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Re-engineering cities as forces for good in the environment

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Previous simulation studies, using a case study of the city of Atlanta within the Upper Chattahoochee catchment, Georgia, USA, have shown how it is possible to re-engineer the water infrastructure of a city so as to restore aquatic ecosystem services in a catchment. The results also suggest that such a re-engineered infrastructure might even enable the city to act as a force for good in its environment. Assessing the sustainability of these prospective engineering transitions depends not only upon matters such as the urban ecological footprint, but more centrally on the concept of a system's spectrum of environmental perturbations and on computation of this spectrum for pre- and post-city states. This paper begins by discussing the core concept of the city as a force for good (CFG) and defining the attributes and vital role of the unfamiliar measure of 'spectrum'. Continuing with the case study of the Atlanta–Chattahoochee city–catchment system, an improved assembly of simulation sub-models was constructed in order to accommodate a change in climate, specified essentially as the difference between a 20-year average of annual precipitation variations across the Chattahoochee catchment for the years 1974–1993 (observed past) and 2020–2039 (forecast future). The outcome of this test is that the sustainability of previously preferred strategies for re-engineering of city wastewater infrastructure in pursuit of CFG is climate-insensitive (i.e. robust under climate change). However, climate change as such has been narrowly and rudimentarily articulated. The paper touches upon assessments geared to the behaviour of the city–catchment system at the margins (extremes) and looks forward to extensive subsequent studies designed to explore these matters much more fully.

1. INTRODUCTION

In April 2008, the *Sunday Times* ran a banner headline over a photograph of rural England asking whether this might not be 'Just the spot for a new Milton Keynes' (Oakeshott, 2008). The biodiversity of present-day Milton Keynes was reported to be better than that of the pre-existing (non-urban) environment of the Bedford–Ouse catchment, upon which the new city had been developed, beginning some three decades ago. The focus of this paper is on conceiving strategies for making cities less unsustainable – ideally, in fact, strategies for enabling cities to become a force for good in the environment, or CFG for short (Beck *et al.*, 2010). In the case of Milton Keynes, there is a hint of what the city as a force for good could be all about.

One of the metrics for thinking through this notion and for gauging what CFG might constitute is that of the spectrum of variability (or 'pulse') in the hydrological, material and energy fluxes associated with a city–catchment system (Beck, 1996, 2005). This somewhat unfamiliar gauge of sustainability – environmental benignity of action within triple bottom line (TBL) accountancy (Elkington, 1998) – makes the same appeal to anthropomorphism as do the more familiar metrics of the city's ecological footprint (Rees and Wackernagel, 1996) and its metabolism (Bai, 2007; Barles, 2007; Wolman 1965). Unfamiliar though the idea of a pulse-spectrum may be (to be elaborated shortly), it has been essential to the conception of CFG (Beck, 2008; Beck *et al.*, 2010).

Climate change will increasingly influence the behaviour of cities, their infrastructure, the surrounding environments and, of course, individuals (Capon and Hanna, 2009). The central concern of this paper is therefore that of exploring how the pulse of the city–catchment system reflects these influences of climate change and whether such a metric might be especially insightful in shaping policies for re-engineering urban infrastructure in a more sustainable manner and, in particular, for CFG.

Insofar as CFG is inspired by the challenge of turning on its head the popular perception of cities as environmental 'bads', so it might in due course become the case that a man-induced (and generally unwelcome) changing climate may even enhance the city's opportunities to act as a force for good in its environment. Perish the thought, might many exclaim. There is talk of 'climate proofing' countries and of 'living with water' in a less combative manner (Kabat *et al.*, 2005). However, there is also inspiration in harbouring the ambition, without naivety, to go beyond these aspirations. Revealing and exploring this potential for working *with* a changing climate – while not forsaking opposing it, actively combating or passively coping with it – should be more readily enabled through the gauge of a pulse-spectrum than through the more familiar metric of ecological footprint. It is also significant that the former is aligned more with the principle of eco-effectiveness (McDonough and Braungart, 2002) than with that of eco-efficiency, again, better known for its attachment to analyses of footprints.

Given the unfamiliarity of this notion of pulse-spectrum, however, we begin by defining and explaining it more fully.

1.1. Viewing sustainability through the lens of disturbance spectrum

Footprint and metabolism gauge sustainability largely according to essentially static snapshots of the extent to which a city's metabolism appropriates resources or distorts the global fluxes of materials. In contrast, the notion of pulse-spectrum is essentially about variability over time, just as is the changing climate itself. We have the kinds of natural capital and ecosystem services found previously in a catchment – in principle, prior to the arrival over geological time of human settlement, agriculture, the city and so forth – because those ecologies were themselves fashioned over the millennia by the decadal, annual, daily, hourly variations in perturbations of their collectively co-evolving environments, including those perturbations arising from climate and the weather (Grossman *et al*., 1990, 1998; Naiman *et al*., 2002; Odum *et al*., 1995; Poff *et al*., 1997, 2003; Reice *et al*., 1990).

Some of the ramifications of these interventions of man in nature are obvious. For example, the creation of dams and impoundments tends to subdue the fast-acting high-frequency components of a catchment's hydrological disturbance spectrum (downstream of the dam) and accentuate the slower, lower-frequency fluctuations. Importantly, 'frequency' here is intended to convey a sense of the speed of changes and variability, as in a Fourier series expansion, or in analysing the dynamic behaviour of electrical and control engineering systems, *not* the frequency of occurrence of an event. In the limit, therefore, temporal invariance, or constancy in a signal, is technically equivalent to a sinusoidal oscillation with an infinitely long period.

The introduction of impervious land surfaces and artificial conduits for removing stormwater from the densely populated spaces of cities tends contrastingly to shift some of the power in the disturbance spectrum from the lower to the higher frequency components. In respect of both stormwater and foulwater sewerage and treatment, it has been argued (Beck, 2005) that such a concentration of disturbance components towards the high-frequency end of the spectrum has engendered a greater fragility and vulnerability in the behaviour of the city–catchment couple. If the dams of stream impoundments are used for hydroelectric power generation, tailored to the demands of socio-economic activities in the city, daily, weekly and seasonal oscillations in downstream flows will become yet more pronounced. All in all, however, we can be reasonably confident that the aquatic ecologies of rivers and catchments did not evolve historically under the pressure of these altered facets of the disturbance spectrum.

The hypothesis, then, is that the form of the disturbance spectrum has something to do with the quantity and quality of natural capital and ecosystem services in a city's catchment. This is rarely expressed in the perhaps unfamiliar terms of a frequency spectrum, but it is clearly apparent in what stream ecologists refer to as 'environmental flows' (Arthington *et al*., 2006). Indeed, prescriptions for manipulating impoundment releases intended to restore some of the integrity and functions of previously existing aquatic ecosystems and fish assemblages make this abundantly clear, albeit in the accompanying time-domain representation of Figure 1 (Richter *et al*., 2006). The prescribed temporal template of flow variations throughout the year, here specifically for the heavily impounded Savannah River (Georgia, South Carolina, USA), can be visualised as comprising various combinations of archetypal pulses (of lesser or greater duration). Their purpose is to compensate for the distortions wrought in the spectrum of streamflows by the civil engineering interventions of the impoundments. The same principles of generating environmental flows, founded upon indicators of hydrologic alteration (IHA), are central to the recent work of Acreman *et al*. (2009) on achieving the good ecological status of water bodies required under the European Union water framework directive.

Since a changing climate so obviously affects hydrology, precipitation and streamflows, something of the complexity of assessing the intermingling of CFG with such a prospect can already be discerned.

1.2. The essential challenge

Elucidation and assessment of other consequences of man's interventions in nature – according to this metric of pulse-spectrum – are less immediately self-evident, in particular for attributes other than streamflow, such as concentrations and

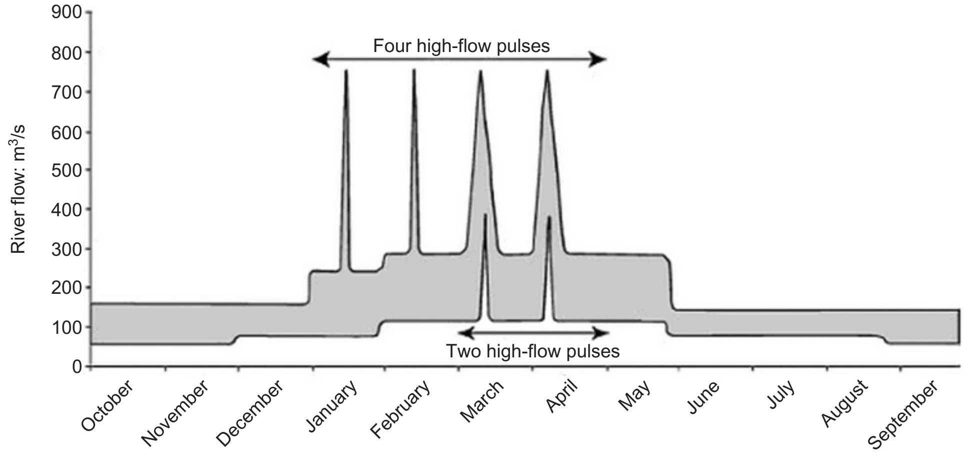

Figure 1. Template of annual streamflow variations required to restore and maintain appropriate fish assemblages in a river whose natural hydrological regime has been significantly distorted by impoundments and other civil engineering interventions (reprinted with permission from Richter *et al*., 2006).

loads of nutrients (nitrogen, phosphorus and so on). It is rather difficult, in fact, to reason through the nature of these consequences – and the steps to be taken to counter and compensate for them – in the absence of some supporting simulation studies (hence their essential role herein). Yet it is decisively this metric of pulse-spectrum – this means of encapsulating something of the environmental benignity of sustainability – through which we have been able to articulate the notion of CFG. The essential challenge of CFG is therefore (Crutzen *et al.*, 2007):

(*a*) How can a city's water infrastructure be re-engineered to restore the natural capital and ecosystem services of the nature that occupied the land before the city?
(*b*) How can urban infrastructure be re-engineered to enable the city to act as a force for good, deliberately to compensate for the ills of the rest of man's interventions in nature, such as, for example, the non-urban structures of dams and diversions for agricultural irrigation?

More of the essence of what is needed can be grasped from the following caricature of an exhortation: given an agriculturally stressed catchment, build a new city to restore its well-being! The *Sunday Times* was thus not altogether spot-on about CFG. It used too pleasant a picture of rural England, which many of us would have thought quite all right as it was – not broken nor in need of fixing. But this art of journalism was surely well put to the purpose of giving us pause for further thought.

A first response to the kinds of questions above, essentially in the absence of considerations of climate change, has already been developed (Beck *et al.*, 2010) and its results will be set out in Section 2 as the base case for the present study. As it turns out, this 'oversight' has been fortuitous for the present purposes, because it enables us now to pose the questions of 'engineering sustainability in the face of a changing climate' in a sharper fashion, as follows:

(*a*) Relative to the prior reference case, to what extent is the pursuit of CFG undermined, or aided, under the prospect of a changing climate?
(*b*) Will substantially different forms of technology and paths of infrastructure re-engineering be needed, for example ones that are less risk-prone, more ecologically resilient *sensu* Holling (1986, 1996) (see also Amin, 2001)?
(*c*) Can these be introduced so as to enable the city to become ever better attuned to adapting (or co-evolving) in the face of a changing climate?

These concepts of, first, CFG and, second, working *with* a changing climate to enhance the original challenge of CFG itself, have their intellectual roots in the ideas of McDonough and Braungart (2002): of eco-effectiveness or of 'waste equals food' and the sense this conveys of restoring, mimicking or improving the given natural endowment of sophisticated and intricate global cycles of materials. CFG and a climate-improved CFG may not be achievable – they have the air of 'missions impossible' about them. But the challenge should be inspiring and enduring. While the original block of a recalcitrant, trans-scientific problem might ultimately not be solvable, it is more than likely that interesting, novel sub-problems – that *are* solvable – might nevertheless be chipped off as fragments from the originally specified block. And they would be 'novel' in the sense of never otherwise having been discovered in the absence of conceiving of the 'mission impossible' in the first place.

With the challenges thus expressed, the paper now goes on to summarise the reference base case of re-engineering city infrastructure in pursuit of CFG (Section 2) and set out the terms and conditions for computational experimentation with the notion of climate-improved CFG (Section 3), before presenting and discussing those results specifically for the hypothetical case study of the Atlanta–Chattahoochee city–catchment couple (Section 4). These challenges, however, are newly formed. They are unrefined, if not seriously flawed. What follows is as much an opportunity for learning about the nature of the challenges as it is for generating provisional responses to them.

2. THE CITY AS A FORCE FOR GOOD – ABSENT THE FOCUS ON A CHANGING CLIMATE

2.1. Case study

The focus of this research (i.e. CFG) currently rests in large part on a case study of the city of Atlanta within the catchment of the Upper Chattahoochee River, Georgia, in south-eastern USA (Figure 2). The challenge is a worthy one. Atlanta stands head and shoulders above all the other cities cited by Newman (2006) in respect of car fuel use per person.

Lake Lanier, located just to the north of Atlanta and lying between the development corridors of interstate highways I-75 and I-85, is the single-most important impoundment in Georgia and the subject of intense public and policy scrutiny (Beck *et al.*, 2002). Created in 1958, the lake occupies 154 km^2 and serves as a multi-purpose impoundment, providing flood control, hydro-electric power generation, water supply, recreational resources and environmental requirements. In this part of the Upper

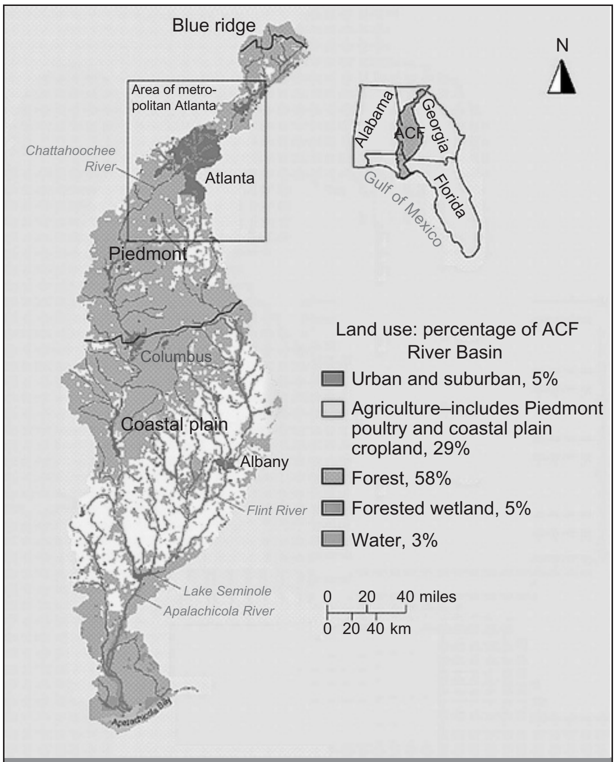

Figure 2. Metropolitan Atlanta and the Chattahoochee catchment in south-eastern USA

Chattahoochee catchment, there are several major interventions of man in nature to contend with, relative to what must have existed prior to European settlement: agriculture (and silviculture); impoundment of the river (Lake Lanier); the use of Buford Dam on the outflow from Lanier for hydroelectric power generation; and the associated city of Atlanta. The effects of the altered flow regime, if not sediment and nutrient regimes, are palpable far downstream where the river discharges into Apalachicola Bay (Gulf of Mexico) and the changed balance of fluctuations between fresh and saltwater flows exerts a discernible influence over shellfish productivity (Wilber, 1992). It was indeed in the context of these coastal interfaces (in Georgia) that the celebrated ecologists of the Odum family first wrote aptly – for our present purposes – of nature's pulsating paradigm (Odum *et al.*, 1995).

More specifically, the challenge of CFG becomes that of asking how the water infrastructure of metropolitan Atlanta might be re-engineered, over the generations, such that the city–infrastructure couple can be deployed to restore and enhance the ecosystem services deriving from the Chattahoochee catchment.

2.2. Reference response to the challenge

Various scenarios can be imagined for what might constitute CFG, according to the inevitable plurality of stakeholder aspirations for the future (Beck, 2008). One, in particular, has to do with the recovery of a perfect fertiliser from the wastewater infrastructure of the city. This was 'well known' in former times (Barles, 2007), then superseded and somewhat forgotten under the imperative of improving and protecting public health in the city, yet resurrected in the great sustainability debate of the 1990s. Paraphrasing the work of Otterpohl *et al.* (1999)

> Once the public health of city-dwellers has been secured, the purpose of the urban wastewater infrastructure is to keep the soil fertile.

Given the present, predominantly water-based, centralised tradition of sewerage and wastewater treatment in cities largely of the global north, how might one systematically and incrementally replace the unit processes in the hull of this existing infrastructure? Could these incremental transitions lead to a wastewater infrastructure 75 years hence, say, whose primary product is a perfect fertiliser, to be returned directly to the land for agriculture, together with the byproduct of crystal-clear water? Coming thus to the nub of the notion of CFG, once this nutrient product is available, could it also be used deliberately to reconstruct the pre-city spectrum of nutrient disturbances in the catchment, hence enhance the quantity and quality of catchment ecosystem services? The hypothesis would be that the nutrient spectrum influences these services in some discoverable and expressly manipulable way, as in the companion notion of environmental flows (and Figure 1), but rather more speculatively for the time being.

Having evolved over the decades and centuries from the introduction of the water closet, the current paradigm of sewerage and centralised wastewater treatment can be called a 'mixed' strategy: water fulfils the essential function of the transport device (an alternative might have been a vacuum system or dry sanitation in the first place). On the downside of the city, therefore, the water and nutrient fluxes of its metabolism are comprehensively and utterly mixed. Since a large proportion of the nutrients in the biological residuals of citizens is conveyed in urine, one technological trajectory for re-engineering the currently less sustainable arrangement of comprehensive mixing is a strategy of 'source separation'. In other words, the intimate coupling between the water and nutrient metabolisms of the city is to be severed, unit-process by unit-process, step by step in time: from the very heart of the matter, as in changing the plumbing of households (or office blocks, etc.), to transport/conveyance between households and a treatment facility (typically, but not necessarily, through a sewer network) and on to unit processes for recovery and preparation of the fertiliser and the reclaimed water fluxes (typically at a centralised wastewater treatment plant).

In the city of Atlanta, the R M Clayton wastewater treatment plant processes the major part of the city's sewage. This plant, as most are, is located adjacent to a river (the Chattahoochee). If, therefore, source separation were to have been fully implemented, and if the strategy were to be to convey the nutrient flux to the neighbourhood of the existing R M Clayton facility (as opposed to alternative locations), a 'perfect fertiliser' would be available there, to be put to a purpose. The obvious purpose would be its onward conveyance into the agricultural infrastructure of the (Chattahoochee) catchment. A much less obvious purpose, but one prompted by the challenge of CFG – with its goal of restoring, even enhancing, catchment ecosystem services – would be to use the fertiliser to issue 'nutrient supplements' to the river from time to time. Imagining this, startling though it may appear at first sight, has been something conditioned upon much prior research on how to design and operate urban wastewater infrastructure for the purpose of managing transient water pollution events. That earlier research revived the relevance (there) of the electrical engineering notion of frequency spectrum and response. It also gave rise to a precursor concept of CFG, wherein the river might deliberately be 'vaccinated' by occasional discharges of 'muted pollution' from the city's wastewater infrastructure, to forearm the river's response against actual future pollution incidents (Beck, 1996, 2005).

Combining detailed simulation models of the Upper Chattahoochee catchment, from Buford Dam at the outlet of Lake Lanier to Lake West Point to the south of Atlanta, and of the R M Clayton treatment plant, as it is now and as it might in the future be re-engineered under the strategies of source separation and nutrient supplements, the results of Figure 3 were generated for the in-stream concentration of TP (Beck *et al.*, 2010). The parallel with Figure 1 should be self-evident. The simulated supplements of Figure 3 were issued in six installments, at times of persistently low streamflow over several days (and weeks) for a dry hydrological year (1986). The diurnal and weekly fluctuations in phosphorus concentration, especially evident during the supplement periods, result from the daily and weekly variations in the crude-sewage flow and composition, as well as the performance of the treatment plant. They do not derive primarily from any daily or weekly variations in streamflow as a result of flow releases upstream through Buford Dam for the production of electricity, although we know these effects are present.

Transformed from the time domain of Figure 3 to the frequency domain, Figure 4 reveals how the argument underpinning CFG and this first response to it have been developed. Specifically,

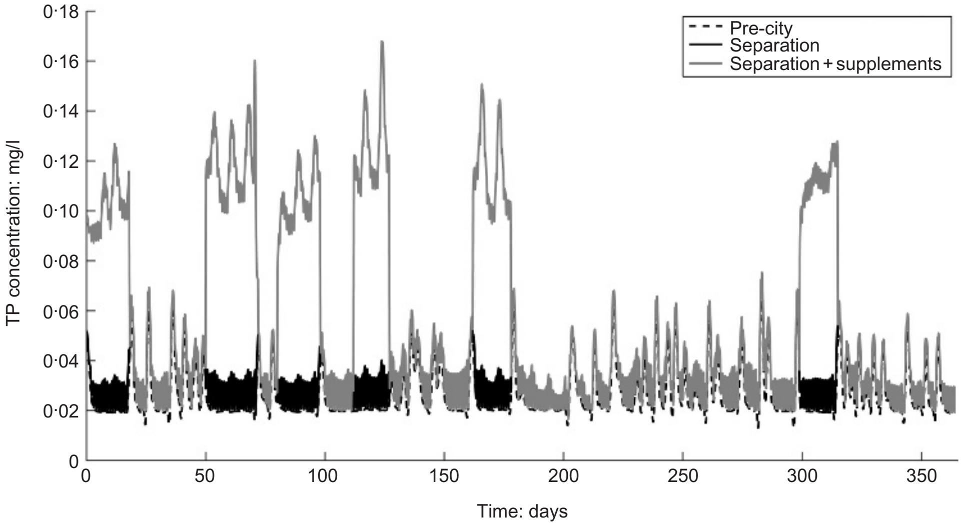

Figure 3. Simulated variations in total phosphorus (TP) concentration for 1986 in the Chattahoochee River immediately downstream of the discharge of the R M Clayton facility for conditions without the city (pre-city), for a basic source-separation strategy (separation) and the same strategy with nutrient supplements (separation + supplements). Note that all similar computational results presented in subsequent figures refer to this same spatial location in the city–catchment system

the spectra of Figure 4 are auto-regressive (i.e. AR(22)) spectra of the time series of Figure 3, with the AR order (22) identified from the Akaike information criterion (see Young, 1999). Such frequency-domain representations, or models, can be obtained in other ways. One important advantage of the particular approach adopted for Figure 4 is the smoothed character of its spectrum curves. We note that the best means of making the computations of Figure 4, for the purposes of CFG, are currently under investigation.

Summarised in each curve of Figure 4, therefore, is one measure of all the dynamic variability in the behaviour of the city–catchment system, where that measure enables comparative judgements to be made. The results of Figure 4 are confined in this instance, and throughout this paper, to fluctuations with a period of less than one year. They span the outcomes of five simulated scenarios for the catchment, only three of which are illustrated in Figure 3 (for clarity), while four are shown in Figure 4: conditions without the city (i.e. pre-city); those with the city and its current form of wastewater infrastructure (the status quo (or what is customarily called a ‘business-as-usual’ scenario)); and, between these two, the outcomes of two variations on the strategic theme of source separation, which are referred to here as basic separation and source separation incorporating nutrient supplements. Unit process configurations of wastewater treatment for the source-separation strategies can be found in Beck *et al.* (2010).

Recalling the introductory discussion of pulse-spectrum, a shift of the power distribution in the spectrum – away from the lower frequency components and towards the higher frequency components (towards the right-hand side of Figure 4) – is

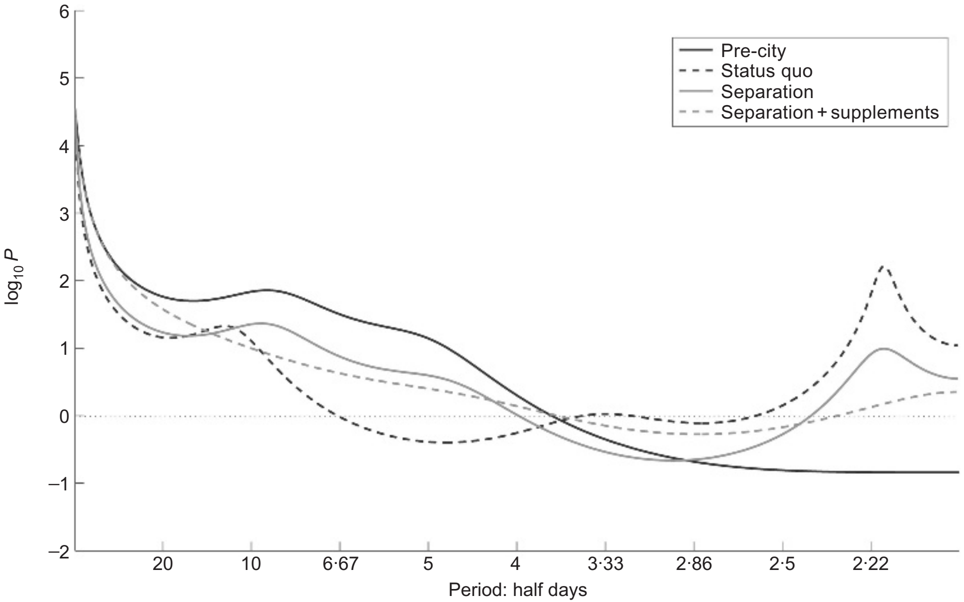

Figure 4. Frequency spectra for simulated time series of Figure 3 for variations in total phosphorus concentration for 1986 in the Chattahoochee River for conditions of the pre-city, the status quo, the basic separation strategy and separation strategy with supplements

apparent with progress from the pre-city status to the present arrangement. The present arrangement is also notable for its salient peak in the spectrum at the daily frequency and, on closer inspection, an accompanying peak at a weekly frequency. The strategies for re-engineering succeed in returning the shape of the spectrum towards that of the pre-city condition. In particular, source separation with nutrient supplements (shown in Figure 4) could be judged to have attained the furthest progress in that re-shaping, with its distinctively successful attenuation of the accentuated daily and weekly fluctuations of the status quo. These attenuations are the greater, moreover, as a consequence of issuing nutrient supplements. It is the broad pulses of Figure 3 – sustained over days and weeks – that are expressly responsible for this.

The strategy of 'source separation' was not conceived with climate proofing in mind, nor were any of its alternatives. They were all addressed to a somewhat differently oriented, and already ambitious enough, challenge (that of CFG). Since a changing climate is being anticipated, however, the promise of the strategy must now be examined for its robustness under this prospect, or conversely its enhancement. It is at least conceivable that the status of a re-engineering strategy, under a changing climate, might come to be judged even more sustainable than originally thought. With a view likewise to what follows, it is apparent from Figure 4 how simulation allows a metaphorical switching on/off of the presence of the city (a logical binary 1/0 facility). Assuming this is illuminating for our thinking in general about the broad ambition of CFG, the same *in silico* switching on and off of agriculture, impoundment of the river, generation of hydroelectricity and/or climate change/variability, are obvious further extensions and refinements.

The challenges of CFG and climate-improved CFG are conceptually immature. Similarly, encapsulating the whole of the rambling, massively complicated concept of sustainability in some 'operational' form is a continuing struggle (Beck, 2008). The work reported here will therefore certainly not be without limitations and pitfalls. Appendix 1 sets these out and indicates additional and future lines of research intended to lessen the present restrictions and avoid some of the pitfalls. In fact, Appendix 1 can be read as a formal statement of the networked programme of research on CFG.

3. INSERTING THE 'CLIMATE SIGNAL'

In an ideal world, we would be able to isolate the city, clear away the confounding elements of man's interventions in the nature of the catchment and proceed to examine solely the switching on and off of a changing future climate. For example, we would like to answer the question: how closely, under a changed, future climate, can the future city and its re-engineered infrastructure approach the pre-city conditions of the catchment? Or, better put, can strategies of re-engineering guide the behaviour of the catchment towards points on its trajectory to which it might have been evolving (into the future) in the absence of the city?

However, a moment's reflection, in which dawns the realisation of 'everything being connected inseparably to everything else', dashes any such hope. Much of the muddled mess of the situation as found in situ for the Atlanta–Chattahoochee system must be addressed as it is, but as unambiguously as possible. No clinically isolated, classical experimentation is yet feasible, even in the laboratory world of computer simulation. Nevertheless, presuming the need to isolate (at the very least) the nature of the relationship between engineering sustainability and a changing climate, the essential question can be phrased as: How is pursuit of CFG undermined or assisted by the prospect of a changing climate? At a more elementary level, and more specifically: How 'climate-sensitive' are the results of Figure 4, or alternatively those of Figure 3 – or, for that matter, those of Richter *et al.* (2006) in Figure 1?

Previous work (Beck *et al.*, 2010) necessarily dealt with (past) climate variability, albeit in a rudimentary manner, through use of a historically wet year (1973), an average or 'moderate' year (1995) and a dry year (1986, as in the results of Figures 3 and 4) – all after the construction of Buford Dam and Lake Lanier (in 1958). In passing, it should be noted that this research has yet to address the companion issues of temperature variability and climate warming. In south-eastern USA, these could have pronounced implications in respect of, for example:

(*a*) short-term, fast transient events ('thermal pulses') of urban stormwater runoff
(*b*) somewhat longer periods of warm weather ('heat waves') and their consequences for water-borne pathogen survival and propagation (Lipp *et al.*, 2002; McMichael *et al.*, 2006)
(*c*) seasonal variations in the microbial biochemistry of both wastewater treatment and in-stream processes, such as those of biological nitrification and de-nitrification.

An assessment of future hydrological conditions requires similar sampling points across the supposed (forecast) distribution of climate variability, for example very dry, shifted average and very wet hydrological years, or something more subtle such as a dry year with much more intense storm events. The Atlantic seaboard of the USA (which includes Georgia) is prone to hurricanes and their extreme precipitation volumes. These are quite capable of inundating the wastewater treatment infrastructure of both cities and (rural) confined animal feeding operations (Burkholder *et al.*, 2004; Novak *et al.*, 2007). The placement of cities and their heat islands, together with site-specific antecedent soil-moisture conditions, are known to influence the course of storm events, including the path of a tornado across the central business district of Atlanta in 2008 (Shepherd *et al.*, 2009). Ever since Hurricane Katrina and the inundation of New Orleans, the debate over the inter-relationship between climate and hurricane intensity has literally raged (Curry *et al.*, 2006; Mooney, 2007). Climate models have demonstrated some skill in reproducing rainfall aggregated to at least the daily duration, including auto-correlation at this scale. This in turn has lent credibility to the use of daily stochastic rainfall generators for simulating sequences of future rainfall (Kilsby *et al.*, 2007). The auto-correlation of rainfall outputs from climate models on long timescales, however, including inter-annual variation, is still questionable.

The purpose of the research at this early stage must therefore remain somewhat rudimentary: to assess how the 'migration' encapsulated within each corresponding pair of sampling points (e.g. from a (now) 'dry' year to a (future) 'very dry' year) alters the frequency spectra of Figure 4 and the time-domain results of Figure 3 (and Figure 1). Subsequently work would need to enquire whether, under uncertainty, the observed changes and sensitivities are significant and, if they are, what might be their implications for the central thrust of CFG, that is, attaining restoration (enhancement) of the natural capital and ecosystem services present in the catchment prior to the arrival of the city. However, studies of these matters go well beyond the scope of the present paper.

3.1. Computational set-up

The assembly of simulation models used to generate the previous results of Figures 3 and 4 (Beck *et al.*, 2010) has been significantly augmented for the present study.

(*a*) The previous boundary conditions of annual variations in the upstream flow and quality of the Chattahoochee River at Buford Dam (the outlet of Lake Lanier) were substituted by re-creating a pre-Lanier catchment. In effect, the results of Figure 3 were generated previously by simulating only that portion of the Upper Chattahoochee catchment downstream of Buford Dam. In the present study, the whole of the Upper Chattahoochee catchment was simulated as if neither Lake Lanier nor Buford Dam were in place, using again the popular HSPF catchment model (Bicknell *et al.*, 1997), driven in this instance by precipitation sequences (to be defined later). Concentrations of nutrients in streamflows upstream of Atlanta and the R M Clayton wastewater treatment facility were generated from the HSPF model. Combining the HSPF and Stand models (Zeng and Beck, 2003) to simulate stream channel flow and the behaviour of in-stream sediment and nutrient interactions has been discussed fully by Shi (2008), where evaluation of the catchment–channel model against (1995) field data for its present application was also reported.

(*b*) The previous boundary conditions of annual variations in the flow and quality of crude sewage influent to the R M Clayton wastewater treatment plant were substituted by use of the Environmental Protection Agency's SWMM model (US EPA, 2008) to account for the crude sewage resulting from more detailed simulation of urban runoff, the upstream combined sewer network, infiltration into the sewer and combined sewer overflows to the Chattahoochee, within four downtown sub-catchments of Atlanta (see also Jiang *et al.*, 2009). For the results of Figure 3, the influent crude sewage flow variations were previously generated in an elementary manner by simply correlating their variations with those (due to precipitation) in the streamflow of the Upper Chattahoochee River. In the present studies, SWMM was calibrated for the hydrologic year of 2006. Flows of water across the urban area of Atlanta were therefore generated (in part) in response to the same sequences of precipitation events used to drive the Upper Chattahoochee catchment model as a whole (as outlined in (*a*)). Concentrations of nutrients in urban runoff and infiltration into the sewer network were based on values listed in the SWMM user's manual (US EPA, 2008), while those in foul sewage fluxes drew upon the works of Larsen and Gujer (1996) and Herrmann and Klaus (1997). The behaviour of the R M Clayton wastewater treatment plant itself was simulated using the West® software framework (MfW, 2009), with extensive evaluation of the models against field data reported by Jiang (2007).

(*c*) For the purposes of simulating past behaviour in the Atlanta–Chattahoochee system, hydrologic years 1986 (dry), 2007 (very dry), 2003 (wet with several intense storms) and the average of 1974–1993 were employed (only the results of this last are presented here). This average annual flow sequence was generated using the corresponding average precipitation data of Cruise *et al.* (1999), which were also used to generate runoff, infiltration and combined sewer flows for the Atlanta urban area, as outlined in (*b*).

(*d*) Future flow boundary conditions under a changed climate were generated for the average of the (predicted) 20-year period of 2020–2039 (to be compared with the corresponding 20-year average of 1974–1993), again using the corresponding predicted precipitation sequences from Cruise *et al.* (1999).

4. RESULTS AND DISCUSSION

The annual simulated sequences of streamflows in the Chattahoochee as it passes the R M Clayton wastewater treatment plant are shown in Figure 5. The sequence for the past (1974–1993) shows two peak flows at around days 85 and 121. That for the future (2020–2039) reflects a single overwhelmingly

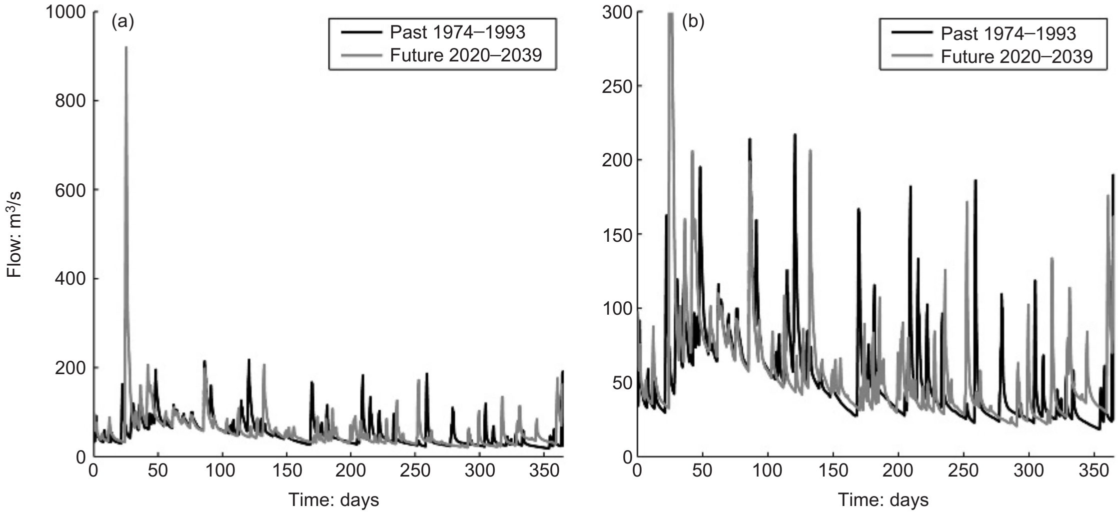

Figure 5. Annual cycle of streamflows in the Chattahoochee for average of observed past (1974–1993) conditions and average of forecast future conditions (2020–2039): (a) full range of variations; (b) truncated range (for clarity)

dominant, large event at about day 25, with two moderate events at days 85 and 134 that are more comparable with those of the past sequence. Given that these assessments of CFG are confined primarily to dealing with differences between average past and future hydrological conditions, it can be anticipated that the associated differences in the sustainability of re-engineering the city's wastewater infrastructure, between the absence/presence of climate change, will be correspondingly small. After all, the overall similarities in the average, annual streamflow variations of Figure 5 are predominant.

Discussions of the impacts of climate change, however, often focus on the margins (extremes) of behaviour. Had we been able to synthesise precipitation sequences for these extremes (i.e. very dry or exceptionally wet years), more substantial differences between past and future annual hydrological fluctuations might have been apparent. It is the years of drought and low streamflows, moreover, that more dramatically expose the sustainability, or otherwise, of a city's wastewater infrastructure. Nevertheless, the precipitation sequences taken from Cruise *et al.* (1999) and used to generate the streamflows of Figure 5 contain some significant differences (by chance, it is presumed) in the relative extremes of high-frequency (short-term) storm events, as already noted.

It is also worth noting that, once Lake Lanier and Buford Dam are removed from the catchment (as here), a more 'natural' simulated annual streamflow cycle is apparent, relative to observed flows post-impoundment, including during dry years (such as 1986, the conditions underlying Figure 3).

4.1. Overview: analysis in the time domain

In the time domain, the past and future hydrological (climate) regimes, coupled with the various scenarios for the status of the Atlanta wastewater infrastructure sub-system, lead to the results of Figures 6 to 9 for the annual sequences of in-stream total phosphorus (TP) concentrations. From Figures 6 and 8 it is apparent how the source-separation strategy is able to achieve better performance than the status quo of the city and its current wastewater infrastructure, as much under a future climate as with the past climate – at least as gauged by the index of lower in-stream TP concentrations.

The results of Figures 7 and 9 (past and future climates, respectively) correspond to those of Figure 3, in which performance is compared across the three scenarios of the pre-city, the basic separation strategy and separation with nutrient supplements. However, given that the results of Figure 3 were generated for a dry year, as opposed to an average hydrological year, using a quite different assembly for the city–catchment model, they cannot strictly speaking be compared with those of Figures 7 and 9 in matters of detail. One feature of Figures 7 and 9, nevertheless, is significantly different from that in Figure 3. Although again there are some six to eight pulses of nutrient supplements, these are issued towards the end of the year in Figures 7 and 9, under low-flow periods (as in Figure 3), but generally not towards the first third of the year. In other words, the choices of when to issue supplements to the river have taken a greater account of when the fertiliser recovered at the wastewater treatment plant would be more likely to be needed for onward transmission instead into the agricultural infrastructure of the catchment. These are still choices, nonetheless, based presently on full foreknowledge of when there is to be a low streamflow in the Chattahoochee.

In general, the following conclusions may be drawn from Figures 6 to 9.

(*a*) There is little, if any, discernible difference for any of the (city-infrastructure) scenarios between behaviour under the average past climate and behaviour under an average future climate, as already anticipated.

(*b*) According to the present measure of what constitutes environmental benignity of action (i.e. the temporal sequence of in-stream TP concentrations), the separation strategy with supplements might well be deemed somewhat unsustainable, since it elevates 'pollution' levels temporarily to those of the currently unsustainable status quo (comparing Figures 8 and 9, for instance).

(*c*) Judging sustainability of action is a subtle, complex and multi-dimensional affair – as if there were any need to be reminded of this.

4.2. Overview: analysis in the frequency domain of spectra

The principal focus of this assessment of what constitutes

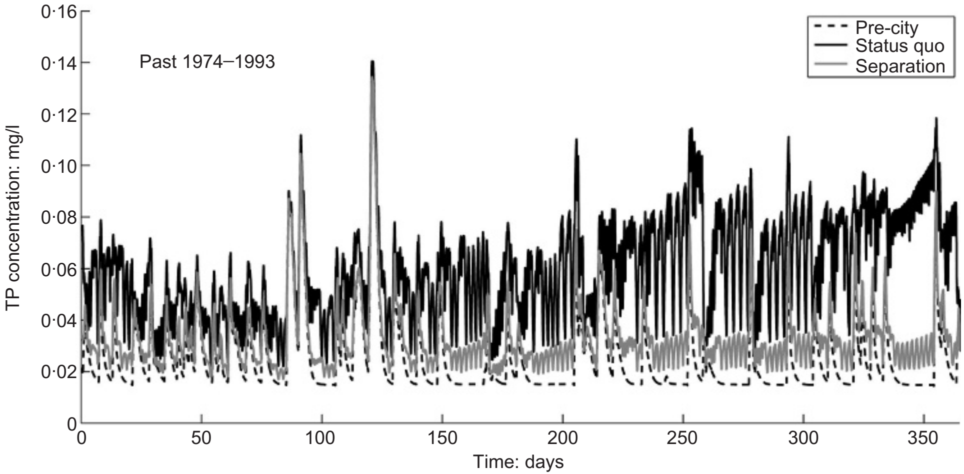

Figure 6. Simulated variations in total phosphorus concentration for the past average precipitation sequence (1974–1993) in the Chattahoochee River under the three scenarios of pre-city, status quo and the basic separation strategy

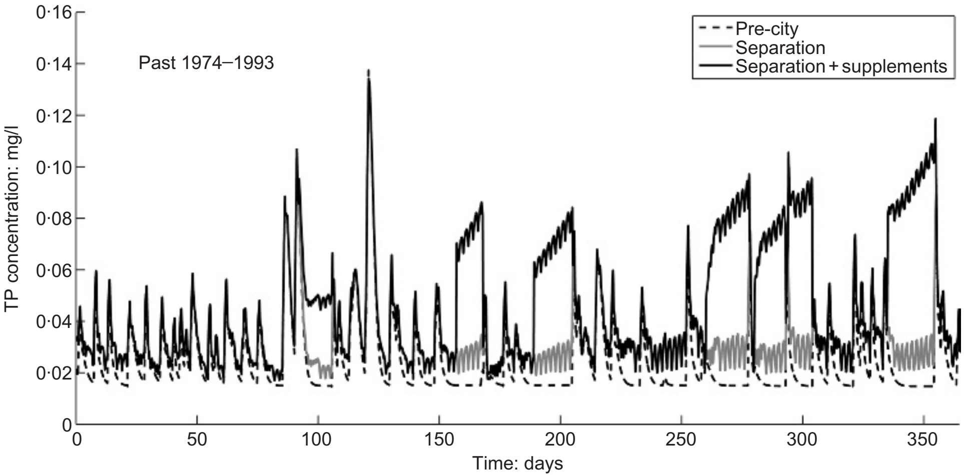

Figure 7. Simulated variations in total phosphorus concentration for past average precipitation sequence (1974–1993) in the Chattahoochee River under the three scenarios of pre-city, basic separation strategy and separation strategy with supplements

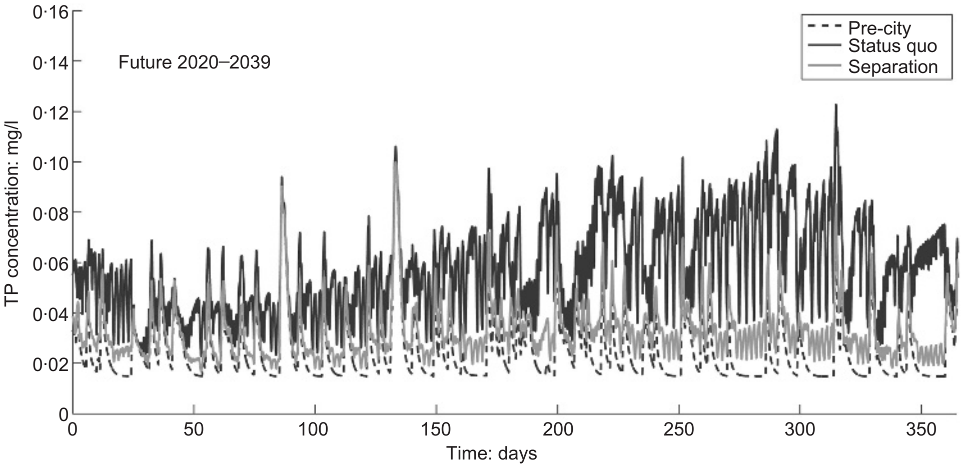

Figure 8. Simulated variations in total phosphorus concentration for future average precipitation sequence (2020–2039) in the Chattahoochee River under the three scenarios of pre-city, status quo and basic separation strategy

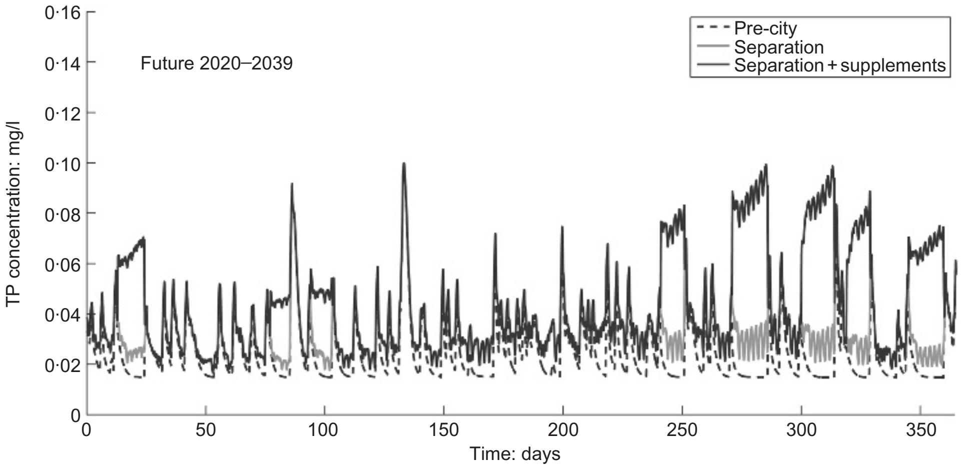

Figure 9. Simulated variations in total phosphorus concentration for future average precipitation sequence (2020–2039) in the Chattahoochee River under the three scenarios of pre-city, basic separation strategy and separation strategy with supplements

preferred strategies for re-engineering the wastewater infrastructure of cities – strategies indeed that might lead towards CFG – is cast in the frequency domain of the pulse spectra of the variations in TP concentrations (within the span of a hydrological year). These are shown in Figures 10 and 11.

One conclusion from Figure 10 is obvious. Differences between the respective past and future hydrological (climatological) years for all scenarios are small. Differences amongst the strategies of engineering and re-engineering for CFG are greater than those induced by any climate-driven changes in an average hydrological year (see Figure 11). This is substantiated by other

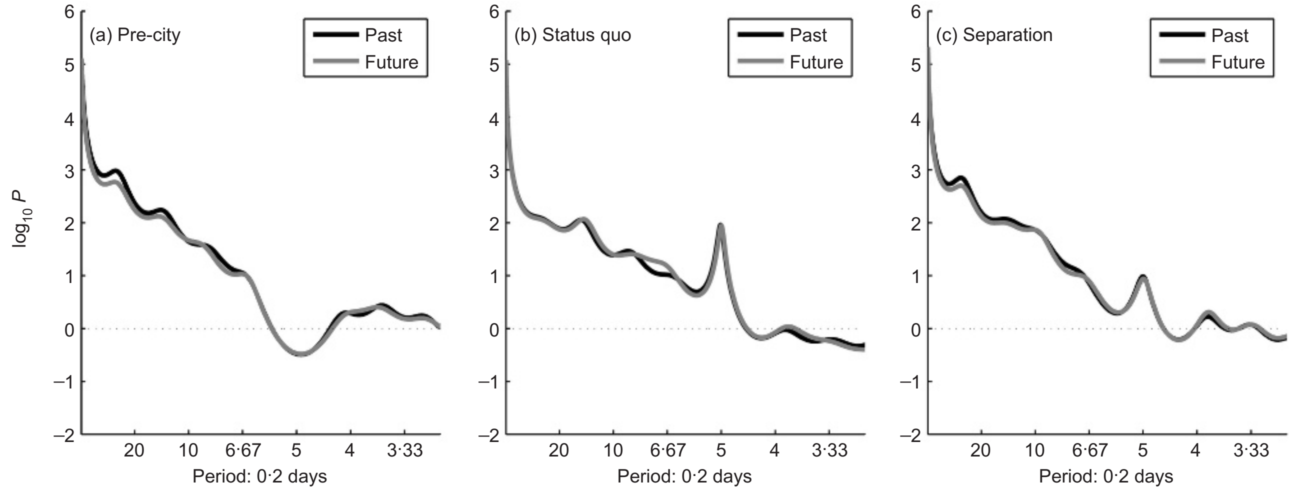

Figure 10. Frequency spectra for selected simulated time series from Figures 6 and 8 for variations in total phosphorus concentration for past and future hydrological (climate) regimes in the Chattahoochee River for: (a) past and future for pre-city; (b) past and future for status quo; (c) past and future for basic separation strategy

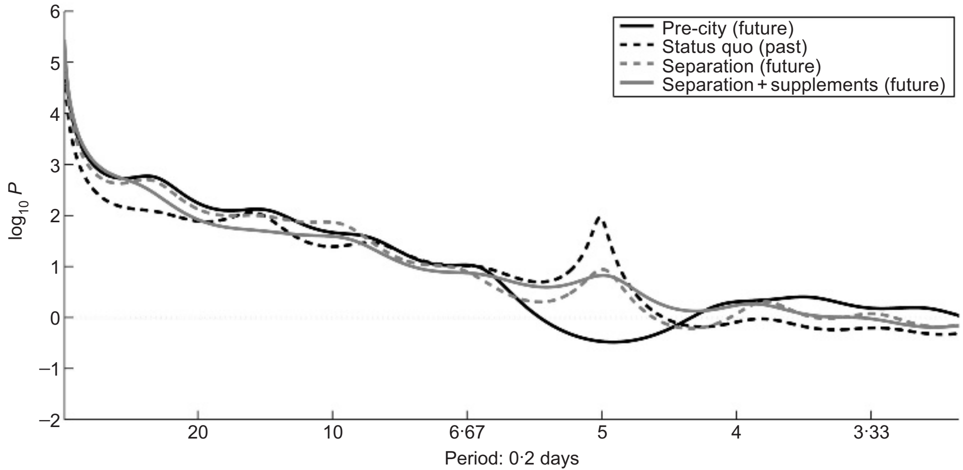

Figure 11. Frequency spectra for selected simulated time series from Figures 7 to 9 for variations in TP concentration for the pre-city scenario under a future hydrological (climate) regime in the Chattahoochee River, the status quo under the past regime and the basic separation strategy and strategy with supplements, both under a future hydrological regime

results for other separation strategies (not presented here). It is also substantiated by supplementary estimates of the ecological footprint of the status quo and future separation strategies for past and future climates. Following the procedure of Lenzen *et al*. (2003), and with attention restricted to the footprint of just the wastewater treatment plant alone, the current arrangement at the R M Clayton facility is estimated to have a footprint of 2751 gha (global hectares) under past average precipitation conditions. Rearrangements of the plant to accommodate separation and nutrient recovery reduce this footprint by some 6% under the same past (1974–1993) conditions. Under a future (2020–2039) precipitation sequence, footprints for both alternatives are increased by less than 2%. All these minor differences are due exclusively to changes in greenhouse gas emissions at the plant, which, of course, are only a small part of the overall city–catchment system being assessed more broadly through the metric of pulse-spectrum. To summarise, these strategies of source separation for CFG should be described as robust under climate change, albeit with such change as crudely defined in this paper.

Drawing upon the previous results of Figure 4 (dry year, 1986) and those of Figure 11, a second conclusion is that opting for source separation with nutrient supplements is to be preferred over the basic separation strategy – according to the index of pulse-spectrum. Adding in the policy of nutrient supplements enables the former, pre-city condition to be more closely approximated. Indeed, this conclusion appears robust under the variety of revised and improved simulations of past hydrological conditions (dry and wet) not reported in this paper. Figure 11 shows the differences in spectrum wrought by the introduction into the pristine catchment of the city with its conventional wastewater infrastructure, and gauges the extent to which the strategy with nutrient supplements is able to re-shape the spectrum under a *future* climate, back towards that of the *past*, as it existed prior to the arrival of the city.

Comparing the assessments in this complementary frequency domain (Figures 10 and 11) with those in the time domain (Figures 6 to 9), there is a *prima facie* case to be made for asserting the presence of greater, more succinct clarity about the former (quite apart from its undoubted novelty of perspective). In general, this may be yet more advantageous for assessments under uncertainty. In the present specific instance, for example, the strong inference to be drawn from the results of Figure 10 is clearly that a formal analysis of uncertainty might well render statistically insignificant the small differences induced in all of the scenarios by the introduction of the climate-change perturbation.

Once more, however, the importance of judging what is sustainable and what is not, under a multiplicity of perspectives, is not to be overlooked. Between just the time-domain and frequency-domain representations of the same results for the separation–supplements strategy (Figures 9 and 11, respectively), different stakeholders could come to sharply opposed judgements: encouraging and positive if they hold to the view through the lens of the pulse-spectrum (i.e. Figure 11); discouraging and negative if they trust the plots in the time domain, where the strategy could be said to lead to relatively more transient ‘pollution’ during the supplements (Figure 9).

4.3. Climate vulnerability of re-engineering transitions

The preceding results are clearly tending towards the conclusion that – on the basis of a change in climate narrowly defined according to 20-year *average* precipitation sequences – the strategies of source separation within a city’s wastewater infrastructure (with nutrient supplements) are robust (i.e. climate-insensitive). The second tranche of more comprehensive simulation results generated for the purposes of this paper (only a modest sample of which has been shown and discussed) confirms the viability of how CFG has previously been conceived (Beck *et al*., 2010). This is a conclusion conditioned, nonetheless, upon working primarily with the (anthropomorphic) concept of the pulse rate of the city–catchment system.

Exploration of behaviour at the margins (extremes) of the distribution, however, may well illuminate climate sensitivities more significant than those gathered around average behaviour. The dry year of 1986 in the Upper Chattahoochee catchment was the focus of the previously reported CFG studies. Indeed, a necessarily rough comparison of the range of the spectra of Figure 11 (average precipitation) with that of those in Figure 4 (low precipitation) shows the higher separation of behaviour in the latter between the status quo and pre-city (no city) scenarios. Dryness, if not drought, exaggerates these historic before/after (0/1) differences. It would therefore be highly desirable to explore changes at the margins much more effectively. However, studies elsewhere in generating precipitation sequences capable of reflecting such longer term, lower frequency, marginal conditions remain insufficiently mature for their results to have been employed here (Kilsby *et al*., 2007).

The only extremes available for examination and assessment are those storm events captured in the precipitation sequences for the two 20-year averages. These, it should be noted, could well be judged to be nothing more than ‘normal’ (i.e. likely to occur, on average, once or twice every year). As already pointed out, Figure 5 shows that the sequence of average past (1974–1993) streamflows in the Chattahoochee (as it passes the discharge from the R M Clayton wastewater treatment facility) has two moderate peaks at around days 85 and 121. The sequence for the future (2020–2039) exhibits a much larger event at about day 25, with two moderate events occurring on days 85 and 134, which are more comparable with those of the past sequence.

Looking now at Figures 6 and 8, we can discern how a storm event provokes a consistent response in the city–catchment system, at least when gauged solely through the (time-domain) variations in in-stream TP concentrations. These rise sharply to a peak before subsiding; during this rise and (initial) fall, the impact of the city and its wastewater infrastructure are substantially diminished relative to the pre-city simulation. In other words, during storm-event responses other non-urban facets of city–catchment behaviour are predominant.

Inspecting Figure 8 more closely, it is evident that the peak response in in-stream TP concentration for the large event of the future, at day 25, is much smaller than the peak responses to the more modest storm events at days 85 and 134. It turns out that the TP concentrations in the crude sewage influent to the treatment plant during storm events are significantly reduced. In addition, if this plant influent exceeds a certain threshold (in the simulation), the excess sewage flow is temporarily stored for subsequent treatment after subsidence of the storm response. Both of these simulated features will have the effect of lowering in-stream TP concentrations during the event itself. While combined sewer overflows (CSOs) are activated at times in the simulations, there is no such overflow (or facility for storage of excess flows) at the point of delivery of the crude sewage to the treatment plant. In reality, and as a result of recent very major engineering works, CSOs across Atlanta are now stored temporarily in in-tunnel facilities (where they subsequently receive treatment), with one such facility being located close to the R M Clayton plant. In summary, simulations of the failure or inundation of the wastewater treatment plant are not yet feasible.

Timing and the fine-grained particularities of circumstances and context are of the essence, however. This will be the case just as much in respect of the timing of a storm event (of a given magnitude) within a particular season and year, as in its occurrence during any specific future strategic stage in re-engineering the city’s infrastructure. Simply put, for some span of several years, if not a decade or more – during 2020–2039, for example – one of the source-separation strategies might be passing through an especially climate-sensitive phase in its development.

4.4. Wholesale introduction of the urine-separating toilet

It used to be the case that wastewater treatment plants were designed under the assumption of persistently low streamflows in the catchment. Technically, the infinitely low-frequency condition of the steady state was generally presumed as describing the behaviour of the catchment. Such design, moreover, essentially banked upon a decades-long plant life in which very little concern would be allocated to dealing with what might happen in the operational span of hours and minutes (Beck, 1981; 2005). Under climate change, the details of what may happen in minutes – in the distant future – cannot necessarily be ditched in the interests of achieving the strategic simplicity of planning for incremental transitions in re-engineering over the decades. We may lack the capacity for implementing any detailed simulation study, but we can still engage in a brief thought experiment on this subject.

Pivotal in one rather realistic (and well-researched) separation strategy would be the introduction of some form of ‘no-mix’ or urine-separating toilet (UST) into households, offices and workplaces (Larsen *et al*., 2009; Lienert and Larsen, 2007). The essential difficulty in doing so, in the context of re-engineering household plumbing in the confined spaces of a city, is that of subsequent conveyance of urine to an appropriate site (such as a centralised wastewater treatment plant) for nutrient recovery and fertiliser preparation (Lienert and Larsen, 2007). Furthermore, as assumed here (and in Beck *et al*., 2010), having the fertiliser available at such a site adjacent to the river greatly facilitates the strategy of issuing nutrient supplements, which has been the focus of these discussions on realising CFG.

The strategy might not be climate-sensitive during all of its incremental transitions. Whenever or wherever conveyance over some distance is required, however, the choice in implementing it may dramatically amplify or eliminate the climate sensitivity. Originally, the following strategy was imagined (Larsen and Gujer, 1996).

(*a*) Introduction of a UST would be accompanied by a household cistern for temporary storage of urine.
(*b*) At predictable times of low flow in the (existing) combined sewer network (typically during night hours given the daily and weekly rhythms of city life), the contents of each cistern would be automatically released into the sewer.
(*c*) Assuming some form of centralised real-time control, releases might best be begun with households/offices in the uppermost reaches of the sewer catchment, followed by releases from the others, moving successively downstream.
(*d*) A controlled 'yellow wave' would thus be unleashed, to be received at the wastewater treatment facility in this generally preferred form of a (nutrient) concentrate. (The generation of 'designer sewage' that is 'ideal' for treatment is an active area of research in its own right, including through real-time control of existing, unmodified, present-day sewerage infrastructure (Achleitner *et al*., 2007).)

Success, of course, would be utterly dependent on not having the wrong timing of precipitation with sufficient magnitude to trigger CSOs. Climate sensitivity of the overall strategy of source separation would be amplified through such a choice of conveyance. Investing instead in laying a strictly isolated, secondary, urine-dedicated pipe system in the existing combined sewerage should attenuate this sensitivity substantially. Opting for truck transport by road (Jiang *et al*., 2009) might eliminate it altogether (see also Matsui *et al*., 2006).

'Sensitivity' should not be confused with 'vulnerability': it matters against what background level of ambient 'good health' of the river such a transient pollution event occurs. Sustainability will be measured in ways other than an appropriate balance among higher frequency (event) changes and lower frequency (ambient) fluctuations, most obviously in terms of the relative amplitudes attaching to the various frequencies of oscillation. The same high-frequency (transient) event will have different consequences according to whether stream dissolved oxygen (DO) concentration is on average high or low (Beck, 1981). One more event imposed on a chronically degraded river of lowly health will cause no diminution in, or interruption of, ecosystem services, since these in all probability are no longer being provided by that river. After restoration of the pre-city natural capital, through installation of the high-performance barrier of the city's wastewater infrastructure, even a high-frequency event of modest amplitude may bring about a significant deterioration in services. Indeed, the restored aquatic ecosystem, rarely tested by the high-frequency disturbance of barrier failure (such as a CSO), may have become mal-adapted to such minor (possibly major) events. The ecosystem may lack resilience. However, as in a public health system, the aquatic ecology of a river might benefit from vaccination through controlled pollution incidents (mock barrier failures), capable of promoting better resistance in the face of eventual and actual barrier collapse (Beck, 1996); hence the line of reasoning leading to the present discussion of pulse, CFG and nutrient supplements.

5. CONCLUSIONS

This paper began by questioning whether the introduction of a change in climate in the future would undermine or enhance previous developments (Crutzen *et al*., 2007) of the concept of the city as a force for good in the environment (CFG) and, in particular, associated strategies for re-engineering the city's wastewater infrastructure (Beck *et al*., 2010). Based on the simulation results and analysis presented here, the answer is that CFG would not be undermined and there is no reason, as yet, to re-consider any of the provisional strategies, technologies or unit processes being explored in pursuit of CFG. However, while being climate-insensitive in this way, it is not apparent that CFG would be enhanced under a changing climate. In short, the sample of strategies currently under consideration for engineering sustainability into a city–catchment system is robust under climate change.

This broad conclusion, nevertheless, must be qualified. Firstly, assessments of the energy and carbon-footprint implications of the strategies of re-engineering for CFG have not yet been undertaken, although they will follow quite logically from the procedures set out elsewhere (Jiang *et al*., 2009; Villarroel Walker *et al*., 2009). Secondly, the definition of climate change employed here is rudimentary: it amounts in sum to nothing more than funnelling all the features of that change into the future behaviour of a precipitation sequence – and an average such sequence, moreover. While this might be criticised as being an ill-targeted articulation of climate change, it reflects nothing more than the limitations of current capabilities (with climate models and the synthesis of future precipitation sequences).

With a view to extensions of the present avenue of research, there is therefore much further work to be implemented with respect to behaviour at the margins and extremes of future climate changes rather than their average characteristics. In the case of CFG, this will tend to be focused on factors affecting the (ecological) resilience of city water infrastructure, as touched upon briefly in this paper. Here too, however, immediate progress may be limited by current capabilities in adequately simulating various modes of failure and recovery in the sewer network and wastewater treatment plants.

This research will continue to probe the benefits of using a frequency spectrum for characterising the pulse rate of the city–catchment system and hence gauging the environmental benignity of any given strategy of re-engineering. From the results of this paper, there appear to be no grounds for not concluding that this metric provides novelty of insight. Looking back, spectrum was the notion that gave birth to the idea of imagining CFG in the first place. The measure acknowledges the fundamental temporal variability attached to sustainability in ways that the urban ecological footprint and, likewise, indexes of the urban metabolism (such as substance flow analysis and eco-effectiveness) do not. Furthermore, the spectrum accommodates temporal variability in both a succinct and relatively complete manner and one that complements those of the familiar statistics of average, variance, auto-correlation etc. that are used to summarise the properties of sequences in the time domain.

However, the implied hypothesis of this paper – that a nutrient spectrum reveals crucial, manipulable features indicative of the volume and quality of ecosystem services in a city–catchment system – remains to be corroborated or refuted, both in general and with respect to the impacts of a changing climate more specifically (Covich, 2009). In addition, the assessment of sustainability in the present paper has been confined to measures of environmental benignity alone. A next step will be to subject the work to penetrating analyses of its merits in respect of economic feasibility and social legitimacy from professional social scientists, as outlined in Appendix 1 and previous work (Beck, 2008).

APPENDIX 1: THE WIDER CONTEXT: CFG THE PROJECT

The work reported here is only part of a wider (CFG) project. In particular, the present paper is directed at constructing a 'pillar' of engineering–technological analysis, self-evidently devoted to achieving predominantly {environmental benignity} of action. Parentheses { } are used here to emphasise the formality of a bottom line of TBL accountancy, not least because these lines can be expressed formally as elements of a mathematical program (e.g. Ashley *et al.*, 2008). The purpose of the pillar is to have something of sufficient substance against which social and economic scientists within the wider CFG project can strike. Thus, they would hold to account current analyses as specifically as possible on the grounds of their possessing or lacking {economic feasibility} and, in particular, {social legitimacy} as the other two bottom lines of TBL accountancy. The networked CFG programme of research is intended, therefore, to ease the following limitations and to uncover and rectify the flaws in framing the relevant questions and challenges set out in the main body of the text. These limitations and pitfalls fall broadly into six categories.

(*a*) *Triple bottom line: social legitimacy.* This paper is confined, as is Beck *et al.* (2010), to accountancy of just the single bottom line of {environmental benignity} and to core matters of engineering and technology. We need no reminders of the fact, asserted by many, that little will come of such analyses without a surrounding site-specific (place-based) context of enabling, as opposed to disabling, forms of governance, *ergo* {social legitimacy}. Based on the arguments of Beck (2008) and Bai (2007), there is a *prima facie* case for fashioning the assessment of such from a starting amalgam of the various core elements of Boulanger (2008), Coglianese (2003), Gatzweiler (2006), Ney (2009) and Thompson (2008). To these – which deal with governance, institutions and the role of sustaining active human intervention in managing city infrastructure, especially under stressful, threatening extremes – should be added the driving force of the very human dimension of individual citizens seeking, or being encouraged, to improve their diets, health and well-being, not least under the prospect of climate change (e.g. Capon and Hanna, 2009; Capon *et al.*, 2009).

(*b*) *Triple bottom line: economic feasibility.* This line of accountancy is also essentially missing from the present studies. Based again on the arguments of Beck (2008) and Bai (2007), it is apparent how the issue of inter-generational discounting under the long view (of sustainability) is vexed indeed. Various promising diagnoses and prescriptions of what {economic feasibility} might be, and might become, can be found in recent works by Farley and Daley (2006), Godard (2008), Lasry and Fessler (2008), Sumaila and Walters (2005) and Summers and Zeckhauser (2008).

(*c*) *Uncertainty.* From the more philosophical perspective of the 'long view' to the more immediate, pragmatic and specific details of Figure 4, considerations of uncertainty are of profound importance. We may speculate about – and fully intend eventually to compute – the extent to which the consequences of any of the strategies for CFG summarised in Figures 4, 10 and 11 are statistically significantly different. The subject of decision making under uncertainty (DMUU) is well known. Alternative re-castings of this foundational problem, specifically decision making under ignorance (DMUI) and decision making under contradictory certainties (DMUCC), are arguably both predominant in the matter of sustainability (Beck, 2008) and much more of an unmet challenge to approach formally and computationally (Beck *et al.*, 2009). Policy too, under the long view and at the highest level (Borenstein, 2009), shows a growing concern to detect, assess and cope with the uncertain threats of any climate-fuelled drift towards tipping points or structural change (Beck, 2002) in the (global) system's behaviour.

(*d*) *Practice.* Sustainability is nothing if it is not about the long view. That long view, if imagined in the terms of 'perfect fertiliser' or 'nutrient supplements', must appear to some as overly conceptual, outlandish, if not absurd. Without abandoning the long view and the (arguably) outlandish, steps can be taken to rein in this seeming conceptual excess. Firstly, by bringing the vision more 'alive' through simulation and scientific visualisation (Demir *et al.*, 2009). Secondly, by anchoring possible realisation of the distant vision in a sequence of incremental transitions back to the status quo, wherein the first such step of 'tomorrow' – with consequences over just the next few years – is maximally, technically feasible in practice (and {socially legitimate} and {economically feasible}) (Jiang *et al.*, 2009). In the case of Atlanta, the simulation studies are currently addressing issues of household plumbing and neighbourhood adaptations of transportation and foul sewerage in the city's downtown catchments (Jiang *et al.*, 2009). These studies complement remarkably well the (2008) award-winning work of BNIM Architects (of Kansas City, Missouri) on transforming Atlanta into a 'city of the forest' over the next century, in particular from a design focus on the city's stormwater sewerage, likewise in its downtown area.

(*e*) *Beyond water.* From a 'systems perspective', which is at the core of this work, focusing solely on the water infrastructure of a city, or on the water sector of a city–catchment economy–metabolism, has its limits. The wider research programme is accordingly multi-sectoral in character, covering the forestry, food, energy and waste-management (fertiliser-handling) economic sectors, and tracking the metabolism of the city–catchment system in terms of its fluxes of carbon, nitrogen, phosphorus, water and energy (Villarroel Walker *et al*., 2009). Here again, as in matters of {social legitimacy}, the purview of life in the city can be logically expanded outwards from a focus on water and citizens to encompass concerns over health and well-being, more generally in the changing urban environment, along with their implications for the food and health care sectors. The International Council for Science (ICSU) is currently developing a science plan for a 'systems analysis approach to health and well-being in the changing urban environment'.

(*f*) *Criteria of assessment*. While much space has already been devoted here to the metric of pulse-spectrum – because of both its unfamiliarity and its central role in opening up conception of the challenge of CFG – any assessment of the {environmental benignity} of strategies for re-engineering a city's infrastructure would be founded on a narrow basis if it were restricted to this metric alone. Climate sensitivity can be gauged in terms of substance flow analyses of the city–catchment's metabolism, if not the city's footprint (Jiang *et al*., 2009; Villarroel Walker *et al*., 2009), and from newly developed criteria based on the principles of eco-effectiveness and 'waste equals food' (Villarroel Walker, *et al*., 2009).

ACKNOWLEDGEMENTS

The work on which this paper is based is part of a network of research – the CFG Network – widely distributed both internationally and across several disciplinary domains. CFG was begun in 2006, enabled through the appointment at that time of MBB as an Institute Scholar at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. We readily acknowledge this stimulus to our work. Throughout, CFG has been funded by the Wheatley–Georgia Research Alliance endowed Chair in Water Quality and Environmental Systems at the University of Georgia, in particular in support of Graduate Assistantships for all the co-authors of this paper, with the exception of JH. The freedom of enquiry enabled through this form of financial support has simply been invaluable.

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