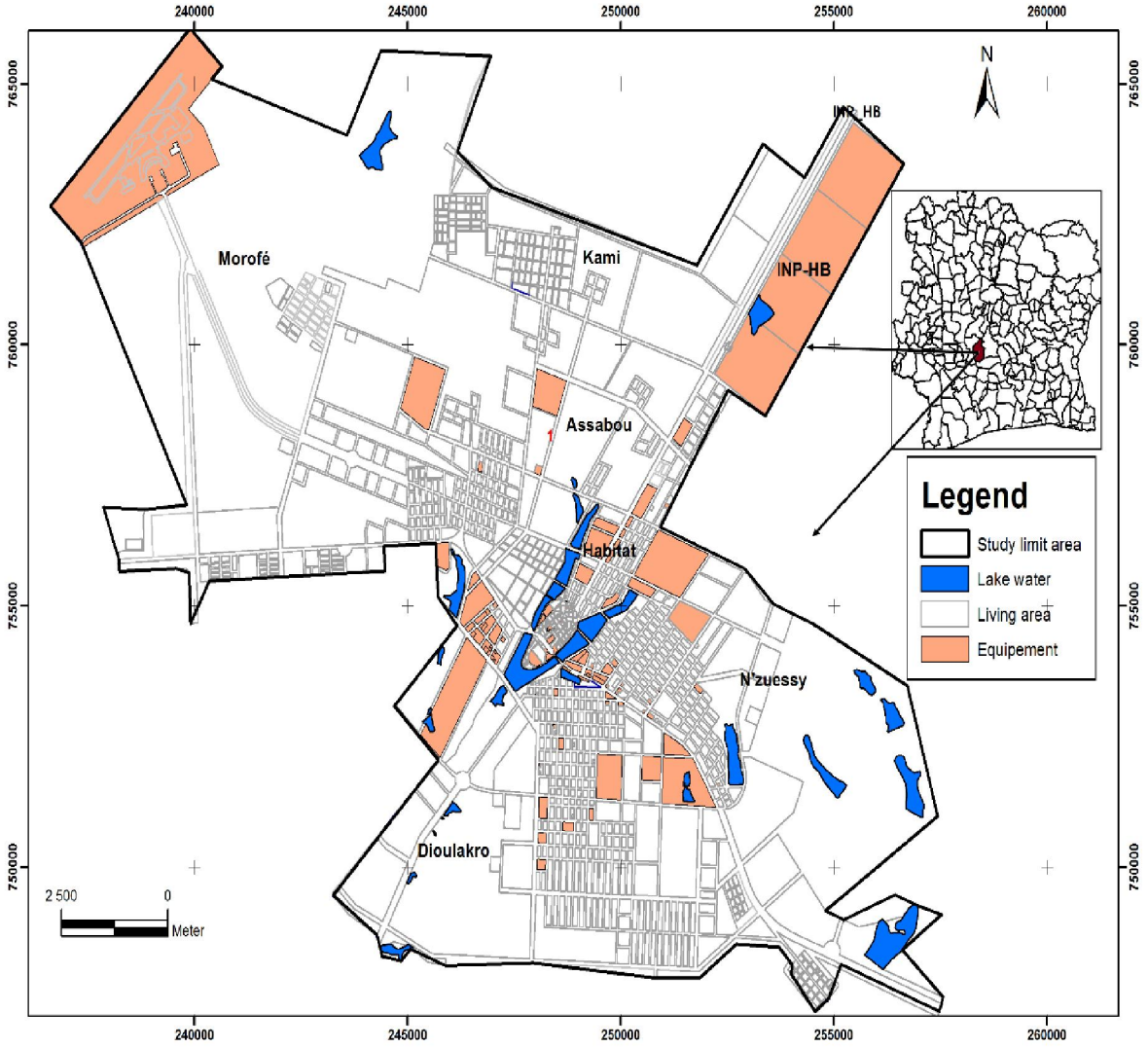

Figure 1: The city of Yamoussoukro showing the study area.

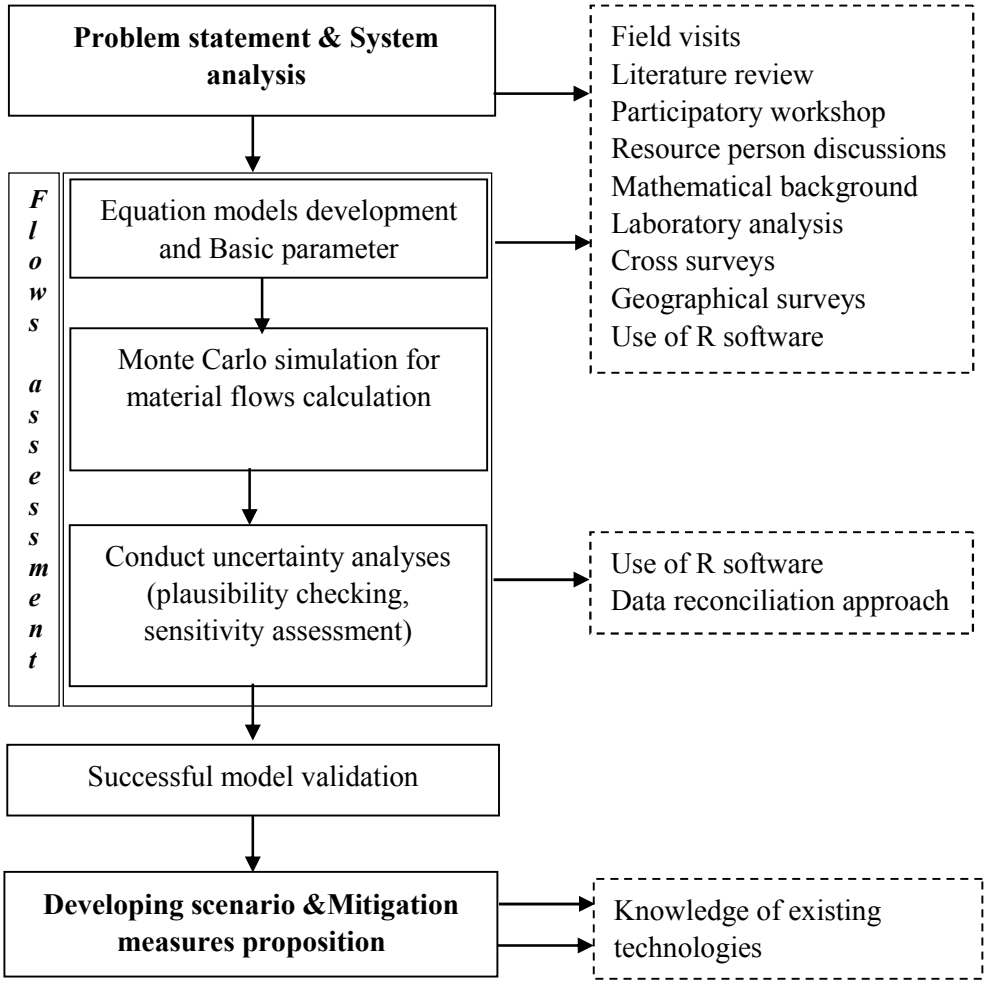

Figure 2: Research framework showing the different steps of MFA implementation in the study area.

Table 2: Examples of models of equations used in the MFA system, case of nitrogen flows.

N°	Symbol	Description	Example of model of equation formula
Eq.1	0.H_water	N flow from household water supply	(H_pop * H _tapw * k_tapw * HN_tapw * 365) / 10^{-9}
Eq.2	H.S_Excreta	N flow in excreta released in septic tanks	(H_pop * HN-exc * k_exst * 365) / 10^{-6}
Eq.3	H.S_W_water	N flow in wastewater released in septic tanks	(H_pop * HN-ww * k_wwst * 365) / 10^{-6}

Table 1: Parameter and probability of distribution.

Parameter	Description	Unit	mean /min.	SD. / max.	Distribution	Prospective data	Study data	Reference
H_pop	Population in study site	Inhabitant	300'000	25'000	normal		X	INS, Côte d'Ivoire (2011)
H_tapw	Drinking water consumption	litre/cap/day	70	0.7	normal		X	Government report (2009)
K_tapw	Ratio of drinking water consumption from the tap	-	0.65	0.01	normal		X	Household surveys (2011)
HN_tapw	Nitrogen content in tap water	mgNO3$^-$/litre	0.002	0.001	normal	X	X	Lab. analyses at CSRS (2012)
HN_exc	Nitrogen content in excreta	kgN/cap/year	4550	110	uniform	X		Vinneras et al. (2006)
K_exst	Ratio of excreta released in septic tanks	-	0.9	0.1	normal	X		N'Guessan (2011)
HN_ww	Nitrogen content in wastewater (NO_3^- and NH_4^+)	mgN/litre	10	80	normal		X	Lab. analyses at CSRS (2012)
K_wwst	Ratio of wastewater released in septic tanks	-	0.58	0.01	normal	X		Seidl (2006)
HN_ksw	Nitrogen content in solid waste	kgN/cap/year	1	0.5	lognormal		X	Lab. analyses at CSRS (2012)
K_swdn	Ratio of solid waste released in open drainage network	-	0.08	0.01	normal	X		Seidl (2006)

RESULTS

Environmental threats linked to waste management

According to the MFA system, four main material flows are, causing serious environmental degradation in the study area due to the amount discharged: (i) untreated waste water discharged into open drainage and from collective sanitation, (ii) infiltrated effluent from septic tanks and dry toilets, (iii) faecal sludge from onsite sanitation, and (iv) openly dumping of solid wastes.

Mass flows from water supply and waste water released in the on-site sanitation system are estimated at about 5,550,188.0 ± 490,098.1 m^3/year and 5,323,233.0 ± 743,197.9 m^3/year, respectively. The mass flow of the removal faecal sludge material from septic tanks is about 10,795.36 ± 951.9 tons/year. The amount of solid wastes discharged into the open dump sites are about 34,522.3 ± 6,162.4 tons/year. Mass flow of excreta released from the septic tanks and that from collective sanitation system were estimated at 164,768.3 ± 28,256.2 tons/year and 6,683.75 ± 1403.5 tons/year, respectively. The wastewater flow released into the collective sanitation system was estimated at 469,483.7 ± 96,790.6 tons/year and the chemical fertilizers flow used for urban agriculture activities was estimated at about 163.9 ± 64.6 tons/year.

Main nitrogen distribution patterns in the MFA system

The main patterns influencing nitrogen distribution in the MFA system were described after the mass flows assessment. Figure 3 presents nitrogen flows distribution in the whole MFA system; the dark thick flows show the most important factor. The faecal sludge from the on-site sanitation, excreta, wastewater, and urban wastes as the key patterns influencing nitrogen flows distribution in the city of Yamoussoukro. The most relevant nitrogen flow (NF) was from the system consumption, which is estimated at 1200 tons of nitrogen per year. NF flows discharged in the on-site sanitation (excreta and wastewater) is higher than that generated by solid waste and chemical by farming activities. Indeed, NF linked to sludge removed from on-site sanitation was about 494.0 ± 309.0 tons of nitrogen per year. Nitrogen flows from the wastewater and excreta released in on-site sanitation were estimated at 140.0 ± 18.0 tons of nitrogen per year and 560.0 ± 43.0 tons of nitrogen per year, respectively. The NF from the household solid wastes was estimated at 236.26 ± 51.9 tons of nitrogen per year. Additionally, nitrogen flows released in the semi-collective sanitation network were about 34.1 ± 2.1 tons of nitrogen per year for wastewater and 53.0 ± 7.1 tons of nitrogen per year for excreta. The nitrogen flow from septic tank effluents infiltrated into the ground was about 147.2 ± 80.3 tons of nitrogen per year, while that from chemical and organic fertilizers from agricultural activities were about 48.3 ± 3.1 of nitrogen per year (Figure 3).

The nitrogen flow from the tap water supply, which is the main water source consumed by the population, was very low (about 0.17 ± 0.01 ton of nitrogen per year), while that from traditional wells was estimated at 54.0 ± 5.0 tons of nitrogen per year.

Sensitive parameters in the MFA model

The study showed that four main sensitive parameters were involved in the dynamic of the surface water and groundwater pollution in the city of Yamoussoukro. Sensitivity analysis provides insight into the most determining parameters. When analysing of effect of environmental contamination, the most relevant sensitive parameter was the emptying frequency of septic tanks, followed by the percentage of households having on-site sanitation contributing to leakage of effluents from septic tanks in the study area. Additionally, the N content in excreta and the population number were considered to be also significant in this process. We estimated the percentages of the contributions in the lake water degradation by nitrogen inputs to be: (i) the emptying frequency 40%, (ii) households connected to septic tanks 25%, (iii) N content in excreta released in septic tanks 14%, and (iv)the population number 13%.

Nitrogen flows based on sustainable options for environmental sanitation management in Yamoussoukro

Three scenarios were developed, based on the quantification of nitrogen flows in the environmental sanitation system of Yamoussoukro. In the first scenario, the management model includes a lagoon technology for the faecal sludge treatment associated with a composting plant. In the second scenario, the system integrates an unplanted drying bed for sludge treatment associated with a co-composting unit. The last scenario incorporates a planted drying bed which allows the reduction of environmental threats from the faecal sludge. These developed scenarios allow the reduction of NF into the environment (lake system, groundwater and soil).

The Table 3 presents the performance of scenarios developed for the city of Yamoussoukro. From a total amount of NF released in the environment which could impact the environment (905 tons of nitrogen per year), the three scenarios provide by the year 2020, a reduction rate of more than 80%: scenario1 (89.3%), scenario 2 (85.1%), and scenario 3 (87.2%). The total amount corresponding to each reduction is 808.6 tons of nitrogen per year, 770.2 tons of nitrogen per year and 789.1 tons of nitrogen per year respectively. The reduction of this NF from wastewater is estimated at 75%, 73% and 77% by scenarios 1, 2 and 3, respectively. The reduction of the environmental threats of NF associated with solid waste is estimated at 87% in scenario 1, scenario 2 (83%) and at 84% for scenario 3. In terms of the faecal sludge management, scenarios 1, 2 and 3 reduced the environmental degradation from NF by 95.1%, 90.1% and 92%, respectively. Considering the year (2012) for model validation, scenarios 1, 2 and 3 allow NF threats management by 56%, 62.5%, and 38%, respectively.

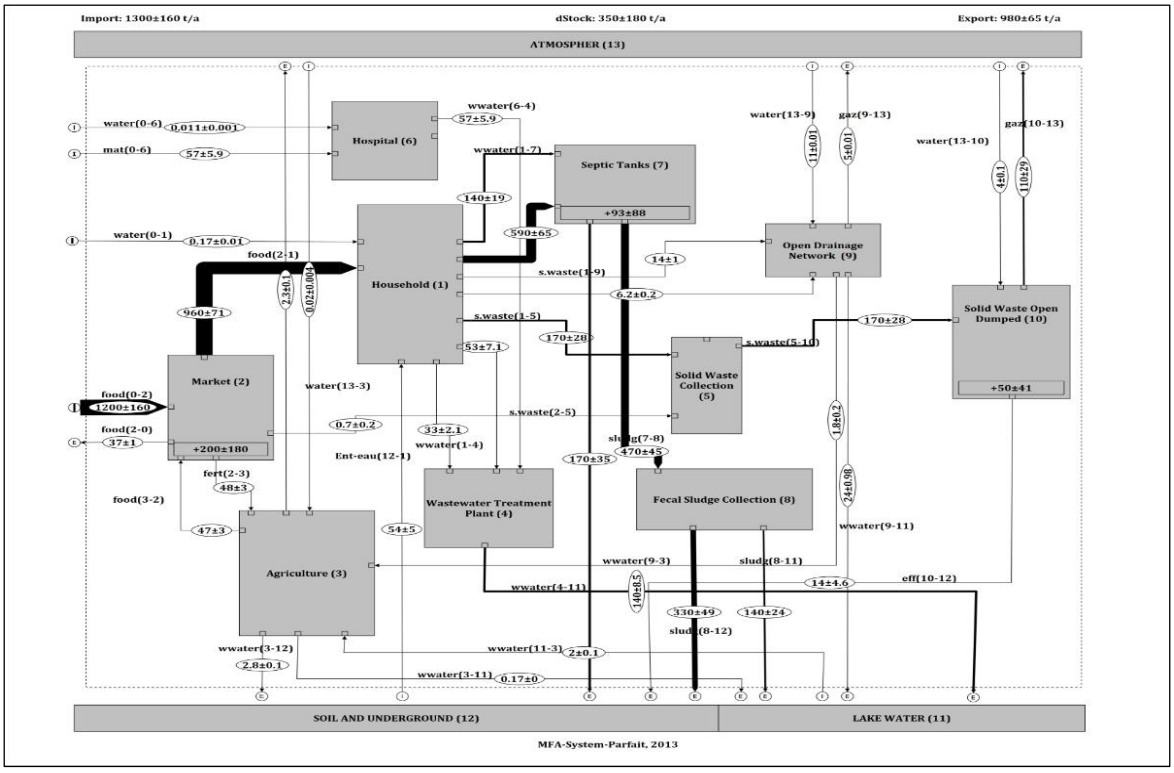

Figure 3: MFA model showing nitrogen flows in the waste management system of Yamoussoukro.

Table 3: Performance of developed sanitation options regardless reducing N pollution and its potential reuse.

Materials	N status quo (tons N/an)	Reduction of N pollution by each developed options					
		scenario 1		scenario 2		scenario 3	
		2012	2020	2012	2020	2012	2020
Wastewater	158	62% (96.6)	75% (118.5)	31% (49.5)	73% (115.3)	65% (65)	77% (121.7)
Solid waste	248	68% (168)	87% (215.8)	66% (166)	83% (205.8)	44% (110)	84% (208.3)
Fecal sludge	499	49% (243)	95% (474.1)	70% (350)	90% (449.1)	34% (170)	92% (459.1)
Total N pollution	905	56% (507.6)	89.3% (808.6)	62.5%(565.5)	85% (770.2)	38%(345)	87.2% (789.1)
Remain N pollution after reduction	-	44% (96.4)	11% (96.4)	37.7% (96.4)	15% (134.8)	62% (96.4)	13% (115.9)

DISCUSSION

Though previous studies have tackled the issues of sanitation management in developing countries using MFA, the originality of this study is the in-depth analysis used to handle the current MFA. Most of the previously implemented MFA studies, followed the same steps, mainly system analysis and modelling, model calibration, uncertainty analysis and scenarios development (Baccini and Brunner, 1991; Montangero, 2007). It is well recognised that for developing countries, the limits of this approach is the uncertainties analysis (Do et al., 2014). So, to minimize those limits and improve the quality of the results obtained, our approach used in this investigation considered specific changes in the steps used until now in the MFA implementation. In terms of the relevance of the research framework itself, the first added value was the use of R programming for waste and nitrogen flows assessments using a probability distribution process. This approach enabled the easier assessment of goods and nitrogen flows and the improvement of MFA results in the study. While it is possible to run simulation studies in other programming environments, R may provide unique advantages to other programs when running simulation studies because it is free, open source, and cross-platform. R also allows researchers to generate and manipulate their data with much more flexibility than many other programs (Bulut et Sünbül, 2017). R contains packages to run a multitude of statistical analyses of interest in a variety of domains.

Also, the sensitivity analysis (SA) of the model's parameters which determines the relevance of the estimations (Chapman, 2003), was optimised with Sobol method under R based on key flows which caused environmental sanitation degradation. This ensured a quality control of the model estimations. Non-linear, non-monotonic

problems are often encountered in everyday model building like MFA. These problems call for a non-linear SA which is independent of assumptions about the model structure as in our study. Sobol' sensitivity measures can cope with nonlinear and non-monotonic models. It can be considered as truly quantitative for global SA for numerical experiments. Thus, the parameters can be ranked in order of their relative importance in the model. All the alternative global methods, variance-based or not, can offer, at best, a qualitative picture of the model sensitivity. The variance-based methods such as correlation-ratio or importance measures are model independent like Sobol, and can evaluate main effect contributions. Sobol is completely automated and is able to compute the total effect indices which allow us to rank quantitatively the parameters in order of their influence on the output. Chan et al. (1997) have demonstrated that Sobol computing can allow investigating the predominance of lower or higher order terms, which is the only way to perform a rigorous quantitative sensitivity analysis . Thus, the use of Sobol in this investigation reinforces the in-depth analysis.

The sensitive parameters which describe how the material flow could be increased or decreased in a given system, should be investigated rigorously (Chapman, 2003). Using the Sobol method implemented with the R software in this study makes it relevantly successful in highlighting the main parameters that increased groundwater, soil and lake water degradation. In this study, key sensitive parameters were the emptying frequency of sludge effluent, the concentration of nitrogen in wastewater and excreta, the percentage of people connected to on-site sanitation and the high population level in the study area. Previous studies conducted in Hanoi (Montangero et al., 2007) have shown that parameters, such as population number and excreta management, were the most relevant for developing interventive measures, thus confirm findings regarding the sensitive parameters in the current study.

The second one was the use of the Monte Carlo simulation to predict material flow values using R in data scarcity conditions of the study area. Given insufficient data and lots of uncertainties on real figures which are not specific to our context, but also met in many developing countries, a Monte Carlo simulation model procedure used allow to capture subjective information into the quantitative model and to allow an adequate sensitivity analysis for important but highly uncertain parameters. Previous investigation has proven the strength of using Monto Carlo simulation in the context of insufficient information (Lauwers et al., 2010). Since within our study some data sources can contain potential errors and/or missing data, therefore, the use of Monte Carlo under R for data simulation has increased the relevance of results gathered. Through Monte Carlo simulation material flows were estimated with intensive simulations, allowing to significantly save computing time required for the whole simulation.

Using this specific performed MFA approach, satisfactory relevant information regarding the issue of urban waste management has then been produced for the city of Yamoussoukro.

In terms of quantitative results, about 905 tons of nitrogen per year from anthropogenic processes is discharged in the sanitation system in Yamoussoukro causing the degradation of the urban environment. "Households", "septic tanks" and "solid waste" processes are the critical points showing the most relevant flows in the MFA system, and on which one should pay attention and act towards sustainable management. Those processes influence nitrogen outputs in the environment (critical points) of Yamoussoukro, suggesting that anthropogenic processes are key determinants in the dynamic of nitrogen distribution in the environmental sanitation system in the city. Previous studies conducted in Arba Minch, Ethiopia (Meinzinger et al., 2009) have identified more less the same processes as key determinants regardless of nitrogen

distribution in urban systems, confirming their importance in influencing the waste management system in low income cities.

NF from human activities constitute then a major source of nitrogen flows which contribute to the degradation of the environment in Yamoussoukro. More than half of nitrogen flows (61.6%) is released in the city environment through human excreta (15.6%) into surface/lake water and (46%) into the ground water indicating the importance of human contribution in the urban systems degradation. Recent investigations in both developed and developing cities dealing with how diet and waste management interact to drive nitrogen flows into nutrient pollution (Cease et al., 2015) showed that in developing countries, 60% (61.6% for the city of Yamoussoukro) of nitrogen from excreta entered the environment as pollution because of a lack of sanitation infrastructure . This confirms the results found in the context of this present study.

For the mitigation strategy, the results of simulations highlighted that nitrogen generation will increase considerably by the year 2020, due to the increase of the population growth in the city of Yamoussoukro which will increase merely the waste production. Developed scenarios showed that there is a potential of NF which contributes to the environmental sanitation degradation of Yamoussoukro to be converted into fertilizer. In scenario 1, the organic fertilizer demand for agricultural practices is covered and the environmental conditions are also improved up to 90%. In scenarios 2 and 3, environmental conditions are improved to 65% and 70%, respectively. The developed options are resource recovery based- model which promote the ecological agriculture in Côte d'Ivoire through the reuse of urban wastes. However, the implementation of any option requires the involvement of all stakeholders and populations in order to achieve an optimum efficiency of the system. As advantages, the options developed integrate agricultural and environmental monitoring dimensions. However, there are, also, limitations concerning the operating conditions and technical constraints, the climate conditions for the optimum development of filters, the choice of filters, and space (Bradley and Bartram, 2013) which should be considered in any option implementation.

Conclusion

This study assessed the environmental sanitation system in Yamoussoukro city considering the nitrogen flows. It describes the potential of using MFA approach to address wastes and nutrients management system despite the limited data available in the context of Côte d'Ivoire.

Integrating R programming interface with the combination of Monte Carlo simulations model and Sobol sensitivity analysis, provide unique advantages for in-depth nitrogen flows analysis in the urban system which ensure more confidence regarding the results gathered. This specific MFA approach is robust, easy to conduct based on a simple research framework and integrates uncertainties in data analysis, thus improving the quality of data.

The study highlights risks for environmental pollution and the potential for linking sanitation with resource recovery and agricultural production. The study revealed that the combination of lagoons and composting plants is the most appropriate technological option for resource recovery in our context. Two key issues have been highlighted: firstly, the content of nitrogen in urban wastes could lead to the degradation of the urban environment such as water bodies and soil; and secondly, the assessment of the loss of nitrogen flow into the environment could potentially be transformed into agricultural opportunity by resource recovery.

The local urban authorities should encourage nitrogen recovery to reduce environmental pollution and improve urban agricultural productivity through the use of any of the three developed options.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTIONS

KD and PKK initiated the study, data collection plan and data analyses. KD provided the text design and drafting of the manuscript; JB, HN-V, CZ and ND-T assisted in the design of the research and data acquisition plan and data analyses.

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