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Innovation, multi-utility service businesses and sustainable cities: where might be the next breakthrough?

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Abstract

A Multi-sectoral Systems Analysis (MSA) model has been constructed for exploring and managing cross-sectoral impacts (both synergies and antagonisms) resulting from technology and policy interventions in the design and stewardship of city infrastructures. This MSA is based on Substance Flow Analysis. It accounts for the flows of water, nitrogen, phosphorus, carbon, and energy into, around, and out of the water, energy, food, waste-handling, and forestry sectors of city-watershed systems. Applications of the MSA to two case studies of the Metropolitan Atlanta Area in Georgia, USA, and the Greater London Area, UK, are compared. The impacts and financial benefits are assessed for four candidate technological innovations in the water sector: urine-separating toilets; pyrolysis of sewage sludge; combined food-waste and wastewater conveyance/treatment; and production of algae-based biofuels from sewage. System-wide environmental sustainability is gauged on four accounts, of attaining progressively more ambitious targets of resource savings/recovery in respect of water, energy, and nutrients (both nitrogen- and phosphorus-based). The paper closes by demonstrating how the MSA can provide assistance in framing questions of a more financial and social nature, i.e., those of 'Who reaps the rewards?' and 'Who bears the costs?' of the various prospective technological changes and (possibly) breakthroughs.

Key words: energy, multi-sectoral analysis, multi-utility businesses, nutrients, technology foresight, urban metabolism, Water

INTRODUCTION AND BACKGROUND

Contemporary observations regarding cities as the engines of the global economy (Dobbs *et al.* 2011; Glaeser 2011) are hardly surprising. Cities are highly significant nodes in the multiple interacting webs of global material cycles. They are the focuses of concentrated, intensively manipulated, and deeply intertwined flows of resources, all required to sustain the social, economic and industrial metabolisms of the city (Villarroel Walker & Beck 2012). In general, these flows of materials-energy within the city, its various infrastructures, and in the surrounding urban environment, such as a watershed, convey indications of resource-use inefficiencies and ineffectiveness in the city's economy and, therefore, the global economy. Self-evidently, in this general sense, we should view the city's metabolism as intrinsically multi-sectoral, i.e., not merely a matter of the water sector.

More specifically, many materials enter the city as foodstuffs (bearing carbon (C), nitrogen (N), phosphorus (P), and so on). Of these, those materials not consumed by citizens will end up as what we readily recognize as fluxes of municipal refuse and solid waste. Those materials metabolized after human consumption are then shed as our biological residuals, generally mixed with water – for the purposes of conveyance – to become fluxes in municipal wastewater. Consequently, re-configuration of the technologies and unit processes in the city's wastewater infrastructure is today the subject of very considerable interest, in particular, from the perspective of resource recovery

(Larsen *et al.* 2012). This too is not novel, as studies of the N metabolism of Paris from 1790 to1970 (Barles 2007a, 2007b) and the P metabolism of Linköping, Sweden, from 1870 to 2000 (Neset *et al.* 2008) clearly show. We are also well aware of the long-standing use of anaerobic digestion for recovering energy from the C-based materials in wastewater. Indeed, under the prospect of a changing climate, there is a burgeoning interest in culturing algae from the N and P nutrients in sewage, hence removing atmospheric CO_2, and subsequently generating various forms of (renewable) biofuels (Lardon *et al.* 2009; Clarens *et al.* 2010; Rittmann 2012).

From another general perspective –that of the rapid rise to prominence on the global political agenda of the so-called water-food-energy-climate security nexus (WEF 2011) – the need for the essential integration provided by multi-sectoral analyses is obvious, even though water in this nexus may (debatably) be considered *primus inter pares* (Beck & Villarroel Walker 2011).

Accordingly, we focus in this paper on how to re-engineer those flows of materials in the city (city-watershed) metabolism that are in some way key to preventing the city from becoming less unsustainable. We do so expressly across multiple sectors (water, food, energy, etc), at one and the same time. In addition, the economics of sparking the transitions towards greater sustainability are addressed (Jiang *et al.* 2012). Where can latent profits from eliminating resource-use inefficiencies or reducing ineffectiveness be made tangible, we enquire? How then might ecosystem services be enhanced and expanded in liberating these financial profits, while yet ameliorating threats from climate change (Beck *et al.* 2010; Beck 2011)? Consideration, however, of the structures of governance enabling sustainable change through such engineering and technological innovations (not stifling them), is largely the subject of work reported elsewhere (Beck *et al.* 2011, 2012).

THE MULTI-SECTORAL SYSTEMS ANALYSIS

The kinds of questions motivating the present analyses are set out below. To provide a more complete appreciation of the wider social and economic framing of our program of work on Cities as Forces for Good in the Environment (CFG; Beck (2011); see also www.cfgnet.org), their expression is not confined to the terms of just the computational studies of the present paper:

(i) What strategies of re-engineering and what kinds of technological innovations might enable manipulation of the city's many material fluxes such that the city can be judged to be less unsustainable, more eco-efficient, and more eco-effective? Are there businesses already providing products and services that meet such opportunities, or do they imply a need for new start-up companies with a breakthrough technology? What types and sizes of market would there be for these new technologies?

(ii) Are there some innovations that are 'privileged', in the sense of being key to the attainability of multiple, cross-sectoral goals, or multiple societal aspirations in the wider context of sustainability (Beck 2011; Beck *et al.* 2011)?

(iii) Which innovations are likely to enhance, and which detract from, attainment of a greater social and economic sense of water-food-energy-climate security?

(iv) Given the multi-sectoral perspective of this paper, but looking somewhat beyond what can be reported herein, do institutional structures of municipal governance favor (or not) the prosperity of multi-utility service companies (or MUSCOs), i.e., businesses providing integrated services, typically across the water, waste-handling, transport, and energy sectors?

Beginning with a case study of the city of Atlanta, within the Upper Chattahoochee watershed in the south-eastern US (Beck *et al.* 2010, 2011), we have developed Multi-sectoral Systems Analysis (MSA) software for the purpose of analysing the metabolism of city-watershed couples, with a view to rendering this metabolism less unsustainable by appropriate technological innovations

(Villarroel Walker 2010). We have since extended our work to a second case study of London, UK. MSA presently accounts for the fluxes of five variables – water, energy, N, P, and C – through five economic-industrial sectors, namely, the water, energy, waste-handling, food, and forestry sectors. In essence, MSA combines the principles of Substance Flow Analysis (Brunner & Rechberger 2003) with a Regionalized Sensitivity Analysis (Osidele & Beck 2003), whose purpose (as demonstrated herein) is to identify which elements (parameters) of the model are key (and which redundant) in discriminating between whether a specified level of resource recovery is attainable or not, under gross uncertainty. In other words, to reiterate, our analysis is directed at answering questions such as this: Which specific material-energy fluxes through the city-watershed couple are key to the prospect of attaining increasingly ambitious community aspirations for urban sustainability? The same sort of question was previously addressed in Chen & Beck (1997).

In responding to such questions with MSA, crucial is our concern to identify and account for cross-sectoral impacts, i.e., the presence/emergence of synergies (and antagonisms) amongst innovations in one sector (e.g., water) with regard to the sustainability of performance in another sector, such as the energy or waste-handling sectors. Increasingly, we are becoming ever more familiar with these multi-sectoral interactions. The water-energy-climate nexus is one such manifestation (EPRI 2002; Kenway *et al.* 2011); the water-food-energy security nexus is another (WEF 2011); and multi-utility service companies (MUSCOs) – we might call them Multi-Sectoral Utility companies – are emerging to take advantage of cross-sectoral business synergies (Villarroel Walker *et al.* 2012).

CASE STUDIES

In 2010, about 5.45 M people were living in the Atlanta Metropolitan Area (AMA), which occupies roughly 22,000 km^2. The Greater London Area (GLA), in comparison, has a population of 7.8 M and occupies just 1,570 km^2. The population of Atlanta has grown by 100% since 1985, London's by 15%. Food consumption is estimated to be 0.6–0.8 tonnes per capita each year in the GLA and 0.8–1.4 tonnes per capita in the AMA. 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. 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 has been projected to increase from 20% in 1987 to 34% in 2010 (Hu 2004).

More specifically now, the intent of the analysis is to respond to the following question:

> Approximating the massively multi-dimensional notion of sustainability (Beck *et al.* 2011) by simply resource savings/recovery, which features and technologies of the water sector are key/redundant in attaining stepwise progressively more ambitious performance targets for (a) water use reduction, (b) energy ratio increase, i.e., the ratio of an increase in energy generation relative to any reduction in energy consumption in the water sector, (c) N recovery, and (d) P recovery?

Four promising, candidate innovations in the water sector are assessed (at assumed rates of eventually 100% market penetration): (i) urine-separating toilets (UST); (ii) pyrolysis of sewage sludge (PSS); (iii) algal (biofuel) technologies for application in wastewater treatment (AWW); and (iv) consolidation and co-treatment of organic (food) waste through sewer transport (COW). Benefit streams arising from these innovations – even though they are interventions *solely* in the water sector alone – are accounted for as accruing across *all* five economic sectors in the MSA.

Tables 1 through 3 present the results of applying the MSA-RSA procedure to the Atlanta and London case studies. Tables 2 and 3 list those features (F1, F2, F3, …, F13, F14) — comprising natural, technological, or social features – found to be key according to the Regionalized Sensitivity Analysis

Table 1 | Key constituent technologies and features of the multi-sectoral metabolisms (of both Atlanta and London) for reducing water use, improving the energy ratio, and nutrient recovery

ID	Description of System's Features
F1	Water supply leakage
F2	Inflow/infiltration to sewer network
F3	Urine separating toilets (UST)[a]
F4	Diet and nutrient content in bodily waste
F5	Pyrolysis of sewage sludge (PSS)[a]
F6	Wastewater treatment (nutrient removal performance)
F7	Algae production in wastewater effluent (AWW)[a]
F8	Consolidation of organic waste (COW)[a]
F9	Water use by domestic/residential users
F10	Water use by commercial users
F11	Water use for coal-based power generation
F12	Water use for natural-gas-based power generation
F13	Direct energy use for water supply
F14	Industrial discharges to the sewer network

[a] Includes degree of implementation and separation efficiency or process conditions.

Table 2 | Summary of RSA results associated with Atlanta for achieving a set of suggested targets

							Nutrient recovery							
Water use reduction, %			Energy ratio increase, %				tonnes N/a × 10^3				tonnes P/a × 10^3			
5	10	15	20	50	100	150	2	4	8	12	0.5	1.5	3.0	5.0
F1	F1		F2	F2	F2	F2	F2		F2		F3	F3	F3	
F3	F3		F3		F3		F3	F3	F3	F3		F4	F4	F4
F9	F9	F9	F5	F5	F5	F5		F4	F4	F4	F5	F5	F5	F5
F10	F10		F6	F6	F6	F6						F6		
F11	F11	F11	F7	F7	F7	F7								F7
		F12	F13	F13	F13	F13							F8	
				F14		F14								

[a] see Table 1 for nomenclature.

Table 3 | Summary of RSA results associated with London for achieving a set of suggested targets

							Nutrient recovery							
Water use reduction, %			Energy ratio increase, %				tonnes P/a × 10^3				tonnes N/a × 10^3			
5	10	15	20	50	100	150	2	4	8	12	0.5	1.5	3.0	5.0
F1		–	F2	F2		F2	F2	F2		F2	F2		F2	F2
F3	F3				F3		F3	F3	F3	F3	F3	F3	F3	
F9	F9		F5	F5	F5	F5		F4	F4	F4			F4	
F12	F12		F6	F6	F6	F6	F5				F5	F5	F5	F5
			F8	F8	F8	F8				F6			F6	
				F9							F7			
			F13	F13	F13	F13								F8

[a] see Table 1 for nomenclature.

(RSA) in respect of discriminating whether a given performance aspiration is reached or not. Table 1 provides the corresponding definitions of these features, amongst which F3, F5, F7, and F8 are the four candidate water-sector (technological) innovations. The results of Tables 2 and 3 refer respectively to the Atlanta and London case studies. They are to be read as follows, for example (Table 2, 5th column): for a 50% increase in the energy ratio for the water sector of Atlanta, features F2, F5, F6, F7, F13, and F14 are found to be key in discriminating whether behavior is above or below that threshold.

Put simply, the MSA is able to identify which of the candidate technologies, together with other features (such as, for instance, citizens' diets, water supply leakage, industrial discharges to the sewer network), are key to, say, reducing water use by 5%, then 10%, and up to 15%, or recovering 1.5, 3.0, or as much as 5.0 thousand tonnes P per annum. In other words, while comparing the similarities and differences of the potential for Atlanta and London to engage more aggressively in resource conservation and recovery, it is also possible to draw conclusions about which technologies/features become crucial as sustainability targets are made progressively more ambitious.

INTERPRETATIONS AND DISCUSSION

We find, first, that UST is the single innovation (feature F3, in Tables 2 and 3) consistently of critical significance across all the savings/recovery targets – and for both Atlanta and London. It is therefore what we could label a 'privileged' candidate innovation. If the targets of Tables 2 and 3 were instead the plural and contested visions (for a more sustainable future) of the several social groupings within the relevant community of stakeholders, UST would offer the promise of not necessarily foreclosing on any of these distant societal aspirations, even though current policy for the immediate future might essentially be pursuing a path towards just one such vision (Beck *et al.* 2011, 2012). However, while UST might look like a most promising innovation on the above largely environmental basis, it overlooks the degree to which changes to basic household plumbing and urban residuals conveyance will bring about social disruption, just as it overlooks the economics (and carbon-footprint) of any associated urban infrastructure re-construction and adaptation.

Second, the technologies/features critical to attaining the targets for N recovery are broadly similar, again irrespective of whether one is considering Atlanta or London, yet they are sensitive to the dietary choices and preferences of the two populations (feature F4). The uncertainties notwithstanding, there is a good potential in the case of London to recover upwards of 25,000 tonnes N per annum (tonnes N/a) by 2050 (Villarroel Walker *et al.* 2012). In contrast, the scope for achieving more than just a 10% reduction in water use for London does not appear feasible, since there are no features identified for the 15% savings target (in Table 3). Otherwise, Table 2 reveals that pyrolysis of sewage sludge (PSS) is promising for both energy and P recovery, but not at all for N recovery. Again, in the case of London, recovery of some 12,000 tonnes P/a is a reasonable expectation by 2050, were PSS to be installed at 100% market penetration (Villarroel Walker *et al.* 2012).

Third, water consumption in the energy sector is key for reducing overall water abstractions. For Atlanta, water consumption by coal-based power generation is more critical than that based on natural gas (hence the presence of feature F11 in Table 2, under 'water use reduction'). For London, the latter is key, as indicated by feature F12 under 'water use reduction' in Table 3.

Fourth, we may note that, whereas algae biofuel production (feature F7) is significant in respect of Atlanta's ambitions for increasing its energy 'independence' for the water sector (Table 2), this technology is absent from the pool of key features with respect to London's future energy-ratio targets (Table 3). This has to do with complex interactions, and notably antagonisms (in the London context), amongst: the degree of centralization/de-centralization of sewerage and sewage collection (given the extent of septic tank use in Atlanta); the amounts of nutrients available in sewage for recovery through

UST; hence the amounts available for supporting algae generation when such UST-directed nutrient recovery is also in place.

Finally, we know from prior experience (Chen & Beck 1997) how it is dangerous to promote one form of technology over others, when technologies are simply assessed in splendid isolation, cut away from the complex webs of the many other technologies that make up the whole of an urban infrastructure. For instance, it may not be that membrane technology is universally ‘sustainable’, dramatic though the advances in this have been in the past two decades or so (Frenkel & Lee 2011). While herein we have broadened substantially the basis on which the promise of a technology can be identified and assessed (within the seamless whole of the multiple strands of infrastructure), the RSA procedure is nevertheless technically a ‘one-dimensional’ form of (statistical) analysis. It fails to identify those technologies/features that are only vital provided other equally vital technologies are present elsewhere in the system, i.e., there is a co-dependency (indeed a synergy) amongst two or more such features (Chen & Beck 1997). There are, however, computational and statistical procedures allowing one to elucidate these higher-dimensional dependencies (Osidele & Beck 2003).

BENEFITS (TO WHOM) AND COSTS (TO WHOM)?

Estimates of the potential financial benefits of achieving the performance aspirations of Tables 2 and 3 are summarized in Table 4. These are based on the US market, hence their expression in US dollars.

Thus, for example, the reduction of energy consumption in the water sector, i.e., for water supply and wastewater treatment – such that the energy ratio for Atlanta might be raised by 150% above its current value – could potentially amount to financial savings of $3.2 M each year. For London, they might amount to more than twice that, i.e., $8.7 M (in Table 4). In part, the difference is due to the fact that such improvement in the energy ratio is grounded in the differing current arrangements of the two metropolitan areas. London presently has a larger base-case energy ratio, because of its more extensive use of sewage sludge incineration (10% for London *versus* 2% for Atlanta), which therefore offers the prospect of higher potential benefits. Significantly larger potential economic benefits can be obtained from the recovery of phosphorus and nitrogen fertilizer (in both Atlanta and London). And yet markedly larger benefits (as cost savings) might follow from reductions in water use, but we should now examine in somewhat more detail what lies below these headline numbers.

For it is, of course, one thing to generate aggregate estimates of benefits (and costs) on a broadly undifferentiated system-wide basis, covering multiple sectors, utilities, and stakeholders, with their quite different and frequently strongly opposed aspirations. It is quite another to reveal who might bear the costs and who might reap the rewards of making the ‘transition’ towards the more ambitious

Table 4 | Potential annual economic benefits of each performance aspiration in millions of US Dollars. Figures in the second row are for London, when these differ from those of Atlanta — the water and energy targets are relative (percentage) changes, hence a function of differing initial (base-case) conditions for the two metropolitan areas

							Nutrient recovery							
Water use reduction, %			**Energy ratio increase, %**				**tonnes N/a × 10^3**				**tonnes P/a × 10^3**			
5	**10**	**15**	**20**	**50**	**100**	**150**	**2**	**4**	**8**	**12**	**0.5**	**1.5**	**3.0**	**5.0**
50	101	151	0.4	1.1	2.1	3.2	2.5	5.0	10.1	15.1	1.7	5.2	10.3	17.2
32	64	–	1.2	2.9	5.8	8.7								

[a] Values considered the following information: U.S. farm prices per ton for Urea fertilizer (46% N) and Super Phosphate (46% PO_4) are about $526 and $633 respectively (data from USDA); electricity price for industrial users is 6.8 cents per kWh (data from EIA); average U.S. residential water cost of $1 per cubic meter (averaged data from www.circleofblue.org), assuming an industrial water rate is 30 per cent less than the public supply water rate.

[b] Estimated as average total savings in the electricity bill.

sustainability (resource-recovery) targets of Tables 2 and 3. At this more disaggregated level, therefore, Table 1 shows that features F9, F10, F11, and F12 distinguish respectively amongst water use by domestic/residential consumers, commercial users, coal-based power generation, and natural-gas-based power generation. The financial benefits associated with the reduction of water use in Table 4, therefore, are benefits accruing collectively to *just* the two groups of domestic and industrial/commercial users. The costs (and savings) attaching to acquiring water for power-station cooling may be very different from those of the domestic and industrial users, since such water is clearly not supplied by a water utility. Accordingly, any financial benefits to the power generators resulting from savings in water consumption have been omitted from Table 4.

Returning to the macroscopic level of Table 4, the benefits listed under the energy ratio increase, N recovery, and P recovery categories should be returned to the water utility, in principle, since it is the enterprise introducing the various technological changes leading to the generation of these benefits. The benefits of water use reduction, however, are those of the consumers of the water, not the utility supplying the water. In more detail, however, and in London, for example, there are just three wastewater treatment plants where the energy ratio, nitrogen recovery, and phosphorus recovery can be beneficially improved, yet literally millions of household water users, amongst whom the cost savings in water use reduction are to be distributed. Otherwise, we note that, in Atlanta, average domestic water consumption per person is almost 2.5 times that in London, hence the greater benefit (Table 4) in the former for each percentage-point reduction in water use: total savings of $10 M (or $1.9 per person) per annum for each percentage-point reduction in Atlanta; $6.4 M (or $0.8 per person) per annum in London. If, therefore, a household of three individuals was able to reduce its water consumption by 10% – from the current, respective, local average rate of water use – it would save $57 annually in Atlanta and $24 in London. Accordingly, we can begin to discern the magnitudes of the incentives for making any change towards improved city-wide resource-use performance.

To be able to have estimates of the distribution and sizes of costs and benefits amongst these several stakeholders (water utility, power generators, other industries/commerce, and householders), would surely have a bearing on how they would negotiate with each other in building (or dismantling) the social legitimacy of the policy and technology options necessary for realizing the various target performance ambitions of Tables 2 through 4 (Beck *et al.* 2011).

CONCLUSIONS

The Multi-sectoral Systems Analysis (MSA) embraces considerations of nutrient (C, N, P) material cycles, together with those of water and energy, in order to study the role of engineering and re-engineering urban infrastructure in improving the sustainability of city-watershed systems, specifically for the Atlanta Metropolitan Area, USA, and the Greater London Area, UK. The MSA was designed expressly to assess such cross-sectoral interactions, both their synergies and their antagonisms. When coupled with the RSA procedure, MSA is capable of identifying those technological domains that might be key for achieving the various and collective goals of water use reduction, energy independence in the water sector, and nutrient recovery. We are well aware, however, of the questionable reputation of procedures of technology assessment and foresight, at least when it comes to ‘picking the winners’ of potential breakthrough technologies (Miles 2010). Nevertheless, the kinds of insights generated with the MSA should prove of significant benefit for those water utility companies well positioned to emerge as future multi-utility entities, able to provide services in multiple infrastructure sectors, hence to open up associated business opportunities for correspondingly increased revenue.

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