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Eco-Effectiveness, Eco-efficiency, and the Metabolism of a City: a Multi-sectoral Analysis

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***Abstract*—The vision of Cities as forces for good within the environment is explored herein by proposing a multi-sectoral analysis that accounts for nutrients, water, energy. The main purpose is to identify those elements in the urban system that can offer more opportunities of improvement with regard to eco-efficiency and eco-effectiveness indicators, and how different sectors, i.e. water, food, forestry, energy, and waste management, interact between each other. For this, (i) a computational model is designed using concepts of Substance Flow Analysis (SFA) together with mass and energy balances, and (ii) a set of indicators are defined to assess the improvement or worsening of the system. (iii) Both model and indicators are simulated under the Regionalized Sensitivity Analysis (RSA) framework to account of uncertainty and test the relevance of prospective technological innovations, i.e. structural changes. The paper presents a case study based on the Upper Chattahoochee Watershed in the south-eastern United States, in which the nitrogen (N) cycle is investigated under two scenarios: 0% and 100% urine source separation implementation. Results reveal that animal feed and fossil fuels are the major flows of N in the system. Urine separation showed to be critical for some aspects of the system as described by the behavior of the set of indicators.**

***Keywords*—urban sustainability; System Analysis; eco-effectiveness; nutrient cycling; water; energy.**

I. INTRODUCTION

Cities are generally perceived as sinks of materials and sources of wastes and harmful emissions. Large amount of engineering and scientific work has been dedicated to the investigation of ways for reducing the ecological impact of cities, mainly by increasing the efficiency of the processes within. However, population increase and changes in consumption patterns can sometimes overcome the improvements achieved by implementing eco-efficiency [1]. Maximizing efficiency measures, although a successful approach in many ways, cannot be considered as the only tool to achieve sustainability from the environmental point of view.

Braungart and McDonough coined the concept of eco-effectiveness [2], suggesting that human processes should behave the same way *trees* do. They emphasize the need for (a) relying in solar energy, (b) keeping the biological cycle (consumable materials: food, shoes, etc.) and technological cycle (products of service: cars, electronics, etc) separated, and that (c) system outputs that have equal or better quality than inputs. This last concept is interpreted as *waste equals food*, which is not the same as *zero* waste or *zero* emissions. Urban Metabolism Analysis (UMA), e.g. [3], also views cities as living organisms and has been used for many years mainly as an accounting tool of material flows in cities. UMA have revealed that urban centers generally exhibit a liner behavior where materials enter the system as products and leave as wastes.

Under the light of the metabolism analogy and eco-effectiveness concepts one could start asking: Is it even possible to turn urban systems, as they grow, into forces for good in the environment? Furthermore, what structural changes within the city are necessary to achieve this? Cities may become adaptable structures to cope with changes in economies and global climate [4]. For this it is important to understand the distortion that cities introduce to environmental cycles [5] [6], and how this distortions can be reversed to *pre-city* conditions. Although these questions are well beyond the scope of the present work, it is our objective to explore, in a quantitatively manner, what elements within the urban system are important to move forward towards the vision of cities as forces for good in the environment.

The work described in this paper is centered on three of the main challenges that engineering faces in this starting century [7]: water, nutrients, and energy. Substance Flow Analysis (SFA) [8] is proposed herein as the tool for investigating the degree of linearity, or circularity, of water, nitrogen (N), phosphorus (P), and carbon (C) through five sectors in the urban economy: (i) water (ii) forestry, (iii) food, (iv) energy, and (v) waste management. Similar studies have investigated the flow of nutrients through the water sector [9], and the food industry [10], but the most comprehensive study found after literature review examined the flow of N and P through four sectors in the Finnish market [11]. One of the main challenges of SFA, similarly to any system analysis tool, is defining the system boundaries [12]. In general, the consensus is that larger geographical areas have better opportunities to close nutrient cycles. Analogously, the analysis of a larger number of sectors can result in a larger number of solutions. The practitioner

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needs to find a balance between the degree of detail desired and available resources and information.

Balkema et al. [13] recognized the importance of articulating system analysis tools in a computational manner as a mean for evaluating different solutions and scenarios based on the performance of a set of indicators. The present paper includes the definition of indicators that reflect concepts of eco-efficiency and eco- effectiveness. The former is well known in Industrial Ecology and other engineering disciplines but the latter has never been instrumented in a computational framework. The following sections describe in detail a computational methodology in the form of a model that aims to assess a system from the point of view of water, nutrient, and energy cycles. This approach is tested within the context a case study examining the flows of Nitrogen through the Upper Chattahoochee Watershed.

The specific objectives of this work are to develop a framework that can: (i) Identify major flows of an urban area, (ii) Identify and assess the effect of implementing a technological innovation, and (iii) Verify the statistical validity of the effects identified.

II. MATERIAL AND METHODS

A. *Multi-sectoral Analysis (MSA)*

A detailed flow diagram was developed for each sector to represent flows and unit processes of interest. Each unit process represents an activity within the system that involves the mixing, separation, or transformation of flows. Figure 1 shows a summarized version of the five sectors involved: water, forestry, food, energy, and waste management. Sectors are interconnected between each other by material and energy flows. Each sector has inputs and outputs from other sectors and the environment. The latter is includes the hydrosphere, the lithosphere, and the atmosphere.

Most flows are calculated as a function of consumption patterns. For instance, the nutrient input in the form of food can be estimated by knowing a typical food intake per person and multiplying this by the population. Moreover, the nitrogen content in food can be estimated after dividing its protein content by 6.25 in weight [10].

B. *Substance Flow Analysis*

MSA is structured in a way that SFA can be easily performed using the flow diagrams designed for each sector. The substances subject to investigation are water (H2O), elemental Nitrogen (N), elemental Carbon (C), and elemental Phosphorus (P) for a total of 4 substances. Energy, although not a substance per se, can be easily related to nutrient cycles and is very much part of the urban metabolism. For instance, different forms of biomass, e.g. poultry litter [14], sewage sludge [15], municipal solid waste (MSW), are seen now as more sustainable energy sources compared to fossil fuels. For this reason, the system analysis proposed includes energy flows in the form of caloric value of materials and fuels. The units for substance flows are metric tonnes per year (tonne.y^{-1}) while energy is expressed in kilowatt-hour per year (kWh.y^{-1}).

In some instances, the nutrient and energy content of a flow is calculated by specifying a typical composition and a caloric value, but for most flows, composition is calculated by material and energy balances associated with unit process equations, e.g. biological wastewater treatment. For the purposes of this paper, substances and energy are called *species*.

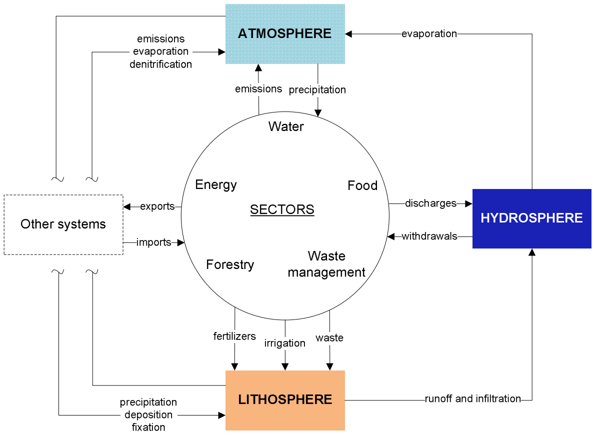

Figure 1. Simplified scheme of sectors and their interaction with the environment.

C. *Indicators*

Imagine the whole system, i.e. all sectors together, as a black box with five compounded flows, one input of resources (R_k) and four outputs: healthy-unhealthy air emissions (E_k), healthy-unhealthy water emissions (A_k), wastes (W_k), and products (P_k), where k = 1, 2, 3, 4, and 5, is the *species* index. Flows (F_k) are categorized as an input or one of the outputs and then aggregated. For example, the quantity of product of any *species* k is calculated as:

$$P_k = \left\{ \sum_{n=1}^{N1} F_{k,n} \right\}_1 + \ldots + \left\{ \sum_{n=1}^{Ni} F_{k,n} \right\}_i + \ldots + \left\{ \sum_{n=1}^{N5} F_{k,n} \right\}_5 \quad (1)$$

Where Ni is the total number of flows categorized as products in each sector i, and k is the *species* index, e.g. N, P, and C. A similar approach is applied for resources, emissions, and waste flows. Mass and energy balances are carried out on a yearly basis, and given that not all *species* have a yearly cycle within the system an accumulation term can be estimated as:

$$\frac{dS_k}{dt} = R_k - P_k - W_k - E_k - A_k \quad (2)$$

Where dS_k / dt is the accumulation term. Now that the interpretation of input resources, products, emissions, and wastes has been introduced let's consider the following eco-effective concepts:

(a) Flows categorized as *products* are assumed to be *resources* for processes of other systems, i.e outside the system's boundaries, and are typically not designated for disposal.

(b) Urban areas must be in harmony with the necessities of the environment, e.g. release to the river the require amount of nutrients. Therefore, a desirable level of emissions to the atmosphere (E_k^0) and aquatic systems (A_k^0) are defined for each *species*. Emissions are regarded as the net flux of a substance between the system and the surrounding environment. One can define a desirable or healthy emission level based on regulations, public preference, or target values.

(c) Based on the eco-effective principle that *waste equals food*, the ideal system is one in which all non-emission *outputs* can be categorized as *products*.

Therefore, from the MSA point of view, a system is eco-effective if three conditions are met: (i) $E_k \approx E_k^0$, (ii) $A_k \approx A_k^0$, and (iii) W_k is converted into P_k .

Note that until now no limitations have been placed on the intake of resources as they are suppose to be returned as a useful product or a healthy emission. However, the efficiency concept, i.e. produce more while consuming less raw materials and produce more while generating less waste, can be introduced as a principle of equality and fair distribution of resources [2].

With the above one can develop a set of environmental indicators (see Table I):

- The PRoduct Index (PRI) is a measure of the ratio of resources consumed that is returned as a useful product.
- WAste Index (WAI) is a measure of the ratio of resources consumed that is returned as a waste for disposal.
- Waste Eco-efficiency Index (WEI) is a measure of the value gained (products) compared to the generation of wastes.
- Emission Eco-efficiency Index (EEI) is a measure of the value gained (products) compared to the emission to the environment (air and water emissions).
- Health of Air Emissions (HAE) is a measure of the distance between actual emissions and the desired emission level to the atmosphere.
- Health of Water Emissions (HWE) is a measure of the distance between actual emissions and the desired emission level to aquatic systems.
- Eco-Effectiveness Index (E2I) encloses together the concepts of waste equals food and healthy emissions. The parameter p_k^i is a weighting parameter with $p_k^1 + p_k^2 + p_k^3 = 1$ while α, β, and γ are parameters to ensure that E2I varies from 0 to 1, in other words, they assume the value of -1 if the numerator of the respective ratio is larger than the denominator, otherwise their value is equal to 1. Φ_k is equivalent to what the flow of products should be if all waste flows can be categorized as products and emissions are equal to the defined healthy level as represented in equation (3).

These seven indicators, while providing information about the environmental performance of the system, are particularly useful when the system analysis is embedded in an automated simulation framework. A better system arrangement or system performance can be defined as the one that best approaches the indicator objective (second column in Table I). In this way, the MSA can serve two purposes: (i) material and energy accounting, and (ii) scenario evaluation.

$$\Phi_k = R_k - \frac{dS_k}{dt} - E_k^0 - A_k^0 \qquad (3)$$

TABLE I. MATHEMATICAL EXPRESSION OF INDICATORS

Indicator ID	Objective	Mathematical Expression
PRI	maximize	$\frac{P_k}{R_k}$
WAI	minimize	$\frac{W_k}{R_k}$
WEI	maximize	$\frac{P_k}{W_k}$
EEI	maximize	$\frac{P_k}{(E_k + A_k)}$
HAE	zero	$\left(\frac{E_k}{E_k^o} - 1\right)$
HWE	zero	$\left(\frac{A_k}{A_k^o} - 1\right)$
E2I	one	$p_k^1 \cdot \left(\frac{P_k}{\Phi_k}\right)^\alpha + p_k^2 \cdot \left(\frac{E_k}{E_k^o}\right)^\beta + p_k^3 \cdot \left(\frac{A_k}{A_k^o}\right)^\gamma$

D. *Regionalized Sensitivy Analysis (RSA)*

Data and measurements have always a degree of uncertainty, and this is particularly relevant in environmental sciences. Regionalized Sensitivity Analysis (RSA) has been successfully used in environmental scenarios [16] for modeling poorly understood natural systems. RSA can be used for two purposes: (i) identifying critical or key elements of the model and (ii) assess the reachability of the goals imposed to the model. RSA is preceded by the creation of parameter vectors by using Latin Hypercube Sampling (LHS) within a predefined parameter range as a way to account for the parameter variability and uncertainty. The results of this initial step are the possible values of the flows within the system. Using the parameter vectors sampled before, RSA proceeds to statistically test the relevance of the parameter variability over the model output. The RSA algorithm involves two tasks: (i) quantitative definition of system behavior, and (ii) a binary classification of model outputs based on the specified behavior definition. The researcher defines a set of constraints that the model output has to comply with in order to be classified as a *behavior*. A non compliance is regarded as a *non-behavior*. For each parameter, two sets of sampled values are obtained, those that the output is categorized as *behavior* (B) and those that resulted in *non-behavior* (NB) outputs.

The Kolmogorov–Smirnov test (K–S test from now on) is now applied to each parameter to statistically test the null hypothesis *Ho*: the two set of parameter values, those that resulted in B and those in NB, come from the same distribution or population. A significant difference between the B and NB distributions rejects the null hypothesis *Ho*, thus suggesting that the parameter is key or critical to producing the defined *behavior*. Please visit reference [16] for more details regarding the advantages and the RSA procedure itself.

III. CASE STUDY

The capabilities of MSA are illustrated here in the context of the Upper Chattahoochee Watershed (UCW) located in north-central Georgia (see Fig. 2), in the south-eastern USA. Nearly a quarter of the Metropolitan Atlanta area is within this watershed. By 2000, the population of the Upper Chattahoochee Watershed was about 1.3 million. The major surface water storage in Georgia, Lake Lanier, is located just to the north of Atlanta and lying within the limits of the UCW. The watershed area, a total of 4,093 km2, is comprised by the Appalachian Mountains to the north, and low to high intensity urban areas to the south. It has a variety of land uses including significant poultry production and silviculture. In 2000 land cover was categorized as follow: open water 4%, forest 53%, urban and sub-urban 29%, pasture and crops 10%, other 4%.

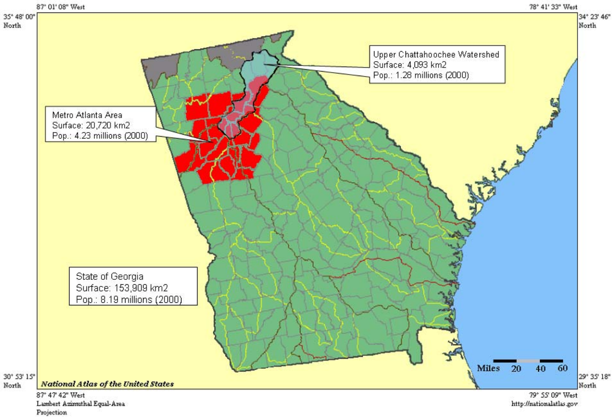

Figure 2. Location of the upper Chattahoochee Watershed in Georgia relative to Metropolitan Atlanta. Original image from http://nationalatlas.gov

The magnitude of material flows can change significantly from one region to another due to differences in consumption patterns, process efficiencies, land use, and other factors. Therefore, the data used in this study is specific to the Upper Chattahoochee Watershed when available. Most of the data is retrieved from official sources such as the Environmental Protection Agency (EPA), Georgia Department of Natural Resources (GA DNR), US Department of Agriculture (USDA), US Geological Service (USGS), the US Census Bureau, the Food and Agriculture Organization of the United Nations (FAO), and the Intergovernmental Panel on Climate Change (IPCC).

A. *Simulation Setup*

Although the broader purpose of this work and the framework described is to examine flows of N, P, C, H2O, and energy, the focus of this specific case study are the different paths of N through the UCW. Nitrogen is the most abundant element in the atmosphere and one of the most studied substances given its involvement in almost every aspect of nature and human activities. Food production relies heavily on synthetic fertilizers as a source of nitrogen, a process that requires the use of methane, largely from fossil origins, and the collection of atmospheric nitrogen. Fossil fuels contain also nitrogen that after combustion is released in the form of nitrogen oxides (NOx) and other N chemical forms. Land application of manure and fertilizer is responsible of the emission of ammonia (NH3), a gas known for its adverse effects on human and animal health. Nitrous Oxide (N2O) is a powerful greenhouse gas, important in climate change, and ozone-depleting substance. It is produced by both natural, mainly microbial action in forests, and human-related sources such as agricultural soils, manure handling, and combustion of fossil fuel.

Due to data availability, the simulation of the UCW is carried out for year 2000. The last estimated water use data reported by USGS corresponds to year 2000, while the last two USDA agricultural censuses are for 1997 and 2002. Energy data are typically available on an annual and, in some cases, on monthly basis.

B. *Evaluation of Anthropogenic Nutrient Solution (ANS)*

One of the objectives is to utilize the proposed framework for investigating the effects that a technological innovation might have in one or more sectors. Source separation technologies, i.e. urine separation or Anthropogenic Nutrient Solution (ANS), have been proposed as a solution for nutrient recovery in the water sector with possible implications on the reduction of nitrogen emissions within municipal wastewater treatment plants (MWWTP) and advantages for the fertilizer production industry [9]. Also in the water sector context, a more deep analysis has been performed [17] with regard to the ecological benefits that such technology, together with nutrient management, might have on the water quality of the Upper Chattahoochee Watershed and the challenges faced during the gradual implementation of the ANS separation.

The present paper tests how the ANS separation technology affects nitrogen flows by comparing two case scenarios: 0% and 100% ANS implementation. The latter assumes that all urine generated within the household is collected and never mixed with gray water, i.e. laundry and kitchen wastewater, or black water, i.e. feces. Urine can later be converted into a synthetic fertilizer, e.g. MgNH4PO4, by the Struvite process [17]. The degree of technology implementation is associated with a parameter that varies from 0 to 1 representing the fraction of the population that has adopted the ANS separation. The RSA procedure is used to assess the significance of ANS implementation parameter for the behavior of each indicator.

The *behavior* (B) threshold is defined for each indicator using values of products (P_k), wastes (W_k), and input resources (R_k) obtained from the 0% ANS simulation, in conjunction with the level of healthy emissions (E_k^0 and A_k^0) derived from typical values for N fixation, N denitrification, N concentration in runoff, and N leaching occurring in forests in the south-eastern region of US.

IV. RESULTS AND DISCUSSION

A. *Analysis of flows*

Table II presents the fifteen largest flows in the system as reported by the base case simulation, i.e 0% ANS implementation. For a region that relies heavily on the poultry industry it is not surprising that the major flow is livestock feed, of which only 16% is for cattle and swine. Feed is almost 100% imported as the production of grain for feed and hay is minimal, 36 tonne.y^{-1}. Although only 11% of the electricity consumed in the UCW is produced within, imported coal is the second largest flow as the major source of energy for electricity generation and responsible of 98.5% of the emissions associated with power generation, ranked 3.

TABLE II. MAJOR N FLOWS FOR 0% IMPLEMENTATION OF ANS SEPARATION (ALL VALUES IN TONNE OF N PER YEAR)

#	Flow	0% Separation	
		Average$^{(a)}$	SD$^{(b)}$
1	Total feed consumption by livestock	42597	627
2	Imports of Coal	20251	2879
3	Total Emissions from Power Generation	(16483)	2579
4	Total nutrient applied to soil for fertilization	19178	1151
5	Imports of Natural Gas	13207	227
6	Total Manure Generated	9675	1700
7	Total food consumed	7620	254
8	Inorganic Fertilizer applied for fertilization	6852	721
9	Emissions from Local Fuel Consumption	(5937)	219
10	Total soil infiltration	(4660)	354
11	Nitrogen biological Denitrification	(5686)	281
12	Total Urine generated	4567	361
13	Total nutrient deposition	4252	673
14	Air emissions from municipal Waste Water Treatment Plants	(4036)	1556
15	Surface runoff that reaches the river	(3774)	987

a. Values in parenthesis refer to outgoing nitrogen flows

b. Standard deviation

Of the total nutrient applied to land for fertilization, ranked 4 with 19178 tonne.y^{-1}, 53% is poultry litter applied to pasture land, while 36% is synthetic fertilizers for crops and lawn care. About 35% of the Nitrogen in poultry litter is available at the time of application due to volatilization losses during handling and storage.

The total consumption of food represents about 7620 tonne.y^{-1} of N, ranked 7. Two thirds of that is discharged as urine while the rest is used as metabolic energy or leaves the household in the form of black water and food refuse. Most of the Nitrogen in urine is released to the atmosphere during biological wastewater treatment, ranked 14. Implementing ANS separation could potentially (a) reduce the amount of synthetic fertilizer imported by 70% as more than 4000 tonne.y^{-1} can be from recovered from urine, and (b) reduce N emissions from municipal wastewater treatment plants to half of the amount reported for the base case.

Atmospheric processes such as dry and wet deposition must not be ignored as they represent 4252 tonne.y^{-1} which is about the same amount of N recovered from Urine. Denitrification reaches 5686 tonne.y^{-1} while N biological fixation is 2590 tonne.y^{-1}. The watershed is a net emitter of N gases (32.7 x 10^{3} tonne.y^{-1} in total), mainly due to fossil fuel combustion which accounts for about 70% and agricultural activities (26%). Hydrological processes are also important as they export a total of 8434 tonne.y^{-1} via infiltration and surface runoff.

B. *Indicators*

Table III shows the average value of indicators for both cases and their relative change. Based on the mathematical objective of each indicator, described in Table I, all indicators exhibit an improvement excepting for HWE, associated with water emissions.

TABLE III. COMPARATIVE TABLE OF INDICATORS FOR BASE CASE SCENARIO AND 100% URINE RECOVERY

Indicator ID	0% Separation		100% Separation		Relative change % $^{(b)}$
	Average	SD$^{(a)}$	Average	SD$^{(a)}$	
PRI	0.023	0.009	0.025	0.010	8.4
WAI	0.049	0.012	0.041	0.014	-15.6
WEI	0.508	0.268	0.698	0.468	37.4
EEI	0.060	0.026	0.065	0.028	9.0
HAE	3.481	17.770	2.881	14.864	-17.2
HWE	113.608	14.869	113.681	14.879	0.1
E2I	0.076	0.032	0.088	0.037	15.1

a. Standard deviation

b. Relative change of averages

However, the analysis derived from table III is not complete, and could be misleading, if RSA is not performed. RSA will allow distinguishing the uncertainty of the model parameters from the actual effect of the ANS parameter. The results of the RSA procedure, shown in Figure 3, indicate that the ANS separation is critical for indicators WAI and EEI at a confidence level of 95%. Recovering N from urine reduces N losses through sewage sludge landfilling, resulting in a lower WAI. Simultaneously, air emissions from MWWTP are reduced, resulting in a higher EEI. At a 90% confidence level, ANS separation is relevant for indicators WEI and HAE. However, the relevance of indicators PRI, HWE, and E2I is low.

The fact that this study is carried out at a watershed scale involving other sectors besides the water sector seems to be responsible for limiting the importance of ANS separation to two out of seven indicators. It is clear from the analysis of flows, Table II, that urine separation has important implications at the household and municipal scale as nearly 60% of the N in food can be recovered. However, involving the energy sector and intensive poultry production activities, i.e. the two largest flows through the system in terms of N mass, diminishes the influence of the ANS separation over the system as a whole.

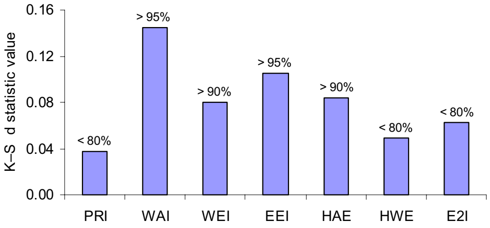

Figure 3. Relevance of the ANS separation for the behavior of each indicator based on the Kolmogorov–Smirnov test performed as part of RSA.

V. CONCLUSIONS

The paper describes a framework that can be used to identify the most important flows of a system and what structural manipulations are critical for its improvement. A set of indicators is proposed to assess a system from the point of view of eco-efficiency and eco-effectiveness with possible applications for sustainability reporting, research prioritization, and identification of critical technologies for sustainability. The incorporation of RSA as part of the framework allows the practitioner account for the uncertainty associated with the large amount of data required for MSA.

The case study, similar to other studies [11], reveals that flows associated with agricultural activities and energy dominate the paths of Nitrogen, while food consumption, although significant, is less relevant. By capturing about 60% of the household input of N, urine separation or ANS turns to be a critical technology for the improvement of two indicators, WAI and EEI, associated with the amount of N lost through wastes and emissions respectively. The magnitude of N that can be recovered from urine appears to be not critical for the behavior of the eco-effectiveness indicator E2I at the Upper Chattahoochee Watershed scale. Other solutions or combination of technologies applied to higher-ranked flows such as animal manure or emissions from power generation plants might have a greater impact.

It is acknowledged that the concepts and computational tools described in this paper are centered only on the technical aspect of sustainability; however, the materialization of any structural change or technical innovation is subject to the acceptance of society. In the particular case of source separation, the Novaquatis final report [18] makes a good effort to explore the social legitimacy component, and more recently, Demir et al. [19] present a forward-looking approach for addressing public perception and acceptance in the decision making process for water quality issues. The work presented herein is part of a broader ongoing research project [20] that also includes C, P, water, and energy, in an effort to achieve a more comprehensive assessment of the system.

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