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RESEARCH ARTICLE

Water — and nutrient and energy — systems in urbanizing watersheds

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Abstract Driven by considerations of sustainability, it has become increasingly difficult over the past 15–20 years — at least intellectually — to separate out the water infrastructure and water metabolism of cities from their intimately inter-related nutrient and energy metabolisms. Much of the focus of this difficulty settles on the wastewater component of the city's water infrastructure and its associated fluxes of nutrients (N, P, C, and so on). Indeed, notwithstanding the massive volumes of these materials flowing into and out of the city, the notion of an urban nutrient infrastructure is conspicuous by its absence. Likewise, we do not tend to discuss, or conduct research into, "soilshed" agencies, or soilshed management, or Integrated Nutrient Resources Management (as opposed to its most familiar companion, Integrated Water Resources Management, or IWRM). The paper summarizes some of the benefits (and challenges) deriving from adopting this broader, multi-sectoral "systems" perspective on addressing water-nutrient-energy systems in city-watershed settings. Such a perspective resonates with the growing interest in broader policy circles in what is called the "water-food-energy security nexus". The benefits and challenges of our Multi-sectoral Systems Analysis (MSA) are illustrated through computational results from two primary case studies: Atlanta, Georgia, USA; and London, UK. Since our work is part of the International Network on Cities as Forces for Good in the Environment (CFG; see www.cfgnet.org), in which other case studies are currently being initiated — for example, on Kathmandu, Nepal — we close by reflecting upon these issues of water-nutrient-energy systems in three urban settings with quite different styles and speeds of development.

Keywords cities, climate change, energy sector, nutrient sector, systems analysis, resource recovery, water-food-energy security

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1 Introduction

With increasing urbanization, it is self-evident that the choices urban dwellers make about lifestyle and diet will increasingly drive what is produced in industry and agriculture. In turn, these choices will impinge upon, for example, the energy and carbon footprints of fertilizer production and the field-market-mouth chain of transfer of foodstuffs. They will influence the consequences arising from the inefficiencies of nutrient (nitrogen and phosphorus) use in food production, most notably in polluted nonpoint-source runoff from agricultural lands.

Of particular significance, however, the environmental ramifications of dietary choices are not confined to the supply side of cities. A very great deal of the effort and energy invested in subsequent, conventional, municipal wastewater treatment is devoted to eliminating the nutrient residuals conveyed out of the city — by water as the medium of transport — in order not to enhance disruptive photosynthetic production in water bodies, i.e., eutrophication. There are strong parallels, in fact, with the way in which nutrients from Confined Animal Feeding Operations (CAFOs) in the food sector have conventionally been viewed as pollutants to be rid of, yet are now increasingly being viewed as resources to be recovered (as discussed herein [1]). And those parallels can be made more dramatic (and deliberately so), when cities are caricatured as Confined Human Feeding Operations (or CHFOs). With regard to pollution control and/or resource recovery, the two (CAFOs versus CHFOs) differ primarily in respect of the large volume of water associated with the operation of the latter (CHFOs), i.e., the water used for water closet (WC) flushing and subsequent waste transport (wet sanitation and "off-site" treatment), and the accompanying energy expended in pumping water into, through, and out of the city.

Much of our own thinking about sustainability over the past 10–15 years has been driven by the challenge of how to recover a "perfect fertilizer" from what is conventionally understood as the urban wastewater infrastructure [2], hence herein the couple of water-nutrient systems. At the same time, growing assimilation of the prospect of climate change in the public's consciousness and professional engineering/design practice has brought about a highly active contemporary interest in the companion couple of water-energy systems [3–5]. It is indeed the primary motivation behind our first case study below of London, UK (in Sect. 3). Our second case study (Atlanta, Georgia; Sect. 4) provides the complementary focus on the water-nutrient couple as the point of departure in conceiving of how to re-balance the nitrogen (N) metabolism of that system. Although the two case studies are motivated by different context-specific issues, both require analysis grounded in the broader framework of water-nutrient-energy systems. Indeed, the recent emergence of policy concern for the "water-food-energy security nexus" gives added impetus to the need for adopting this stance of the "bigger picture" [6]. In Sect. 5, therefore, the differences (and similarities) between these case studies — for highly urbanized (London), urbanized but still urbanizing (Atlanta) and, in addition, the rapidly urbanizing Bagmati watershed (Kathmandu, Nepal) — are brought together for their assessment in respect of the speeds and dynamics of development over the longer term.

1.1 Long view: recounting some history of urban water-nutrient-energy metabolism

From a macroscopic, strategic perspective, it can be argued that structural change in the water infrastructure connecting the city to its watershed has historically been — and will be in the future — predominantly that of change in the "downside" wastewater component of this infrastructure, as opposed to the "upside" potable water supply and distribution component [7]. Such change is motivated by the need to deal in some way with the materials that are entrained into the flow of water as it participates in the metabolism of the city. This applies equally so to those elements of infrastructure dedicated to managing storm-water drainage and modulating urban hydrology [8–10].

In Barles' historical analysis of the roles of water, waste, transport, and sanitation systems in the N metabolism of the city of Paris over the period 1790 through 1970, she has shown how the symbiosis between the city and its rural surrounds rose, from the return to agriculture of 20% of Paris's human (as opposed to horse-cattle) dietary N in 1817, to 24% in 1869, and 40% in 1913 — with population growing all the time — only then to fall [11,12]. The symbiosis was severed by the advent of today's conventional water-based paradigm of wastewater infrastructure, marked by a tripling of the re-direction of the city's dietary N into the Seine River by 1931, when it had reached 36%. From a basic structural configuration of dry sanitation in the 1850s (configuration I, let us say; see Table 1 for definitions of this and the other configurations), Paris had thus passed through a form of progressively wetter sanitation with yet "separation at source" (configuration II; Table 1), to what all of us recognize today as the paradigm in which the water and nutrient metabolisms of the city are comprehensively mixed and inter-mingled (configuration III; Table 1). They are so, of course, for one supremely vital reason: the role of the WC, wet sanitation, hence sewerage and wastewater treatment, in securing public health in the city.

These longer-term historical changes are well reflected in the words we use to describe the wastewater component of the city's water infrastructure: from a pre-industrial "sewage farm" to the more industrial "sewage works", then "wastewater treatment works/plant", hence to the contemporary "water reclamation facility" or "water resources center". These changing phrases signal a deepening, and now essentially exclusive, focus on *water*. In the setting of our present discussion of water-*nutrient*-energy systems for cities/watersheds, there is a very great deal to be learned from recalling history and the (past) changes in the configurations of Paris's infrastructure [7].

Similar insights can be found in the companion historical analysis of the phosphorus (P) metabolism of the city of Linköping, Sweden, over the period 1870–2000 [13]. Not surprisingly, it mirrors the demise of the city-watershed symbiosis of Paris. Significantly, however, it shows something of a return to former times in the final three decades of the 20th century (noting that Barles'

Table 1 Description of strategically different configurations of urban wastewater infrastructure

configuration	definition
I	dry sanitation system, with resource recovery at a composting facility, for example. The system has no foul sewer network, hence no wastewater treatment facilities (since no wastewater as such is generated)
II	wet sanitation system, with a combination of cess-pool and night-soil removal — with an accompanying recovery of liquid and dry forms of fertilizer — but progressively being penetrated by WCs increasingly introduced into households (hence the beginnings of a foul sewerage network)
III	conventional, centralized sewer network and wastewater treatment plant — focused on pollutant elimination
IIIa	centralized sewer network and wastewater treatment plant — re-focused on resource-energy recovery (predominantly with re-engineering interventions at the treatment plant)

analysis ended with 1970). There is an upward trend (from 0%) in the proportion of P recovered from city wastewater and recycled into agriculture through the land application of treated sewage sludge. We might label as configuration IIIa (Table 1) this bending of the contemporary, customary, structural paradigm of configuration III of city water/wastewater infrastructure to the goal of nutrient (and energy) resource recovery [14]. Though topologically identical in their macroscopic structural arrangements, progressing from III to IIIa may involve significant technological substitutions, yet not major — or potentially socially disruptive — changes. For Linköping, it is estimated that some 25% of its sewage-borne P might be recovered in such ways [13]. Much the same recovery rate (20%) is quoted for the global population as a whole [15], i.e., under sanitation infrastructures more akin to those of configuration I.

Unlike the recovery of nutrients from today's (seemingly) "water-driven" metabolism of the city, where an originally inherent practice was lost but is now to be revived, there appears always to have been a slowly growing trend of interest in, and capacity for, energy recovery from human excrement [16]. In the absence of any detailed case histories, however, we can only but observe upon the following generalities. First, for the goal of energy recovery, it is clearly the carbon-resource base that is to be tracked through the city-watershed metabolism, including for the purpose of sustaining "renewable" microbial populations (as qualified below). Second, over some 150 years of applying techniques of anaerobic digestion [16], successful implementation of the technology — for energy recovery — has had to struggle against the progressive "wetting" of sanitation systems, in proceeding from configuration I to that of III. And third, microbial electrolysis/fuel cells are emerging as a viable, if not yet competitive, alternative branch of technology, hence the role of renewable microbial populations, as noted above [17,18][1]; likewise promising are the emerging technologies for cultivating algae biomass as a precursor of biofuels (as we shall see below [19,20])[1]. This latter technology, notably, utilizes atmospheric carbon (C) resources (in the form of CO_2) instead of the C-based resources in the human residuals of the city's metabolism.

2 Multi-sectoral systems analysis (MSA) in the context of cities as forces for good (CFG)

Our approach herein will be that of what is called a multi-sectoral systems analysis (MSA [21])[2]. Such analysis is an important part of the program of work of the International Network on Cities as Forces for Good in the Environment, or CFG for short (www.cfgnet.org; see also [7]). To give a sense of this broader context, the core challenges of CFG are these [22]:

> How can the built infrastructure of the city be re-engineered to restore the natural capital and ecosystem services of the nature that inhabited the land before the city arrived there, in "geological time"?
>
> How can this infrastructure be re-engineered to enable the city to act as a force for good, to compensate deliberately and positively for the ills of the rest of Man's interventions in Nature?
>
> How can cities of the Global South avoid adopting the same technological trajectory as those of the Global North? Can they, as it were, "leap-frog" the Global North by forgoing the entire human-waste-into-the-water-cycle phase, thereby ending up one step ahead?
>
> More profoundly, how can the engineering of city infrastructure be deployed expressly so that those at the bottom of the pyramid of dignified human development may be brought to a level where they care to engage in a debate over such a grand challenge for this century — of cities as forces for good — beyond their desperate needs of survival for just today and tomorrow?

For the purposes of conceptual organization, CFG's program is gathered around the framework of the Triple Bottom Line (TBL [23]). Decisions, the shaping of policy, and/or the invention and introduction of new technologies are to be guided according to their bearing greater degrees of: 1) environmental benignity, including being robust under the prospect of climate change [24]; 2) economic feasibility[3]; and 3) social legitimacy [25].

2.1 Framework, models, and procedures within MSA

MSA itself was developed as a function of classical systems thinking. If our goal were to re-configure the water infrastructure of a city so that it may become less unsustainable, could we yet not generate a richer and greater variety of options by casting analysis initially over the wider purview of the interactions among the city's water and waste-handling and energy sub-systems (before focusing back on the water sector)?

At the core of the MSA software [26] is a set of material flow analyses (MFA), i.e., simple mass balances and a simple procedure of accountancy for the flows of materials between a set of "unit processes" (or sub-systems) under

1) Rittmann B E. Energy. In: Larsen T A, Udert K, Lienert J, eds. Wastewater Treatment: Source Separation and Decentralization. London: IWA Publishing, 2012 (forthcoming)
2) Villarroel Walker R, Beck M B. What is key for London's future aspirations of sustainability? Journal of Industrial Ecology, 2013, (in preparation)
3) Jiang F, Villarroel Walker R, Beck M B. The economics of recovering nutrients from urban wastewater: transitions towards sustainability, 2012, (in preparation)

steady-state conditions, which are assumed to reflect annual average properties of the system and its many sub-systems. At a macroscopic level, the chosen city-watershed system comprises essentially the five economic/industrial sectors (of water, energy, waste-handling, food, and forestry) at the center of Fig. 1. This set of five sectors interacts with other relevant systems through imports and exports of materials, as well as with the air, water, and land environments (or atmosphere, hydrosphere, and lithosphere, respectively, in Fig. 1). Typically, one supposes the city is engaged in emitting pollutants to these three environments.

This model (the MFA) has five state variables: water, energy, C, N, and P. In other words, each flux between unit processes and sub-systems within the five sectors will be characterized by a vector of five elements. Thus, for example, the states of the fluxes in the waste-handling sector shown in Fig. 2 are defined by five-element vectors. Having extracted this "layer" (sector), as it were, from the entire model, Fig. 2 shows as dashed system blocks the way in which the waste-handling sector interacts with the other (four) sectors, each of which will have similar model representations, each characterized by the 5-element state vector. It is also apparent from Fig. 2 how this particular sector interacts with all three environments. The shaded blocks identify candidate technological innovations, which will be the subject of the MSA assessments. Within any unit-process or sub-system block, such as, for instance, "digestion" or "incineration" in Fig. 2, fluxes of materials are subject to biochemical transformations, represented (in general) by relatively simple nonlinear algebraic expressions (for the kinetics or stoichiometry of reactions). The parameters (α) of these input-output transformations across any sub-system, as well as consumption patterns, physical attributes, and partition coefficients, are considered to be uncertain, with uniform probability density functions between their specified upper and lower bounds.

At this level of an MFA, MSA is similar to studies of the phosphorus and nitrogen flows in Finland [27], materials and money flows in the waste-handling sector in Switzerland [28], and phosphorus flows in the Swedish food sector [13]. The capacity of MSA to analyze simultaneously more than a single material, or more than energy alone, constitutes the principal difference between it and these other studies. In particular, synergies and antagonisms between sectors can be easily identified, since the MSA is implemented within a modeling framework, i.e., Matlab, rather than as a budgeting or accounting exercise. This modeling approach also facilitates the implementation of uncertainty and sensitivity analyses within the MSA.

To gauge the metabolism of the city-watershed system as whole, for better or for worse (in respect of the environment), MSA calculates the eight numerical criteria listed and defined in Table 2. Accordingly, these criteria allow cross-comparisons to be made between the present status of the system and any future status, with (or without) the various, candidate policy and/or technological innovations.

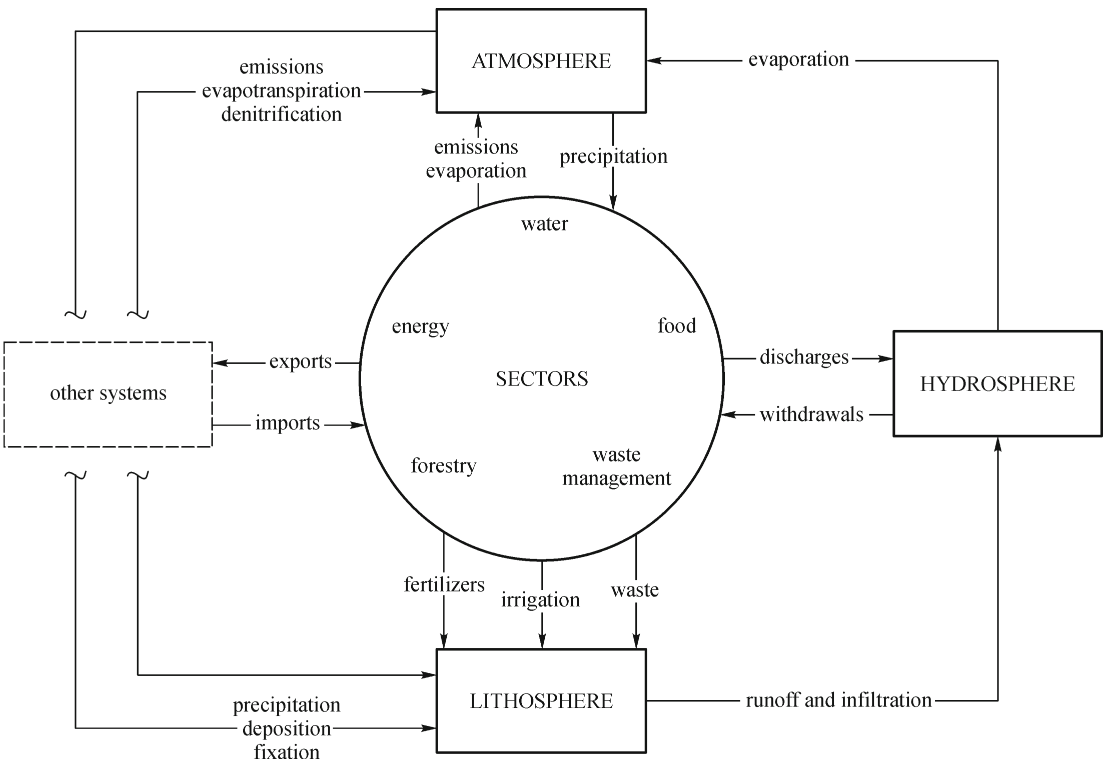

Fig. 1 Simplified overall framework of the multi-sectoral city-watershed system

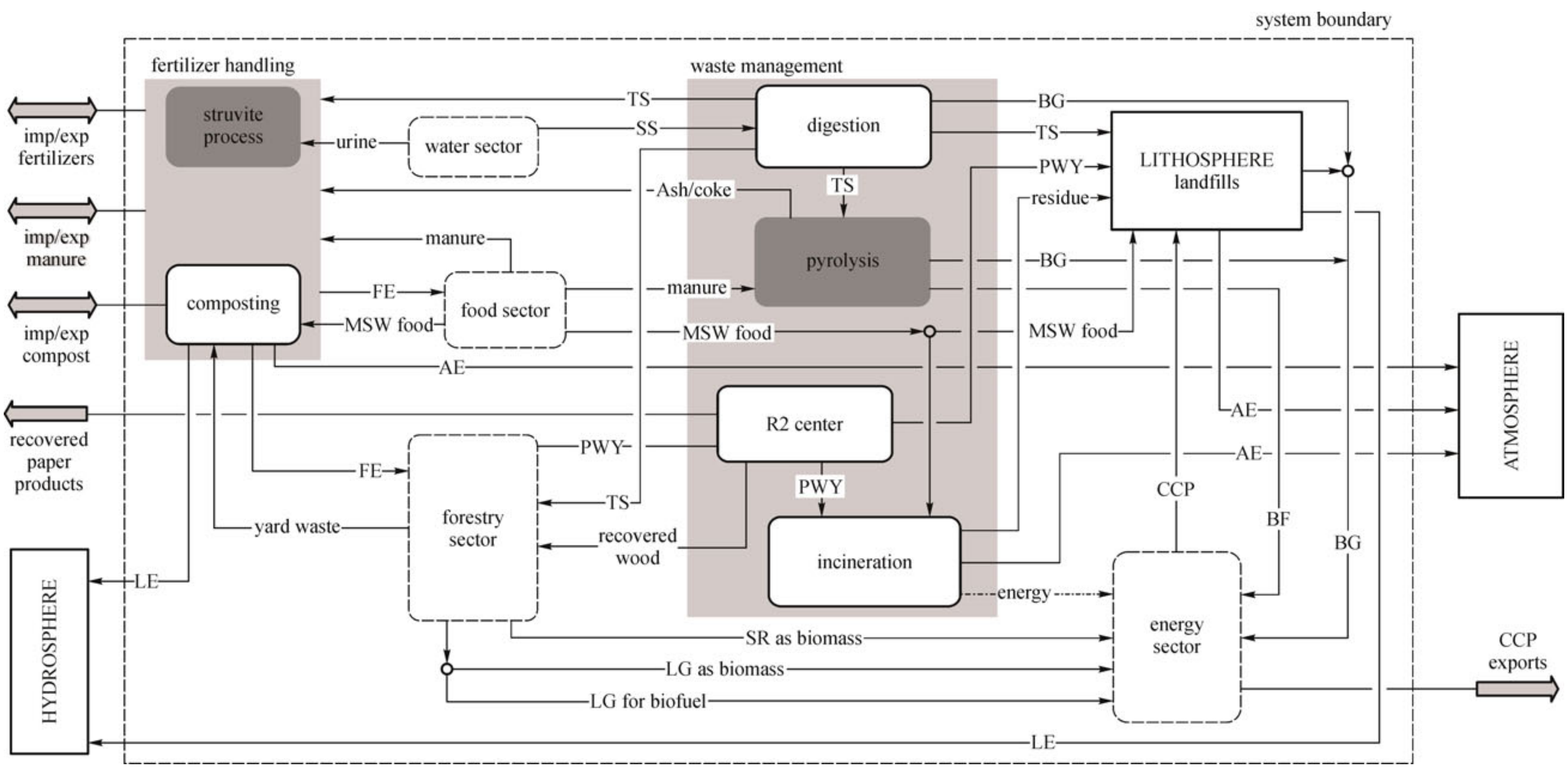

Fig. 2 Detailed flow diagram of the waste handling sector. Dashed-border boxes denote other sectors that receive or deliver flows from or to the given sector (waste handling). Shaded boxes illustrate candidate technological innovations. Abbreviations: BF, liquid biofuel; BG, biogas; AE, air emissions; MSW, municipal solid waste; R2, recycling and reusing; TS, treated municipal sludge; SS, fresh municipal sludge; SR, sawmill residue; FE, fertilizers; LG, logging residue; LE, leaching; CCP, coal combustion products

The whole of the MFA model is embedded in a regionalized sensitivity analysis (RSA) [29] (see also [30], in more advanced form), which (in part) draws upon the use of Monte Carlo simulation. Given the uncertainty in the parameters (α) of the model, the foregoing policy assessments and technology screening can be conducted under uncertainty, which may be sufficient to render statistically insignificant any differences between present/future status and presence/absence of a technological innovation. Such an assessment is illustrated below in the London case study. In its present form, the MSA computes separate ensembles of annual, average conditions for any one year. These ensembles are therefore generated as being quite independent of the ensembles computed for the preceding year. Thus, the time-series of annual behavior across the specific period 2010 through 2050 for the London case study is a 40-year sequence of annual "snapshots".

Equally importantly, if not more so, the RSA can be employed to undertake the following kind of analysis, which will be the subject of the Atlanta case study below. Suppose current arrangements of the city-watershed system are such that X thousand tonnes of a nutrient resource are being recovered, or that overall the system's eco-effectiveness (E2I in Table 2) is attaining a value of Y. Under consideration is a future target performance of, say, at least a 30% improvement in either of these measures, such that (desired) future behavior is at least 1.3X (or 1.3Y). Let us label this as behavior *B* and its complement, i.e., future performance less than or equal to 1.3X (or 1.3Y), as not-the-behavior *NB*. Suppose now that a set of candidate policy or technology interventions is under consideration, such as the shaded blocks in Fig. 2, and that these interventions are numerically encoded in the parameterization (α) of the MFA model. Expressed thus, and under (gross) uncertainty (including that attaching to α), the RSA allows identification of those parameters that are key to determining whether *B* or *NB* is attained, say the subset of parameters α_{key}, and those that are redundant to such discrimination.[1)] By inference, of special significance is whether any of the candidate interventions are found to be in the vector α_{key}.

The computational results presented below are all broadly juxtapositions of current circumstances, i.e., the status quo (configuration III of Table 1), with those that might obtain were various infrastructure technologies substituted into the city-watershed system at a level of 100% "market penetration". Such substitution would obviously require a considerable amount of time for completion — doubtless a span compatible with the inter-generational time-scale that is defining of sustainability. Work elsewhere within the CFG network is therefore being devoted to the social, environmental, technical, and, in particular, economic practicalities of enabling transitions from the status quo to these various possible distant futures [7].[2)]

3 London: water-energy interactions

Our over-arching questions for the MSA are: are there synergies to be sought out (and antagonisms to be avoided) among the dense entanglement of cross-sectoral interactions in the city's multiple strands of infrastructure; and

Table 2 Summary of environmental sustainability indicators defined for the MSA framework

abbreviation	objective	description
PRI	maximize	measure of useful products generated within the system per unit of resources consumed
RWI	maximize	measure of resources consumed per unit of waste requiring disposal
PWI	maximize	measure of the amount of products per unit of disposed waste
EEI	maximize	measure of the amount of products per unit of emission to the environment, either to the atmosphere or to water bodies
HAE	unity	measure of the disparity (ratio) between the actual amount of emissions to the atmosphere and a healthy emission level
HWE	unity	measure of the disparity (ratio) between the actual amount of emissions to water bodies and a healthy emission level
WEF	unity	compares the amount of products versus the quantity that the system would generate if no flows are classified as waste and all emissions correspond to healthy emissions, i.e., waste equals food
E2I	unity	encloses together the concepts of waste equals food and healthy emissions, describing thus the overall eco-effectiveness of the system

1) Alternatively, one can express this as follows. Were a candidate intervention to fall under the category of a redundant parameter, that intervention — in concert with the occurrence of a whole set of outcomes of random events elsewhere in the city-watershed system — is just as likely to succeed in bringing about the desired target behavior (*B*) as it is to fail, i.e., to lead to the complementary not-the-behavior (*NB*).

2) Jiang F, Villarroel Walker R, Beck M B. The economics of recovering nutrients from urban wastewater: transitions towards sustainability, 2012, (in preparation)

what kind of institutional arrangement might best be suited to maximizing the synergies and minimizing the antagonisms? National policies, for instance, are quite capable of generating cross-sectoral antagonisms, as UK utility Severn Trent noted in 2005 with regard to its water and waste-handling businesses, when reviewed from the perspective of UK Government expectations in respect of water policy and those in respect of climate (carbon) policy [31]. United Utilities, having made a number of acquisitions that positioned it as the multi-utility in the North West of England, has since divested itself of most of its energy and solid waste operations, in part because of the finance sector's current distaste for conglomerates that are distracted from their core business, i.e., a water-focused business in this instance.

Elsewhere, for example, in the case of French utility companies, specifically Veolia Environnement, institutional arrangements appear conversely to favor the emergence of multi-utility enterprises [7]. Spreading out from its origins in the water sector, Veolia now conducts business in the further three sectors of energy, waste, and transport. Indeed, it is seeking to build on its experience of the resulting synergies to offer "tailor-made solutions to companies in the industrial and tertiary sectors" [32]. It estimates these markets "generated revenue of about €10 billion in 2008" [32].

Our present London case study is cast firmly in the water sector, with yet considerations directed outwards from that sector into (first) the energy sector and (second) the nutrient sector. With regard to the capabilities of the MSA described above, it illustrates an analysis over a span of several years using a straightforward application of Monte Carlo simulation.

London has adopted a target of reducing its carbon emissions by 60% by 2025 (relative to its 1990 emissions) [33] and has developed strategies for adapting to climate change, alongside a range of other economic, social and environmental policies. One policy alternative for reducing carbon emissions across London is a requirement for at least 20% of the city's energy to come from on-site renewable sources. At the same time, the UK has adopted legally binding targets for emissions reduction. One of the mechanisms for achieving this reduction is the Carbon Reduction Commitment energy efficiency scheme, which is aimed at improving energy efficiency and cutting emissions in large public- and private-sector organizations, including water utilities. These legislative drivers add to the motivation, already spurred by increasing energy prices, to curb energy use in the water sector and enhance the recovery of energy from the materials (nutrients) entrained into the city's water metabolism, in particular, through the promotion of renewable energy schemes.

Four technologies are considered for substitution, all of which are technologies of the (traditional) water sector:

1) urine-separating technology (UST [34]), which separates urine from feces, for the production of struvite ($NH_4MgPO_4 \cdot 6H_2O$) and ammonium sulfate ($(NH_4)_2SO_4$), respectively via crystallization and chemical reaction with sulfuric acid;

2) the consolidation and co-treatment of household organic (food) waste through its conveyance in the sewerage system (COW) – this implies the use of food grinders and the mixing of kitchen organic waste with the usual contents of household sewage, i.e., laundry and bathroom/toilet fluxes [35];

3) pyrolysis of separated sewage sludge (PSS), by which organic material is decomposed at high temperatures and in the absence of oxygen to produce gas, bioliquids, and biochar [36] – dewatering is included in a lumped manner for the entire wastewater treatment plant, but dehydration, which might be needed prior to pyrolysis, is not included; and

4) algae production in wastewater treatment facilities (AWW), utilizing any remaining nutrients in treatment plant effluent flows (for example, those remaining in the event that this technology is implemented in concert with UST) [37,38] – it is assumed that algae cultivation is undertaken in unit processes with the format known as "raceways" [39].

Three drivers of change for London over the period 2010–2050 are assumed: population increase, from 7.8 M to 9.9 M; reductions in residential water demand, from 160 L to 80 L per person per day (which is, we note, quite a strong assumption); and more stringent constraints on the quality of wastewater treatment plant effluents in respect of their biochemical oxygen demand (BOD) concentration, from $20\ \mathrm{mg \cdot L^{-1}}$ progressively down to $10\ \mathrm{mg \cdot L^{-1}}$ (mention of which, i.e., as an "EU Elite Requirement", has been mooted [40]).

Figure 3 illustrates the results of the MSA in terms of the energy demand of the water sector, comprising the energy requirement for water treatment and distribution, wastewater treatment, and the operation of prospective technologies (such as those above), estimated according to various studies and benchmark analyses, e.g. [35,39,41]. Comparing Figs. 3(a) and 3(b) reveals how the comprehensive installation of UST might achieve the greatest reduction in energy consumption of any single technological innovation (Fig. 3(a)), relative to a continuing "Business-as-Usual" scenario (Fig. 3(b)), wherein none of the candidate technologies of 1) through 4) above are implemented. Simply put, some 15% less water on average would need to be pushed through and around the city's metabolism at 100% market saturation with UST. Yet this inference is by no means clear cut. The two sets of results in Figs. 3(a) and 3(b) are subject to relatively high levels of uncertainty. Before one could be more confident in promoting the energy-savings benefits of UST, it would be necessary to identify which are the largest sources of uncertainty in generating the results of Fig. 3 and then to seek ways of

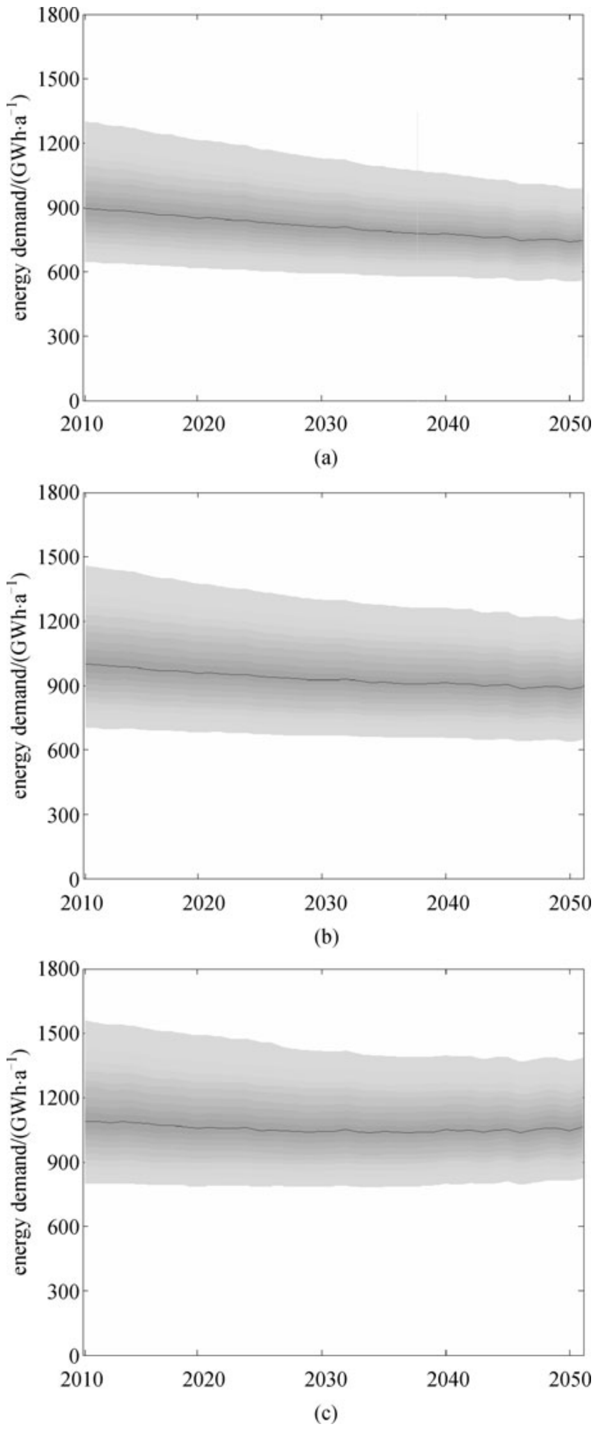

Fig. 3 Energy demand (in electricity terms) for water supply and wastewater treatment, with and without the innovation of UST, where (a) represents the scenario with the introduction solely of UST, (b) is the "Business-as-Usual" scenario, with none of the candidate technologies being introduced, and (c) refers to the scenario with the three other technologies (COW, PSS, and AWW) having been introduced, but without UST. The black line is the median of the distribution; the shaded envelope represents the span of the distribution lying within its 95% confidence intervals

reducing them. For further comparison, Fig. 3(c) shows the energy demand when the other three technologies (COW, PSS, and AWW) are introduced (but not UST). Relative to the Business-as-Usual scenario of Fig. 3(b), the broad implication is that operation of these three technologies will increase the demand for energy (which is generally the opposite of the impact of introducing UST). Nevertheless, such system-wide introduction of the UST, i.e., a moving back from strategic infrastructure configuration III to that of configuration II (wet sanitation with "separation at source"; Table 1), would very probably occasion significant social and economic dislocations in households, if not wider upheavals [7].

While UST extends the prospect of saving energy, not surprisingly it is not as significant in contributing to overall energy recovery (in various gaseous and liquid forms). The best results, i.e., the recovery of up to about 2300 GWh·a^{-1} by 2050 in terms of fuel energy content, would follow from the combined substitutions by then of the other three technologies (COW, PSS, and AWW) – even though there is, of course, a broadly increased demand for energy for their operation relative to the Business-as-Usual scenario (as evident in Figs. 3(b) and (c)). In turn, roughly 160000 t·a^{-1} of London's emissions of carbon would by then be from renewable sources of energy deriving from this combination of technological changes within the water sector (Fig. 4). Here, in Fig. 4, what distinguishes between membership of Figs. 4(a) and (b) is the presence and absence, respectively, of the COW strategy, which adds organic material to the sewerage system and consequently increases energy recovery as fuels, primarily generated by (first) digestion of the sewage sludge and then its pyrolysis. In contrast to the results of Fig. 3, the bounds of the 95% probability intervals refer to the distributions of multiple scenarios for the various combinations of technological innovations, i.e., not merely single scenarios (as in Fig. 3). For clarity, we note that the energy associated with the tonnes of carbon emissions will in practice depend largely on the efficiency of the energy-generating process using these recovered fuels. In the (simulated) year 2010, for example, the total energy content of fuels recoverable from the triplet of COW, PSS, and AWW technologies (had they been in place) would have been 1200 GWh·a^{-1}, with a corresponding carbon release of 100000 t·a^{-1}. If the efficiency of the energy-conversion process were assumed to be 30%, there would have been a release of about 280 t of carbon for each GWh generated. For comparison, energy conversion based on natural gas (as opposed to these fuels recovered from the water sector) emits about 100–170 t of carbon (or 350–600 t in CO_2 terms, assuming full combustion) for each GWh generated.

In respect of AWW, the recovery of nutrients from the water sector — or, more accurately, the wastewater sector — would serve the (arguably) higher purpose of generating the N and P required to accompany the removal of atmospheric C through the photosynthesis of algal biomass, for then its subsequent, downstream conversion into fuels. However, if the focus were on the nutrient sector as the priority, instead of the energy sector, the wholesale introduction of UST is key to N recovery, with a potential yield in excess of 25000 t $N \cdot a^{-1}$ by 2050, while pyrolysis of sewage sludge (PSS) would be the single most promising innovation in respect of P recovery. As Fig. 5 (a) shows, it could deliver up to some 12000 t $P \cdot a^{-1}$, for any scenario in which PSS is present.

Energy, nevertheless, will always be a vital consideration. It will be needed to remove the water (added upstream for the purposes of transport/conveyance) in the downstream processes of fuel recovery, especially for COW, as well as in sewage sludge separation and treatment. This is not so for UST, however, which takes advantage of the concentration of N and P in urine [42] and circumvents the disadvantage of their (otherwise) substantial dilution through the addition of water for conventional WC flushing and transport.

And yet, in the midst of a continuing global economic crisis (in 2012), to which the UK economy is far from immune, one should ask whether any of these proposed changes might ever be initiated in practice. We argue elsewhere [43] that the present may, in fact, be a moment when viewing the C, N, and P materials in "wastewater" as pollutants to be eliminated, driven by government regulations and incurring only costs to the "public purse", might be pivoting around to the prospect of their being recovered as resources with significant financial benefit streams. Thames Water, which is responsible for London's water sector, well illustrates embrace of the two perspectives: a potential commitment of \$3B of expenditures in order to eliminate polluting combined sewer overflows; and, in contrast, an actual commitment to recovering a P-based commercial fertilizer from Slough Sewage Works, just to the west of London [43].

To provide a deliberately different sense of perspective — one that challenges the rooting of our thinking in the water sector, illustrates other important features of our MSA framework, and points toward the potential benefit streams of resource recovery — we turn now to a case study of Metro Atlanta, within the Upper Chattahoochee watershed, in the south-eastern US.

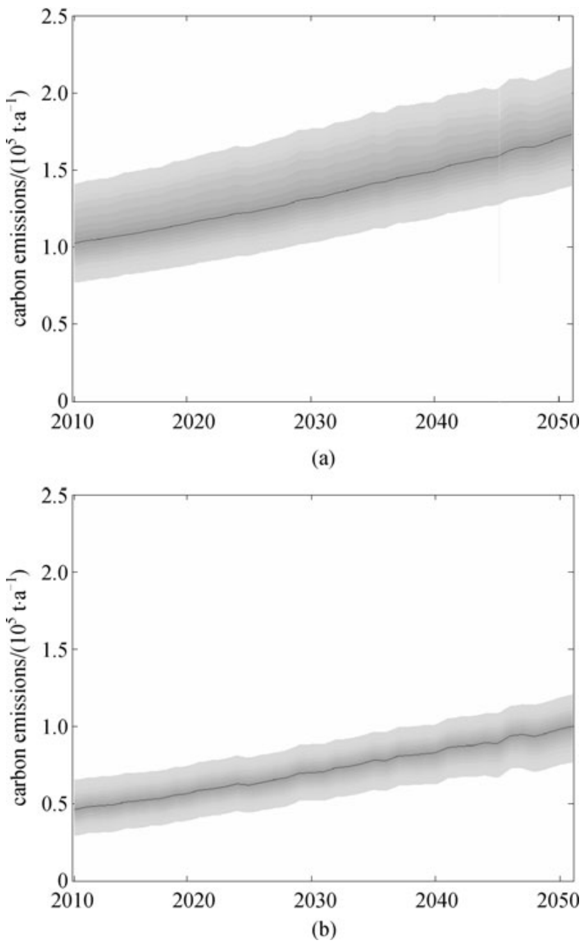

Fig. 4 Direct carbon emissions associated with the (bio)fuels generated in the water sector and the prospective candidate technological innovations, where (a) represents several scenarios for those technological combinations that involve COW, while (b) represents those several scenarios for technological combinations that do not consider COW, including the base case (Business-as-Usual), in which none of the candidate technologies are implemented. The shaded bands correspond to 95% confidence intervals and the black line is the median of the distributions; here, as noted, the outcomes of multiple uncertain scenarios (with or without COW) are subsumed under each distribution

4 Atlanta: nutrient-water interactions

For London, the focus of the MSA was on changes and innovations in the water sector and their cross-sectoral ramifications for the energy and nutrient-recovery (waste-handling) sectors. Our perspective on the Atlanta-Chattahoochee (A-C) system will be largely the reverse. It will be a study in re-balancing the system's N metabolism and, from there, enquiring into the attaching consequences for the water sector and the aquatic environment [21].[1)]

To begin our assessment, some 10000 t $N \cdot a^{-1}$ were transported in the crude sewage flow entering the city's wastewater treatment plants in the year 2000 [21].[2)] The potential exists for recovering some 4000 t $N \cdot a^{-1}$ from this

1) This is not, however, what currently drives the environmental agenda of the A-C system. The minimization of P-related pollution of aquatic bodies is, not the recovery (as resources) of these P-based nutrients, or their complementary N-based nutrients.

2) This figure refers to that portion of Metro Atlanta lying in the Upper Chattahoochee watershed, with a population of some 1.3 M people (out of the total 5.4 M of Metro Atlanta as a whole).

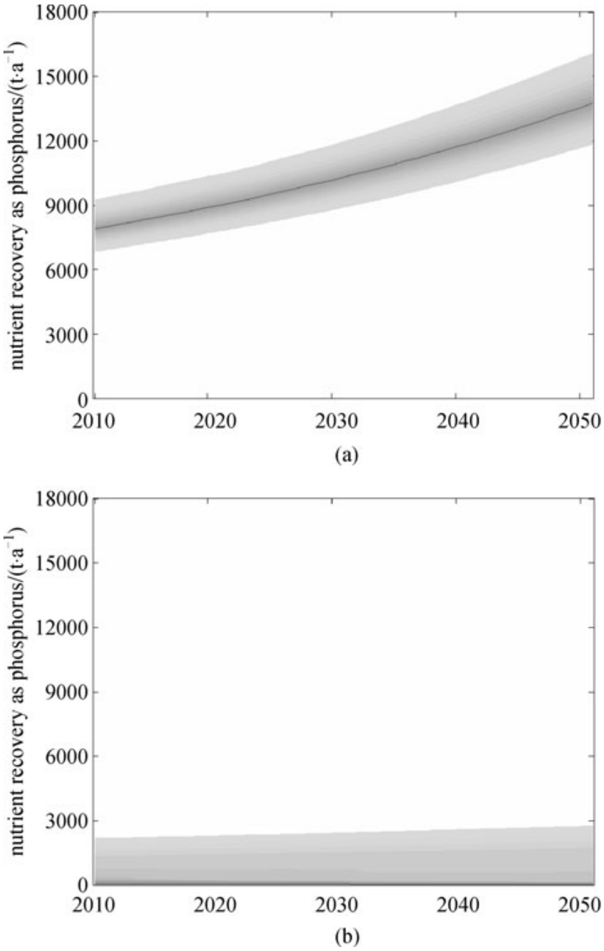

Fig. 5 Recovery of P fertilizer, where (a) represents several scenarios for those technological combinations that involve PSS, while (b) represents several scenarios for those technological combinations that do not involve PSS, including the base case (Business–as-Usual), in which none of the candidate technologies are introduced. The shaded bands correspond to 95% confidence intervals and the black line is the median (again, as in Fig. 4, for the distributions of the outcomes of multiple uncertain scenarios)

amount (worth about \$4.3 M as fertilizer), given a 100% city-wide rate of substituting UST for present plumbing arrangements in households, office blocks, and so forth, across the portion of Atlanta lying within the Upper Chattahoochee watershed.

Significant though these figures are, about 28000 t $N \cdot a^{-1}$ enter the A-C system in feedstuffs for livestock production and a further 52000 t $N \cdot a^{-1}$ enter via coal and natural gas imports (in roughly equal parts). A proportion of this latter pair of input flows emerges subsequently as 20000 t $N \cdot a^{-1}$ in emissions to the atmosphere from power generation; their “metabolic residuals” also constitute a portion of the 27000 t $N \cdot a^{-1}$ emitted likewise from non-power applications associated with domestic, commercial, industrial, and transportation activities [21].

These predominant bulk fluxes of N associated with the food and energy sectors — or rather, their emissions to the aquatic, atmospheric, and land environments (Fig. 1) — are opportunities for resource recovery, in principle. In fact, a measure of take-up of such opportunities is already beginning to be apparent in practice in the food sector, with respect to the recovery of fertilizer and fuels from the P, N, and C components of poultry litter [1]. Looking again to the distant future from the status quo, what then (we enquire) is the scope for N recovery, not only from the water sector (through the comprehensive introduction of UST), but from the following additional innovations beyond the four (1) through 4)) set out for the water sector in the foregoing London case study:

5) poultry litter pyrolysis (PLP), in the food sector, in which organic material is decomposed at high temperatures and in the absence of oxygen to produce gas, bioliquids, and biochar [1];

6) algae production fueled by the recovery of N from power plant flue gases (or APF, for short) – here algal growth is enhanced by the injection of CO_2 (present in flue gas), while benefitting from the N content of the flue gas (mainly in the form of NO_x and N_2) [44,45]), with assumptions regarding the unit processes for culturing the algae being similar to those of innovation 4).

PLP and APF, therefore, are respectively food-sector and energy-sector equivalents of the water-sector PSS and AWW technologies considered above in the case study of London. More specifically, the N input for algae biomass production in the Atlanta-Chattahoochee system is being derived primarily from gaseous N components, whereas for the companion AWW process in the London case study the feedstock is drawn from liquid N materials. Both are manifestations of the mantra of “waste equals food”, hence a re-balancing of a system’s metabolism, which lies at the core of the notion of eco-effectiveness (as opposed to eco-efficiency), as discussed at length by McDonough and Braungart [46] (see also the MSA criteria of Table 2).

In headline terms, installation of APF at 50% of full capacity would recover 1200 t $N \cdot a^{-1}$ as fertilizer (worth \$1.3 M per annum) together with the equivalent of 510 $GWh \cdot a^{-1}$ of energy (worth an additional \$28 M per annum) [21].

Taking advantage of the RSA procedure in which our MSA is embedded, however, we can pose a rather different question: what are the key factors across *all* the economic-industrial sectors and within the natural and built environments of the A-C system that determine the attainability of a 30% increase in that system’s eco-effectiveness, as encapsulated collectively in the indexes of health of emissions to the atmospheric environment (HAE), health of emissions to the aquatic environment (HWE), and waste equals food (WEF) (as defined in Table 2)? Expressed more formally, if we consider the current performance of the “waste equals food” indicator, i.e., WEF_{now}, what might be identified as the set of parameters α_{key} that are key in discriminating whether performance exceeding $1.3 \times WEF_{now}$ (i.e., desired future behavior B)

Table 3 Key factors (parameters; α_{key}) to achieve a 30% improvement in three environmental indicators: HAE, health of air emissions; HWE, health of water emissions; and WEF, waste equals food [26,47]

	HAE	HWE	WEF
pervious area infiltration		×	
monthly cloudiness		×	
nitrogen fixation rate (forest land)	×		
denitrification rate (forest land)	×		
nitrogen leaching factor		×	
% implementation of poultry litter pyrolysis			×
surface runoff from impervious areas		×	
N in natural gas			×
N in O horizon layer (forest land)		×	
N in dry deposition	×		
air temperature		×	
latitude of the region		×	

is achieved or not (as in not-the-behavior *NB*)?

Table 3 summarizes the results of posing such a question to the MSA. According to this measure of eco-effectiveness (i.e., waste equals food, WEF) [26,47], the rate of PLP substitution is indeed found to be key, alongside the N-content of natural gas imports. That is to say, both are identified as members of the sub-set of parameters α_{key}.

Nonetheless, features of the natural environment dominate the factors key to improving the HWE. Constituents of the A-C setting associated with climate (cloudiness, temperature, latitude), water management (infiltration and runoff), and N availability in soils (leaching, O-horizon content), all appear to be key to the attainability of any improvement in the status of the watershed's aquatic environment — insofar as this participates in the N metabolism of the A-C system [21].

Frustrating though this last set of computational results may be from a policy perspective, it nevertheless illustrates the power now achievable with the MSA to generate insights about cross-sectoral and cross-media interactions — and this is the primary focus of this paper.

5 Long view: dynamics of change into the future

There are differences in circumstances between London and Atlanta. The former is undoubtedly a mature and land-constrained city, whereas Atlanta is less land-constrained. About 5.45 M people live in the Atlanta Metropolitan Area (AMA), which occupies roughly 22000 km^2. The Greater London Area (GLA), with a population of 7.8 M, occupies just 1570 km^2. The population of Atlanta has grown by 100% since 1985, London's by 15%. The proportion of land-use classified as "urban" in the GLA has fluctuated between 57% and 62% over the past 25 years, while that of the AMA was projected to increase from 20% to 35% during the period 1987 through 2010 [48]. Densely populated London is served entirely by a conventional, centralized sewerage and wastewater infrastructure, whereas almost 40% of Metro Atlanta's population occupies dwellings utilizing septic tanks.

5.1 Lock-in: perceptions and sustainability

On the whole, the arrangement of both London's and Atlanta's wastewater infrastructure is what we would until recently have regarded as the environmentally beneficial "culmination" of configuration III (Table 1), in which water and the entrained N, P, and C resources are comprehensively mixed. This view is no longer held by all [49]. What had come to be known during the second half of the 20th Century as conventional environmental engineering was no longer considered self-evidently to be "doing good by the environment". In particular, the growing (global) contemporary interest in introducing urine-separating technology (UST [42,50]) reflects a desire in cities of the Global North to return to the "separated at source" arrangements of configuration II of former times [7] (Table 1). In fact, further computational studies with the MSA (to be reported elsewhere [51]) confirm the foregoing *prima facie* case in favor of comprehensive UST installations, for attaining a variety of resource savings/recovery targets, for both London and Atlanta.

The challenge, however, is that the existing conventional patterns of un-separated wet sanitation in London and Atlanta are parts of an infrastructure — the water infrastructure — with just about the highest rate of technological "lock-in" of any kind of infrastructure, when judged according to Collingridge's criteria of lock-in [52–54]. Hence, as already noted, pursuit of the transition from configuration III to II may entail major social and material upheavals, in a way that the transition from III to IIIa should not occasion (Table 1). Such social and economic issues, foreshadowed in the paper's introduction, must now be addressed.

Irrespective of the potential environmental benefits to accrue from any wholesale transition to separation at source through the introduction of UST (or any other "paradigm-breaking" innovations), what, for the futures of London's and Atlanta's water infrastructures, will spark the transition to viewing nutrients (N, P, and C) as resources to be recovered (with financial benefits as fertilizers or fuels), instead of as pollutants to be rid of, at increasingly substantial costs?[1)] Among the social, community, and institutional arrangements surrounding the water infrastructures of Atlanta and London, who has the power to effect change and in which parts of the infrastructure? Is the prevailing structure of governance such that these agents are appropriately convinced of the outlook of N, P, and C nutrients as recoverable resources [25,43]? Who derives the benefits of resource savings and recovery and who bears the costs of any related changes of infrastructure?

Addressing such questions would by no means be a novel line of enquiry. Anthropological analysis of the history of changing attitudes toward the renewal of London's housing stock during the 1960s through the 1980s illuminates how a superior environmental outcome was achieved as a result of the interplay among the plural moral and social outlooks (of those times) on the Man-Environment relationship [55]. Tellingly, if not presciently for our present study, the superiority of the environmental outcome had to do with community actions and policies that – as we would now describe it in the modern idiom – minimized the city's carbon-energy footprint through minimizing both demolition and new construction.

As suggested elsewhere [25], we can imagine experimenting with the set-up of the MSA to elucidate how the social spark for any "transition" might come about, broadly along the lines of the earlier work of van Asselt and Rotmans [56] on the shaping of climate-change policy (under the uncertainty of disagreement among the plurality of outlooks on the Man-Environment relationship). Yet in many ways, such theoretical policy-relevant insights are being preceded, in effect, by companion insights already being elucidated in practice in the context of our third case study [7,25,54,57].

5.2 "Freedom" of not yet being locked-in

The city of Kathmandu, in the Bagmati watershed in Nepal, is in a quite different developmental state to that of London and Atlanta. In the two decades between 1981 and 2001 the population of the Kathmandu Valley more than doubled from 0.76 M people; and given the high in-migration since (of Nepalis fleeing the insurgency of the past several years), the population is currently (2012) estimated to be close to 3 M. As a result, "You don't have to be a trained ecologist to know that the river is polluted", says a study of the Nepal Water Conservation Foundation [58].

The Bagmati river itself flows through the three districts of Kathmandu, Lalitpur, and Bhaktapur. There, the unique Bagmati civilization has flourished; and to this civilization, the rivers and tributaries of the Bagmati watershed are sacred. The same Nepal Water Conservation Foundation (NWCF) report [58] goes on to state:

Water quality near the shrines of Pashupati, Sankhamul and Teku, places where people offer prayers and carry out rituals like funerals and bathing, has degraded.

It provides photographic material indicating the restrained under-statement here of the word "degraded".

These cultural and urban development circumstances in Kathmandu are very different indeed from those of London and Atlanta. Furthermore, if urban *industrialization* of Kathmandu follows from urbanization in the Bagmati watershed, as has happened in cities and watersheds in China [59,60], these circumstances may become different yet again from many cities in the Global North (including Atlanta and London). For heavy industry is increasingly absent from them. In such circumstances, the lot of many urban dwellers may be desperate (a visceral struggle to survive for today and tomorrow), but the system overall has much potential: not to lock into configuration III, i.e., the prevailing convention in cities of the Global North (Table 1); possibly to achieve some kind of technological and infrastructural leap-frogging, *vis à vis* these cities of the Global North; not to lock into N, P, and C as pollutants, but to view them as resources (as is happening already in comparable situations [61]) and to arrange and locate units of heavy industry deliberately to achieve what today would be some much vaunted "industrial ecology" [59], so as to benefit the environment, even nourish it.

The breadth of perspective of MSA leads us to conjecture that it may not be all that difficult to set up an MSA for the metabolism of the Kathmandu-Bagmati (K-B) system, just as described and illustrated above for London and Atlanta. What is more, the idea of responding there to the original challenge of Cities as Forces for Good in the Environment is becoming manifest in the aspirations of the local community, including through its deployment already of resource-recovering "Eco-san" toilets [58]. But the dynamics of change in the built environment of rapidly urbanizing watersheds exhibit other vital features that are not as readily accommodated and addressed within the present scope of MSA.

1) Jiang F, Villarroel Walker R, Beck M B. The economics of recovering nutrients from urban wastewater: transitions towards sustainability, 2012, (in preparation)

5.3 Land-use change, spatial infrastructure dynamics, and the construction sector

Both the urban built environment and the natural environment are comprised of physical structures and biogeochemical processing (i.e., metabolism therein). While the current form of MSA lends itself especially well to this latter *and*, in particular, the study of cross-sectoral interactions across multiple sectors — which is why it was developed in the first place — it is not well suited to considerations of the variegated spatial patterns of infrastructures, hence the dynamics of changes in land-use, which are pronounced in rapidly urbanizing watersheds. Even for the mature and relatively static configuration III of the water/wastewater infrastructures of London and Atlanta, it is not immediately obvious how MSA might be employed to assess the impact of decentralizing those infrastructures, without substantially disaggregating its presently highly lumped spatial account of metabolism. Furthermore, the construction sector and the transport sector are absent from the MSA. Yet any strategic switches and transitions among configurations I, II, and III — and especially from III to II (or I) (in Table 1) — imply significant fluxes of material and embodied energy that should be accounted for, as was key in the superior environmental outcome of the rather similar transitions in the past of London's housing stock [55].

The necessary changes to MSA are now apparent, as well as some of the required alternatives and complements to it. Some are being employed elsewhere within the CFG program (as in [24]).[1)] Were the construction sector to be incorporated into the MSA, we believe there might also be much merit in coupling the present software with a geographic information system (GIS), along the lines illustrated by Tanikawa et al. [62]. They used GIS to show where in the city of Kitakyushu (Japan) the greatest flows of material might be liberated were demolition to occur.

From a different perspective, Dong et al. [63] have shown how a landscape mosaic of pixels across an about-to-be-urbanized area (near Beijing, China) can be optimized with respect to the installation of de-centralized sewerage, wastewater treatment, and water re-use facilities. Each pixel has a set of potential future land uses. Spatial integer programming was used to optimize the choices of land use, subject to various constraints; in principle, recovery of resources *other* than that of just water can be included in the goal function of the optimization [63]. This work, however, clearly exploits the freedom of planning the development of a city (and its metabolism) *ab initio*, in the absence of any prior built environment. Such is not the status of Kathmandu (or Atlanta, or London). In his survey of studies in energy consumption in cities under the prospect of climate change, Lefèvre laments a lack of joined-up thinking in the planning of urban land-use and the planning of urban transport (under the prospect of climate change) [64]. We submit that managing these two drivers of the spatial evolution of the built environment of an existing city, which is yet to be locked into the paradigm of configuration III for its wastewater infrastructure (such as Kathmandu), should be coupled with, if not governed by, its oft-forgotten wastewater infrastructure. Specifically, for instance, the commercial success of any algae-based system of urban biofuel production may be critically dependent on the co-location of (centralized) power-generation facilities and (centralized) wastewater processing facilities.

In short, and not surprisingly, whereas cross-sectoral synergies and antagonisms among the water, nutrient, and energy sectors have been the subject of this paper, there are further synergies (and antagonisms) to be considered among spatial arrangements of facilities in the sectors of land-use/property, transport, and water.

6 Conclusions

Over the past two decades or so, analyses of sustainability in the urban water sector have been extended to consider the water-climate nexus, then the water-energy-climate nexus, and now the water-energy-food-climate security nexus [6]. Our research in applying an MSA for understanding and manipulating the biogeochemical metabolism of city-watershed couples parallels this fruitful (and timely) broadening of perspective (see also [65]).

There has doubtless long been awareness of the cross-sectoral impacts embedded in the water, nutrient (food), and energy infrastructures of cities. MSA enables their more systematic exploration, herein with a focus on technological innovations for nutrient recovery. Such a focus reflects the almost historic nature of changing our perceptions: from viewing the carbon, nitrogen, and phosphorus species in urban wastewater as pollutants — to be eliminated and non-beneficially, if not damagingly, dissipated in the air, land, and aquatic environments — to seeing them as resources to be gainfully recovered. And when recovered from the water sector (as conventionally understood), these nutrients can be re-deployed in the agricultural (food) sector, or used to generate biofuels for the energy sector, or issued as "nutrient supplements" to the ecosystem services "sector" [7,24]. Not only are cross-sectoral interactions readily apparent under such a (changed) view, but so too are the implications of contemplating, hence addressing, the water-food-energy (WFE) security nexus in the rounded manner it requires.

Given two currently active case studies in the application of our MSA, the paper has reported on a first cross-

1) Jiang F, Villarroel Walker R, Beck M B. The economics of recovering nutrients from urban wastewater: transitions towards sustainability, 2012, (in preparation)

comparison of the potential benefits (and costs) of innovations in the WFE infrastructures of Atlanta and London. From there the paper has extended its discussion to assess the scope and limitations of applying MSA to a third case study of the city of Kathmandu, in the Bagmati watershed of Nepal. This is a city-watershed system with a profoundly different set of developmental circumstances to those we find in London and Atlanta. In such rapidly urbanizing and industrializing watersheds, we conclude that MSA (in its present form) might be able to contribute to thinking about shaping some kind of sustainable industrial ecology for Kathmandu. However, it would not be well suited to charting any more (or less) sustainable courses of spatial urban development, since that matter is dominated by considerations of the behavior of the construction and transport sectors and of land-use changes (at quite a spatially disaggregated level). MSA is currently effective precisely because 1) it is relatively lumped in its spatial account of developments and 2) it does not cover all the economic/infrastructure sectors of any possible conceivable relevance.

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