'FACTOR 10' ENGNEERING FOR SUSTAINABLE CITIES – WATER

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1 THE CHALLENGE

Think of the examination question for the student of Engineering: Discuss – with examples – the case for designing cities as environmental "goods", not "bads". Now sit back and reflect on the nature of a city's water "metabolism". Much of the current debate about sustainability in the water sector is directed either at halting the transfer to the South – to caricature it – of the water-wasteful, linear (once-through), centralized, end-of-pipe Northern paradigm, or at starting from scratch, by building new eco-villages, even new eco-cities, such as the designs for Goa, India (AtKisson, 2005), and Dongtan, Shanghai (to which we shall be introduced at this meeting). And if it is neither of these, the debate is about stakeholders, governance, the need to be participatory, place-based, and equity-sensitive, and reminders aplenty of the fact that sustainability amounts to more than just technical and financial considerations. At times it can seem to be all a matter of people, politics, and public relations, and sincerely meant so – witness the annual Stockholm Water Symposium (www.siwi.org; see also Falkenmark, 2005).

Those of us schooled in the technocracy of the second half of the 20th Century might well wonder what we have to contribute to achieving sustainability in the urban water sector. For our question undoubtedly demands inspiration from the student engineer and – more so – from we elders. Yet who these days deems what is an environmental "good" and what a "bad"? The pursuit of conventional environmental engineering – that "water-wasteful" paradigm – is no longer seen intrinsically to be "doing good by the environment" (Niemczynowicz, 1993). It is no longer self-evident what constitutes the "benefit to mankind" in the classical definition of Engineering: of understanding and harnessing the great forces of Nature to the benefit of mankind (Thompson, 1989). We are told "engineers are fine at doing what has been decided, *not* at deciding what should be done in the first place", as much as they are "great at maintaining the wrong direction". Engineers, asserts Beder (1999), arise from families with a prevalence of autism in their background[1]. Manifestos from stream ecologists cite "quick engineering fixes", as exemplars of precisely what is *not* being sought in their new model of watershed management for the 21st Century (Poff *et al*, 2004). The unfavourable perception of Engineering in Society is thus manifest and ubiquitous, but nothing new (Florman, 1994).

It is inconceivable, however, that Engineers will not have a prominent role to play in shaping and re-shaping the future wastewater infrastructures of cities, thereby to wrestle around the mightily persistent image of the city, to point it more towards being something of an environmental "good", less of an environmental "bad". But they, the Engineers, and/or their education (Mulder, 2006), will need to undergo a change of culture. *Inspired* and *charismatic* – and let us not shy away from these words – they should indeed be.

To embark on this path is our purpose herein, biased albeit towards the longer-term, inter-generational imperative of the Brundtland definition of sustainability and buttressing our argument with supporting computational results, towards the end of the paper. Likewise, we shall touch only in passing upon the

[1] This plays, however, off the popular, negative image of autism, not its startling benefits as recorded in Grandin (2004).

"economically feasible" and "socially acceptable" components of the triple bottom line, as dealt with in Davis (2006a), and with (there) uncommon, refreshing candour.

2 CONTEXT: ENGINEERING FOR SUSTAINABLE DEVELOPMENT IN THE WATER SECTOR

2.1 Joined-up Thinking and Doing

It is estimated that over 1 billion people in the world are without a safe supply of clean, potable water; yet more than 2 billion lack hygienic systems of sanitation. It should be no surprise, therefore, that the UN's Millennium Development Goals (MDGs) call for a halving of these numbers by 2015 (Zehnder *et al*, 2003; SIWI-IWMI, 2004; Unesco, 2006). For well over a decade, the global water community – in the form of the World Water Council (www.worldwatercouncil.org), the Global Water Partnership (www.gwpforum.org), the World Business Council on Sustainable Development (www.wbcsd.ch), the Stockholm International Water Institute (through its annual Stockholm Water Symposium; www.siwi.org), the UN's World Water Assessment Program, under the auspices of Unesco (www.unesco.org/water; Unesco, 2006), the International Water Association (www.iwahq.org), the Global Water Systems Programme (www.gwsp.org), and many others – has been mobilizing itself to meet the challenge. No-one, however, has paid much attention to charting paths of technological innovation into the longer-term future of water infrastructures; at least, not as they have done for the energy sector, in the context of mitigating climate change (Ringuest *et al*, 1999). To which, just as much, the entire water sector will need to adapt.

Addressing what is to be done about the urban water environment cannot be divorced from the equally vital water issues associated with food production in the rural setting. For there, after all, is where 70-80% of our appropriation of water is harnessed to the benefit of mankind (SIWI-IWMI, 2004; Falkenmark, 2005; Pearce, 2006). "Thinking globally, acting locally" seems such a trite slogan, even a platitude. Yet it is exactly what is needed here. At the global scale, migration of people to cities, the consequent increase in urban consumers (and decline in rural producers), changes in distributions of populations along the poverty-affluence continuum, and shifts in health and dietary preferences, can have profound implications for the world's trade in agricultural products and, therefore, the (virtual) water embodied in their production (Allan, 2003; SIWI-IWMI, 2004). It takes some $15m^3$ of water to produce 1kg of (grain-fed) beef, as opposed to at most $3m^3$ per kg of cereal (SIWI-IWMI, 2004). From this perspective, it makes no sense for water-intensive foodstuffs to be cultured in sunny but arid regions of the globe for export to consumers in water-rich countries.

At the intensely local scale of the household or office, the manner in which resources are recoverable from the biological "residuals" of our daily lives can substantially affect the fertility of the soil and the consumption of energy, in particular, in generating and employing nutritious, reactive species in the global cycling of nitrogen (Galloway *et al*, 2003). Writ large and rough – thinking globally, that is – the concomitant of producing food in certain regions of the world is a net flux of nutrients from the soils of these regions to the waters downstream of cities on other parts of the globe (Færge *et al*, 2001; Grote *et al*, 2005). But in this increasingly consumer-sensitive world, if the new urban affluents desire more of a diet of "water-intensive" – and "nitrogen-intensive" – foodstuffs, farmers are very likely to follow this market signal.

Writ very small, for the individual deciding and acting locally, things can be rather desperately personal. Ecological sanitation systems – "ecosan", for short – allow adopters of this technology to cut water use and provide a source of fertilizer. Claiming a degree of "eco-insanity" in all of this, however, Mara (2005) begins his polemic with these words:

> The basic philosophy of ecosan is beguilingly attractive: we each produce enough nutrients in our excreta to grow all the maize or wheat that each of us needs. We need to use, not waste, these nutrients; if we waste them by mixing our yellow [urine], brown [faeces] and grey waters [wash waters] together (to form domestic wastewater), then we end up spending a lot of money removing

> them at wastewater treatment plants, or else they get into our rivers and lakes where they may cause eutrophication.

He continues, to issue the bluntest of market signals: "If I'm a poor rural villager in India, why should I spend 4200 rupees on an ecosan toilet, rather than 1900 rupees for a single-pit pour-flush toilet?". And there we have it in a nutshell: the tension between eloquent grand vision and hard – very hard – personal pragmatism, with the rest of the debate being played out in McCann's (2005) article.

What then of our bequest to Brundtland's next generation? How much of an investment in the longer-term future – into fungible, natural, or other forms of capital – would an ecosan toilet be, relative to a single-pit pour-flush toilet? What then too for resolving Solow's moral dilemma: that those of us who would care so much for the well-being of the next generation – by bequeathing to it, at the very least, no less natural capital than that in the world today – might thereby seem to care so little for the masses of the world's poor (Solow, 1991)? For they need something to be done right now about their water situation – and something inevitably consumptive of current natural capital, quite the opposite of a constructive bequest to some distant future.

This prospect – the two-way interplay between changes in household budgets, diets, and toilet habits (Matsui, 2006; Beck and Speers, 2006) and the shifting pressures on global trade and global water and nutrient cycles (Grote *et al*, 2005) – encapsulates why the calls for more joined-up thinking in the sustainability debate are so shrill (Hawken *et al*, 1999; McDonough and Braungart, 2002).

2.2 Engineering Analyses and Public Scrutiny

The engineering/technology domain of the water sector is well aware of the wider sustainability debate (Beck, 2002a). Here is a grave difficulty, however. The tendency is for the wetting front of engineering enumeration to move outwards to embrace ever more of the triple bottom line (van der Vleuten-Balkema, 2003; Brunner and Starkl, 2004; Morimoto and Hope, 2004). There is a yearning, as it were, to find the scheme of quantitative weights that somehow will allow us to add up all the incommensurate, qualitative, value-laden, subjective elements in the matrix of indicators of "sustainability", to generate the single number – telling us to choose this design over that for a more sustainable activated sludge unit of wastewater treatment. Some things simply cannot be poured into the number-crunching device. And we know it; but not the shifting line that separates systematic engineering analysis from democratic debate amongst stakeholders.

The engineering community is uncomfortable in the presence of "vagueness", such as that of the Brundtland definition of sustainability, and in the absence of agreement on definitions[2]. *Vagueness* simply does not *square* with codified procedures. We might be even more troubled at the prospect of democratic debate amongst stakeholders being reflected back onto very much closer scrutiny of the kind of systematic engineering analyses being undertaken – along the lines (for Engineering) of the now prominent arguments regarding "Science's New Contract with Society" (Gibbons, 1999; Nowotny *et al*, 2001). Indeed, Gyawali (2001) has argued that success in the future for Nepali water science will *only* be achieved providing the democratic debate is framed by a *plurality* of culturally conditioned styles for that science: market science, which is of an innovative and risk-taking nature; government science, born of a regulatory and risk-managing background; and voluntary science, dominated by precaution, scepticism (about technology), and risk-avoidance. In other words, there can – and should – be a plurality of water sciences (and engineering*s*) gathered around the three active social solidarities of Cultural Theory (Thompson *et al*, 1990), just as there could be, less surprisingly, three or more culturally conditioned, possibly widely differing understandings of what is meant by "sustainability". Other than agreeing with the strategic inspiration of the Brundtland expression of

[2] Something abundantly clear at both of the (2002 and 2004) Leading-Edge Conferences of the International Water Association on "Sustainability in the Water Sector" (see, for example, Beck, 2005a). The International Hydrological Program of Unesco has also wrestled with the issue, at length, yet in the end producing a definition falling back largely onto the original Brundtland form (Loucks and Gladwell, 1999).

sustainability, then, it might be that disagreement on strict definitions of things that flow therefrom is not necessarily bad.

In short, the challenges for the Engineer are at least twofold: first, to know instinctively how to draw that fine line separating public democracy from technical, professional analyses and judgements – thereby to regain the self-confidence ceded to the insecurities engendered by all the uncomplimentary remarks of the great sustainability debate of the 1990s; and second, to make *prudent* use of the inexorable drift towards computational virtual realities – the destiny of engineering enumeration (Beck, 2002b; National Science Foundation, 2006). For what the bald, economic choice between the ecosan toilet and the single-pit pour-flush toilet could not constructively debate, was not merely the environmental benignity and social acceptability of one *versus* the other, but also the respective risks of optimizing the part (choosing an ecosan toilet) while pessimizing the whole (consequences for the global cycling of materials of a city of ecosan toilets), and the respective depths of eventual technological "lock-in", across distant future generations.

3 POINT OF DEPARTURE: CORE PARADIGM IN NORTHERN CITIES

Many – very many – cities are entirely vested in the Northern paradigm of metropolitan wastewater infrastructure. Water fit for drinking is conveyed into the city (often from afar), where it is employed as the universal solvent and carrier for taking all manner of the residuals and detritus of life out of the confined spaces of the city. On the upside of water in the city the paradigm has pipes fanning out in a dendritic network from a single point of treatment to us spatially distributed consumers. On the downside the multitude of leaves on the tree of the network coalesce back into the singularity of the main trunk sewer terminating in the centralized, end-of-pipe treatment plant. From the upstream point of intake to the downstream point of discharge, things flow but once through the water metabolism of the city. The networks of conveyance are not impervious, even though every attempt may be made to achieve this state of perfection. Water will leak out of the distribution network on the supply side. Sewage will likewise leak out of the sewers, while water from the surrounding earth and rock will infiltrate into them. Water, as in precipitation, may readily find its way into the foul sewage network, no matter the intention of keeping the storm-runoff and foul networks strictly separate.

The accompanying generic arrangement of wastewater treatment reflects its evolution over the past century: a linear sequence of unit process technologies; each almost literally tacked on to the ever extending "end-of-pipe". Each was an incremental response to the rise (and fall) in public and regulatory perceptions of what *the* problem was, one by one: from gross, palpable and visible pollution from solid/particulate materials (addressed by so-called physical treatment); to easily degradable soluble and particulate organic pollutants (addressed by biological treatment); to excessive nutrients, most notably compounds of phosphorus (addressed by chemical treatment); and with disinfection being pushed in each era to the actual end of the pipe, in order there to deal successively better with pathogenic (bacterial) pollution. The language we have used to describe what is achieved therein says much of how Society has viewed this subject over the past century or so. Perceptions have evolved from the "sewage farm", through the "sewage works", "wastewater treatment plant", "water reclamation facility", to the contemporary (if not futuristic) "water resources centre".

This core paradigm of metropolitan wastewater infrastructure has been spectacularly successful in enabling millions of people to live healthy and productive lives in cities. We now recognize the cost of this achievement: the substantial and wasteful diversion of valuable nutrients into the water environment, the ensuing disruption and depletion of ecosystem functions and services. We shall have to do better in the future. Cities in the North, just as much as the cities of the South and new settlements everywhere, must take some steps towards greater sustainability. But how can they make the most of the current, initial conditions they have inherited from 100 years and more of historical engineering development? Being of large volume in terms of their production, requiring long lead times, and being capital intensive, they are the epitome of the technological system most vulnerable to deeply entrenched lock-in across Brundtland's generations (Thompson, 1996). How, then, are we going to engineer our way out of technological lock-in (in the North) and avoid driving head-long towards it in the South[3], while yet being "socially robust" in our choices (Gibbons, 1999; Nowotny *et al*, 2001)? How will we know that the first steps of adaptation away from today's initial conditions are ones moving in a favourable direction?

Our responses will come in two parts: first, in examining a procedure for making cities and their water infrastructures less of an environmental "bad"; second, thereafter, in turning them around, away from being all of an environmental "bad" to something of an environmental "good". Our discussion focuses, therefore, on strategic technological trajectories towards Brundtland's distant future (for cities in the North) that are environmentally benign. Yet we shall close with some computational experiments, as small, specific steps towards the grand conceptual vision, including assessment of the potential of these trajectories in respect of their being economically feasible and socially legitimate.

4 GAUGING SUSTAINABILITY IN THE URBAN WATER SECTOR

Let us set out a vision, and a metaphor. In the long run, if we are by turns first pessimistic (cities will initially degrade their environment) and then optimistic, all watersheds ought eventually to become rehabilitated. Intense social and economic activity will be set in the midst of a reasonably healthy but vulnerable environment (Beck, 2005b). Think of the life of the city, its metabolism, pulsating with the unparalleled intensity of its activities, set in the midst of an intricate, quasi-pristine ecology (a metaphorical "Garden of Eden"). This, then, is what we are about: enabling that throbbing organism to sit more comfortably in a healthy environment. And we wish to explore those patterns of technology for the city's wastewater infrastructure that will make this more, not less, likely to come about.

To do so, we shall reach up to some grand, macroscopic criteria; three, in fact. We call them "appetite", "metabolism", and "pulse", culminating in this third as the lens through which to conceive of cities as forces for good in their environments. That these criteria are so grand, and therefore so vague and uncodified, as to be "operationally impotent" in discriminating a promising from an unpromising pattern or trajectory of technology, will be a fair criticism. It is a point to which we shall therefore return. Yet vagueness is not necessarily a bar on discerning how – specifically – to proceed. History encourages us in the view that the original Brundtland expression of sustainability, for all its vagueness (indeed perhaps precisely because of it), may have the power to inspire, motivate, and innovate *in practice* – just as did Aldo Leopold's land ethic of six and more decades ago[4]. The alternatives to vagueness, in any case, have clearly yet to succeed in having any more tangible impact (Uhlmann, 2006), especially in respect of urban wastewater infrastructure (Unesco, 2006).

4.1 Appetite: Ecological Footprint

Our business is that of reducing the footprint of the city on its environment. We know the extent of the Earth's surface, the area of land occupied by the city, the number of people in the city, and their economic and commercial activities. In the life of the city, resources for its metabolism are drawn in and the residuals and detritus of its activity evacuated. If we could calculate the areas of land and sea required to generate the incoming resources of the city and assimilate its outgoing residuals, we would have a real estimate of the city's footprint. Which we already have (Wackernagel and Rees, 1995; Jansson *et al*, 1999; Lenzen *et al*, 2003; Jenerette *et al*, 2006). The result, like so many other indices, reveals the scale of our misdeeds in terms we can all readily grasp. We might need anything from another two to five planet Earths (if not double this range), if we were to achieve "build-out" to

[3] We are *not* suggesting those cities not currently so confined should don the straitjacket of the "modern sewage treatment paradigm" of the North, hence to benefit from the creativity of discovering new ways of casting it off.

[4] Leopold's inspiration was expressed thus: "a thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community". No matter how vague, almost tautological, this may be, the evidence shows it has motivated many over the years to restore and treasure landscapes and environments in palpable ways.

accommodate the 9-10 billion people expected to be with us during this century (Rees (1996), as cited in www.global-vision.org/city/footprint).

But behind these apocalyptic visions, in the hard-headed, sober domain of having a prescription for doing something to avoid such an intolerable future, the concept of the ecological footprint of the city gives us a metric, and an obligation: to adapt the design of the Northern wastewater infrastructure to lessen the areal extent of the footprint. The city of Seattle, Washington, USA, seeks thus to: use the clouds as conveyance – instead of pumps and pipe networks; increase "natural" evaporation where possible – instead of employing other "unnatural" flood conveyances and defences; and use the soils and aquifers as storage – instead of alternative engineered constructions. Beyond the rubric of such macroscopic principles, it is quite conceivable we could have the specific calculus to do it: to translate the consequences of following these principles, for individual items of technology, back into reducing the areal extent of the city's footprint. From their analysis of the Sydney Water Corporation (SWC), Lenzen *et al* (2003) conclude:

> The EF [ecological footprint] appears promising as an *educational and communication tool* and may have potential as a decision support tool. However, further research is needed to incorporate downstream impacts into the EF, which would have significant benefits to SWC in terms of assessing and *communicating* the organization's overall progress towards sustainability. [emphasis added]

For the moment, therefore, we appear to have achieved a kind of "passive", retrospective assessment of the areal extent of a footprint, as if for dramatic effect, on the upside of water supply to the city dwellers (Lenzen *et al*, 2003), as opposed to active, prospective guides to infrastructure re-design and adaptation, on the downside of recovering resources from their biological residuals[5].

Yet while we have the image of the city as an organism with a metabolism, its mere footprint is a rather lifeless form. It is as though just a snapshot of the metabolism has been taken, much as the photographic still of a speeding athlete, frozen in time, one foot impinging on the ground. It renders lifeless and static all the live forests, wetlands, agricultural lands, marine fisheries, and so forth, as sheer amounts of "stuff" required to keep us going – like the bulk of the inanimate mineral resources of conventional economic production.

How is this stuff circulated around the Earth, including through the body of the city?

4.2 Metabolism: Webs of Interaction and Material Cycles

Our species inhabits the land surface (not the water environment). Before reaching us, our nutrients (C, N, P, K, and so on) arise from the earth and are not naturally passed through the aquatic environment in the cycle of their being returned to the earth. As in ecology, or as for the Earth as a whole, natural behaviour of the system – as it evolves over the millennia – can be understood in the terms of conceptual models of global material (element) cycles (Schlesinger, 1991; Galloway and Cowling, 2002; Galloway, 2003; Galloway *et al*, 2003). It is indeed these – the images of the "perfection" of the "balanced", "complete", "closed" material cycle – that are celebrated in current visions of the future of engineering, industrial, and economic design (Hawken, 1993; Benyus, 1997; Hawken *et al*, 1999; McDonough and Braungart, 2002). The concept of the global material cycle and, in particular, its form prior to the industrial revolution, conveys the notion of man living in a desirable harmony with the Earth. But the city, as it lands down on the ground in geological time, so to speak, induces distortions rippling through the pre-existing cycles of water, C, N, P and the other materials (Beck *et al*, 1994; Beck and Cummings, 1996).

The global carbon cycle is most familiar to us; the hydrological cycle too. Nitrogen, however, is "the very stuff of life" according to Galloway and Cowling (2002). They tell us that in the late 20th Century anthropogenic N fixation from the atmosphere overtook natural terrestrial N fixation. Of the

[5] However, alternatives for wastewater treatment facilities for the city of Petaluma, California, USA, have been evaluated (in 2000) on the basis of the relative extents of their ecological footprints (Davis, 2006b).

amount of nitrogen in fertilizer, only 14% reaches the human mouth *via* a vegetarian diet, just 4% in a carnivorous diet. If these numbers do not foreshadow (again) the scale of our misdeeds, the prospect of the following should: were the 9 billion people or so expected in the late 21st Century to have the same per capita rate of producing reactive N – the essence of its form in fertilizer – as currently in North America, there would be a six-fold increase over the 1995 estimate, which itself was 9 times larger than in 1890. Are we destined to pedal ever faster on this cycle?

Much of the reactive N produced in the world finds its way, through one route or another, into the aquatic environment, whither it would not previously have been naturally headed. Certainly, if we struggle mightily to increase the efficiency of its chain of transfer from fertilizer to the mouths of city-dwellers, the focus on managing its fate thereafter should be all the sharper (Færge *et al*, 2001). The city's wastewater infrastructure ought to compensate for these distortions of the global cycles of material, not exacerbate them. Yet current technologies of wastewater treatment designed to manipulate the nitrogen cycle may be just such a source of exacerbation. From one perspective – because nitrogen tends to be the growth-rate limiting element for green matter in the marine environment (as opposed to phosphorus in freshwater systems) – cities close by the coast, especially around the Baltic Sea, have invested heavily in broad-scale N removal from wastewater. In the grander sweep of things, however, perhaps not all is well with this picture. The effort and cost of accelerated biological nitrification and denitrification of sewage during (downstream) wastewater treatment will have the net effect of shunting N into the atmospheric environment, whence it must then – with effort and cost – be fixed for incorporation back into the (upstream) production of artificial fertilizer. This does not seem a sympathetic way of organizing the metabolism of the city and its compensatory wastewater infrastructure; of enabling the city to sit more comfortably within its surrounding environment.

Better put, given the inevitability of reactive N species in wastewater, one might argue these should be endlessly recycled – indeed "upcycled" – into the system of food production, neither diverted into the aquatic environment nor converted back to unreactive nitrogen gas in the air we breathe. As in recycling paper and textiles, where the recovered material spirals downwards (its quality being degraded at each turn) eventually to reach the landfill, albeit after more than just one rotation of the recycle, it would be so much better if the recycled reactive-N never entered the water environment; and better still, if its efficiency and retention within the "inner" fertilizer-mouth-urine cycle were elevated systematically towards 100% – upcycling, then, in the words of McDonough and Braungart (2002).

But there is still something wrong with our picture. The footprint conveys a sense of the sheer volume of stuff required to support the city; these biogeochemical cycles give us a sense of flux, circulation, and the connectivity of the city suspended in a web of interactions with the rest of the biosphere. Something is missing yet, however.

4.3 Pulse: Speed, Variation, and Frequency Spectrum

The body belonging to the foot that makes the print, is quintessentially dynamic: mainly growing, sometimes declining, but bounding up and down, hither and thither, all the time.

Consider this, then. Before cities existed, the terrestrial portion of the hydrological cycle was subject to a particular spectrum of perturbations, with frequencies of fluctuation and variation ranging from millennia to minutes. Imagine too that these spectra must represent not only perturbations in the hydrological cycle, but also in the cycles of C, N, P, and so on, somewhere notionally in the region affected by the city. We know that the installation of sewers for urban drainage has "quickened the pulse" of the aquatic environment, by replacing low-frequency, slower transfer times with faster, "flashier", high-frequency disturbances. The drop of rain that once hit the ground and took its leisurely meandering course through soils and aquifers thus to enter the river, is now sped immediately on its way through gutters, gulleys, and concrete conduits. Such artificial urban drainage, augmented with sewerage for the carriage of municipal wastes out of the confined spaces of the city, alters the pre-city spectrum of disturbances. Dominant peaks appear at the weekly and daily frequencies reflecting the metabolism of life and society in the city – *not* its environment. As more infrastructure is put in place in the city – as successful wastewater treatment is more fully realized – this will have the effect of quickening the pulse of environmental disturbances yet further. Construction and installation of the treatment system, as planned for, should restore an ever elevated average level of stream water quality, but arguably a condition ever more prone to fast, transient mishaps and failures in the installed web of city infrastructure (Beck, 1981, 1996, 2005b; Beck and Cummings, 1996). At the very least, for example, there will be more pumps, more blowers, more gates, and more valves to be operated in the ever more comprehensively implemented wastewater infrastructure, all of which will be subject to abrupt failure, including the very system of control designed to pre-empt failure. Studies of the interdependency of multiple infrastructure elements (transport, energy, water, and so on) emphasize repeatedly the likelihood of their increasing vulnerability to cascading failures from their growing reliance on information technology for effecting communication and operations (Zimmerman, 2001; Rinaldi *et al*, 2001; Little, 2002).

We have the ecosystems we once saw because of the spectrum and variability of disturbances – including things of pulsating intensity and pounding strength – through which they survived, evolved, and prospered (Poff *et al*, 2003). In geological time, the city appeared in the landscape. The persistent, day-in-day-out, year-by-year, decade-on-decade, chronic stress of untreated sewage discharge eliminated fish from the river. The previous existence of the fish was lost from the living memory of the city dwellers. With comprehensive wastewater infrastructure the fish returned, even to prosper again. Citizens regained the pleasure of angling for them, by way of recreation. And then came the combined sewer overflow – or some other acute fault – to wipe the fish away, in just a heartbeat.

As geological time passes, the pulse-rate of our athlete of a city has been quickening. It is as though, to be more precise, the bass tones are progressively being removed from his voice, pushing him to an ever more dominant falsetto, frenetic pitch. He can be provided with the very best of trainers to cushion the jolting, jarring, pounding of his footprint on the ground; but this will not stop him from crashing to that ground.

It is the wastewater infrastructure that prevents polluting activities becoming pollution actualities and, if successful for long enough, makes the city's environment all the more vulnerable to such events when they happen, as they do. The River Rhine, now rehabilitated, is reported to be less resilient in the face of accidental spillages of certain kinds of noxious chemicals, essentially because of removal of the persistent stress of inadequate urban and industrial wastewater treatment, which forearmed the river against such insults (Malle, 1994). When outbreaks of infectious diseases are no longer commonplace, because of the success of pre-emptive vaccination of the human population, the obligation of a public health system to prevent further epidemics becomes ever more onerous. Its very success can make public health all the more vulnerable to the higher-frequency, faster-propagating perturbations. Does this mean our aquatic environment should be subject to the analog of vaccination – the repeated and deliberate release of transient (but muted) pollution events from the city's wastewater infrastructure (Beck, 1996)?

Could we even – and this is of strategic significance for the student still puzzling over our introductory examination question – entertain such as *deliberate* action by the city to "do good by the environment"?

5 BACK TO THE PRESENT — FROM DISTANT FUTURES

We have created our city as a trainer-shod bull in the restored china shop of its environment. That "bull", far from being all bad, is something from which – perish the thought – we might hope to benefit.

This, therefore, is our challenge: if we took out all of today's technologies, leaving the empty concrete, steel and brick hull of our existing Northern metropolitan wastewater infrastructure, what would we put back into this shell – to do better next time, some several decades hence? How might we move away from the present conditions, adapting one step at a time, towards a continually evolving set of plural (community-based) visions of target aspirations for a distant, inter-generational future?

5.1 Thought Experiment

If we peer far into that future – say, 75 years or so – we can discern and invent some sunlit uplands in which to place cities whose water metabolisms could be deemed more sustainable than those of today. Let us give these target scenarios some names: (i) Business as Usual; (ii) Control Freak's Delight; (iii) Return to Mother Nature; (iv) Perfect Fertilizer; and (v) Dry as Dust.

We need the baseline of the first (Business as Usual), the paradigm of the North set out earlier, against which to gauge progress, but itself evolving with incremental adjustments, somewhat at the fringes of the core design: through unit process technologies such as flow equalization, for stabilization of the raw material input to treatment, and polishing technologies, such as reverse osmosis or granular activated carbon.

The second (Control Freak's Delight) amounts to the musical score-sheet of virtuoso performances we could extract from this paradigm, if it were fully instrumented and orchestrated (like the city's traffic infrastructure) and institutionally seamless, being thus a complete realization of the principles of Integrated Urban Water Management – nested within the kind of Integrated Water Resources Management (IWRM) promoted by the Global Water Partnership (and essentially all the other significant players on the global water scene, as already listed above; Unesco, 2006). It would be a paradise for those with a penchant for "hi-tech".

The third is the antithesis this. The Return to Mother Nature would have us remove the horny hand of the technocratic engineer from everything, installing in its place the greenery and earthiness of swales, wetlands, infiltration trenches, aquaculture ponds, and the "living machines" of Ocean Arks International (www.oceanarks.org).

The fourth brings us up sharp. Think on this (to paraphrase Otterpohl *et al*, 1999): if the needs of preserving hygiene in the city have been met, the goal of integrated urban water management is to keep the soil fertile! For 150 years we toiled to this end: to install a wastewater infrastructure to produce a crystal-clear liquid product – regrettably, with a bothersome solids by-product once called sewage sludge, now marketed as biosolids. The fourth of our target scenarios turns this focus inside out: imagine the goal being to produce the Perfect Fertilizer with – yes, as it happens – a crystal-clear water by-product. Driven by the environmental motivation *not* to quarry phosphates ultimately to be perverted into growing green matter in our freshwater systems, sales of the P recovered from metropolitan wastewater can be commercially significant (European Chemical Industry Council (CEFIC), 2001).

The last target scenario (Dry as Dust), built around the notion of on-site, household, dry sanitation, has salutary reverberations. If anything, we of the North are to project our expertise – with all humility, for we may well have nothing to contribute (and everything to learn) – into the cities of the South, in due course to have their success sold back to us, in the North.

These, then, constitute our array of distant target futures to be shot at, across the generations. Suppose they are worthy targets, in the public's mind. Given the current Northern paradigm of metropolitan wastewater infrastructure, what steps should we take over the next 5-10 years in order to start evolving towards any one of them, without foreclosing on the reachability of any other?

We know that a Sustainability Science is in sight (Kates *et al*, 2001). Its agenda embraces this kind of question (Beck *et al*, 2002): what science – *and* technology *and* policy — might be key to minimizing the risks of having the people's, *not* the scientist's, *nor* the engineer's, *nor* the policy analyst's, worst fears come to pass; and what science – *and* technology *and* policy – might be key to maximizing the probability of having their best hopes realized? These are "inverse" problems to be solved; inverted, first, because they imply a projectile sent far into a "known" target future, thence to determine the unknown steps back from that future to the present; inverted, second, because they shift emphasis away from what we desire towards what we fear (Beck *et al*, 2002)[6].

Our Perfect Fertilizer scenario might be attained thus, along this strategic technological trajectory into the future (and it will be told backwards, for effect): 75 years' hence, a metropolitan wastewater infrastructure delivering perfect-fertilizer; 50 years' hence, a comprehensive, additional secondary pipe and treatment network for nitrogen-rich Anthropogenic Nutrient Solution (ANS, or urine) laid entirely within the hull of the current (but by then, *dual*-conduit) sewer network and treatment plant; 25 years' hence, the "yellow wave" scenario of orchestrated household night-time cistern releases – a cascade of switches going down the street – unleashing a gathering wave of urine sweeping through the *single*-conduit sewer network to the (by then) *dual*-purpose *fertilizer*-water treatment plant; 5-10 year's hence, system-wide installation of re-engineered urine-separating toilets and cisterns in the city's households of today (Larsen *et al*, 2001).

5.2 Computational Experiments

There is a fundamental asymmetry about our very personal choices. We can choose our diet; the nature of our clothing; our personal shelter and its contents and furniture; our personal mode of transport; and, up to a point, influence the status of our health, thus to influence in turn – again, to some extent – our ability to benefit from the nutriments in our food and manage our need to take medications. In other words, we can exercise choice over what we take into us from the environment. And now we can link the essence of that very personal, strictly local "doing" to the literally global "thinking" about all the strands in the web of global trading that must thereby be threaded into the "eye of the needle" of our individual existence. Yet by and large we are *not* free to choose the time and place of our bodily functions, to evacuate the entangled strands of this very existence – the yellow and the brown, as Mara (2005) has coloured them – back into the web of the environment about us. Furthermore, what the human organism separates so marvellously well – burden of nutrients and pharmaceutical residues into the yellow strand; burden of carbonaceous materials and pathogens into the brown strand – the water closet and the Northern paradigm of metropolitan wastewater infrastructure mix so intimately back again, together with the grey strand of household wash waters. Separation, or better still, not mixing in the first place what passes through and out of the household, has a very great deal to recommend it, in principle.

Simulation experiments are entirely possible, to take thus our argument beyond a mere thought experiment. Under today's Business-as-Usual scenario, there are no separations in the household and

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[6] We call our nascent approach "adaptive community learning", in general (Beck *et al*, 2002), or here, more specifically, "participatory technological envisioning". We know what adaptive management is (Holling, 1978). In essence, policy therein fulfils two functions: to probe the behaviour of the environmental system in a manner designed to reduce uncertainty about that behaviour, i.e., to enhance learning about the nature of the *physical* system; and to bring about some form of desired behaviour in that system. Adaptive community learning ought both to subsume the principles of adaptive management (so defined) and include actions, or a process of decision-making, whereby the community of stakeholders experiences learning about *itself*, its relationship with the valued piece of the environment, i.e., the community-environment relationship, and the functioning of the physical environment (Beck *et al*, 2002). Just as adaptive management celebrates a prudent measure of experimentation, so should adaptive community learning (Norton and Steinemann, 2001), with policies designed, for example, with the deliberate intent of promoting community self-awareness. The process will be iterative and continuous, one of "always learning, never getting it right" (Price and Thompson, 1997). In this, the community of stakeholders is interpreted in a much broader sense than merely stakeholders as policy persons/managers. Indeed, the scientifically lay stakeholder is pivotal in the procedure (Beck *et al*, 2002). To them falls the responsibility of imagining the plurality of more sustainable futures to which they aspire and the more unsustainable futures they would seek to avoid at all costs. The professional engineer, as participating stakeholder, has the obligation of composing impressions (extrapolations) of the plurality of technological paths by which those futures might/might not become reachable – and of possessing the skill to devise computational schemes for identifying upon which key combinations of technologies such reachability appears to hinge (and all under gross technical uncertainty, if not the uncertainty of the wider democratic debate; Chen and Beck (1997), Tsai *et al* (2004)).

downstream infrastructure (Figure 1(a)); but the Engineer can already explore in some detail[7] how we might attain universal separation of the grey from the black-yellow strands within a generation (Figure 1(b)); while some 25 years hence, migrating along a slightly different technological path, we might alternatively attain separation of the yellow from the grey-brown strands, i.e., the "yellow wave" scenario as labelled above (Figure 1(c)). Either of Figures 1(b) and 1(c) could be a provisional stepping stone away from the current arrangement of Figure 1(a), *en route* to realization of the Perfect Fertilizer scenario, where that distant image itself will evolve and change in the coming decades. Each configuration is but a part, however, even of the *sub*-system of the wastewater treatment plant, being essentially just the liquid treatment train thereof (and excluding the accompanying solids treatment train). Each can be simulated with ease on the computer (Jiang, 2006), without recourse to anything like a virtual reality.

Now recall the urine-separating toilet, that particular piece of technology whose prospective, broad-scale innovation is singularly instrumental in designing the "yellow wave" scenario for the entire urban wastewater infrastructure (as implied in Figure 1(c)). And focus on the minutiae of this one constituent, metaphorical "nail" — "for want of which a kingdom [the entire system] was lost". Could we instead thereby gain not only the kingdom of the Perfect Fertilizer, but those too of Dry as Dust and Return to Mother Nature, even Control Freak's Delight, and that which has yet to be imagined? For this is not a once-and-for-all long shot, of course. We are capable of maintaining continually evolving imaginations of the future that will equally continually re-direct the placing of our city's foot, just at the next step. If such additional prospects for the *whole* were made more probable – not foreclosed – by the single, specific innovation of this *part*, the urine-separating toilet, think what a highly commercially attractive technological innovation it might be. For the real promise of the part (the urine-separating toilet) can only be illuminated when judged according to the performance of the joined-up whole, of the city and the entirety of its infrastructure, all embedded within the surrounding watershed – a kind of "Computing globally, assessing particularly". Such grander computational assessment – nothing less than the kind of *system-wide* assessment called for in Section 2.2 above – is not at all a distant prospect (Beck, 2005b).

The rub remains, however: of how to draw the fine line separating systematic engineering analyses from democratic debate amongst stakeholders, likewise as called for in Section 2.2. Figure 2 summarizes a numerical assessment of the three (composite) designs of Figure 1 against a typical, contemporary suite of sustainability indicators. How could we have persuaded ourselves to come up with a numerical score for a "public awareness index" or "cultural acceptance index"? How could we credibly – under the ever closer scrutiny of a culturally and politically diverse community of stakeholders – proceed to aggregate them into a single scalar quantity? Would the urine-separating toilet be deemed "socially robust", in the sense that it is found to be key across the plurality of culturally conditioned aspirations for the future of the various social solidarities amongst the community of city-dwelling stakeholders, i.e., robust against this heterogeneity of aspirations?

In closing, let us examine how we might inch incrementally beyond this rhetoric.

5.3 How *Do* We Make Strategic Criteria Work?

We have dared to depart – in our thinking – from the confines of the visceral pragmatism of Mara's poor rural villager in India, to reach up and out to – to be inspired by (no less) – the prospect of screening future infrastructure technologies against the grand ideas of a city's appetite (gauged by its ecological footprint), its metabolism (its connectedness in the web of global material cycles), and its pulse (the spectrum of frequencies of variation in its metabolism).

What troubles us yet, however, is the potential impotence of these grand, but vague criteria. How, in the utmost specifics of detail, would the urine-separating toilet shape up, as just one item of candidate technology for a future wholesome technological web? Yes, if it drew in less high-quality water for

[7] We have too the innovation of the web to assist us in much more effective means of "horizon-scanning", for spotting all manner of reports on nascent and novel technologies from which to compose our infrastructures.

flushing and eliminated some wetland areas for shunting the urine back to the atmosphere as unreactive nitrogen, it should reduce the areal extent of the city's ecological footprint. Yes, if it substituted an amount of industrially fixed atmospheric nitrogen – by way of the urine being upcycled, as already available reactive N, rather than damagingly diverted into the aquatic environment – it could rectify a kink in at least one of the distorted global material cycles. Yet no, down the line, perhaps 25 years hence, it might not fair well in cushioning the crash of the trainer-shod bull in the restored china shop. For there had better be no risk of rain in the night (of the cascading city-wide twinkle of household cistern switches), with which inadvertently to use the still-existing combined sewer most successfully to flush the yellow wave to quite the wrong destination: through the city's sewer overflows to its then quasi-pristine receiving rivers. Fish do not fare well in the face of ammonia.

This is a start, but such mental reckoning is rather unsystematic, and a far cry still from the restricted detail of the results of Figure 2. Table 1, therefore, has been composed to illustrate, above all, the substantial gap in the logical ties between the "current specific" criteria employed to generate Figure 2 and the "future strategic" criteria at the core of the rest of this paper. Our obligation now is to populate the vacant central column of Table 1, thus to fashion a comprehensive agenda of research: on what these logical links should be; how to construct them formally, possibly quantitatively; hence, to enable consistent assessment of the alternatives against the grand aspiration of "being less unsustainable".

For instance, starting from the right-hand column, under the sub-heading of "environmentally benign", and elaborating upon the bullet of "pulse" – to make the connection back, say, to the bullet of "environmental impact, water" in the left-hand column – it would be necessary to understand better how aquatic ecologists would characterize the quasi-pristine spectrum of nutrient-flux variations in rivers. Subsequently, to prize open the scope for a city's wastewater infrastructure to be manipulated deliberately in moving towards partial restoration of that spectrum, something of the controllability and control authority vested in the unit processes of treatment shown in Figure 1(a) would need to be known – typically through extensive experimentation with the simulation model already used by Jiang (2006).

This suggests imminent, if incremental, progress. But what of the crucial central column under the sub-heading of "socially legitimate" in Table 1; the something that will take us beyond the rhetoric above, of questioning the value of a numerical index for "public awareness" (in Figure 2)? Some of the best work on what might occupy the currently blank central column of Table 2, derives from the hard-won *practical* experience of Davis (2006a), with the Public Utilities Commission of San Francisco, USA. She would begin by pencilling the following kinds of considerations into the space under the sub-heading of "socially legitimate":

> ***On aesthetics***: That the issue causing (objective) engineering analyses to over-reach into (subjective) public debate and democracy is the inability and/or reluctance of engineers to acknowledge and declare their latent aesthetic/subjective values regarding water – their reluctance to be open and honest about this, in short.
>
> ***On communication***: That technical experts (in water utilities) should be learning from the lay public in an equal, two-way exchange (Darier *et al*, 1999; also Beck *et al*, 2002).
>
> ***On social justice***: That strategies of adaptation away from the current Business as Usual paradigm should pursue decentralization of the wastewater infrastructure, to put the odours and dis-benefits of sewage treatment facilities into everyone's back yards, therefore, not just those of the poor and disadvantaged.

Yet these too leave us wondering whether such considerations could, or should, ever evolve into (non-numerical) types of criteria, for gauging whether the public would give house-space to the urine-separating toilet, for instance.

6 CONCLUSION: CITIES AS ENVIRONMENTAL "GOODS"

We think of cities as environmental "Bads". Why not be inspired (by McDonough and Braungart (2002)) to turn them into environmental "Goods"?

Our bull may not be the only beast in the china shop. Indeed, the very obvious animation and agility of the (beefy) athlete we first imagined may be an asset. For there was once a pounding and pulsating elsewhere in the watershed, now hushed and stilled by dams, reservoirs, and diversions of irrigation waters; a symphony now compressed into the monotony of the average – and not just in terms of water flows, but also in terms of the cycles and fluxes of nutrients, silt, and debris (for habitat). Stasis and the average may be anathema to those flora and fauna that evolved to take advantage of the former pounding and pulsating variability. As much as species diversity may be eroded, and habitat spatially fragmented, dismembered, and rendered more uniform, so in this third dimension (of time) can diversity be undermined, degraded, and homogenized.

Could the city and its wastewater infrastructure exploit its own metaphorical movements, in the way it manipulates the forms and fluxes of nutrients, for example, to compensate for the relative immobility of the rest of the watershed in which it sits? Could it restore treble, even bass, to the now restricted tenor sounds of the whole watershed, to recover the full spectrum of perturbations to which the aquatic ecosystem was once subject? As a voice in the choir, or as an instrument in the orchestra – with the *technocracy* still to modulate its voice at will (through its very agility as an athlete) –it might then sing and dance wonderfully to all manner of tunes, thus to right some of the dull-sounding wrongs of reservoirs, diversions, irrigation, fields of mono-culture corn, broad-scale cattle grazing, and the like.

It might, just might. The florid prose notwithstanding, hard, dispassionate, computational effort has already been invested in starting to respond more systematically to such challenges. From this we find three conclusions:

(i) System-wide assessment of individual technologies, within the whole of a metropolitan water infrastructure, itself nested within a simulated account of the surrounding watershed, is by no means a distant prospect.

(ii) Where this computational assessment should be bounded, relative to public debate over the social legitimacy of any technological path into the future, remains unclear – except for our intuition that such assessment should not seek numerically to encompass whatever constitutes "legitimacy" for a given community of stakeholders.

(iii) Our current scheme of adaptive community learning (Beck *et al*, 2002), or participatory technological envisioning, (a) already caters for the driving force of stakeholder aspirations as expressed through imagining *their* futures (*not* those of the Engineer), (b) already caters for role of the Engineer in implementing computational assessment of the reachability of these futures, where (c) the Engineer's role in this collective effort can be significantly enhanced by drawing upon web-based, horizon-scanning software in order to compose future patterns of whole water infrastructures, to be embedded into the computational assessment.

But would the people want any of this? Do they need to participate in shaping and re-shaping these kinds of distant visions? Could they have imagined any of them, with or without any technocratic engineer? Would it help them and their cities to step out, now, into the immediate future, and for Liverpool, Marseilles, Helsingborg, Seattle, Goa, and Shanghai, for example, to move off along experimentally different pathways – that may still allow them to reach the same vision by different routes, yet (better still) provoke the continual adaptation and evolution of collectively richer distant visions? The point is not necessarily that any vision will become a reality, but that the *temporary* suspension of pragmatic disbelief – as in the student forced to contemplate designing a city as an environmental "Good" – should be brought to bear, albeit tenuously, on tomorrow's task of engineering our way out of the technological lock-in of today's water infrastructures in cities of the North.

REFERENCES

Allan, J (2003), "Virtual Water – The Water, Food and Trade Nexus: Useful Concept or Misleading Metaphor", *Water International*, **28**, pp 4-11.

AtKisson, A (2005), "The Goa 2100 Project: A Breakthrough Project from India", in *The Natural Advantage of Nations – Business Opportunities, Innovation and Governance in the 21st Century* (K J Hargroves and M H Smith, eds), Earthscan, London, pp 306-315.

Beck, M B (1981), "Operational Water Quality Management: Beyond Planning and Design", *Executive Report 7*, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Beck, M B (1996), "Transient Pollution Events: Acute Risks to the Aquatic Environment", *Water Science and Technology*, **33**(2), pp 1-15.

Beck, M B (2002a), "Sustainability in the Water Sector: Reflections Within on Views From Without", Background discussion paper, First Leading-edge Conference on *Sustainability in the Water Sector*, International Water Association, Venice, Italy, November, 2002. [available on-line at www.iwahq.org.uk]

Beck, M B (ed) (2002b), "*Environmental Foresight and Models: A Manifesto"*, Elsevier, Oxford.

Beck, M B (2005a), "Sustainability – Seen in Sydney", *Water21*, pp 18-20 (June).

Beck, M B (2005b), "Vulnerability of Water Quality in Intensively Developing Urban Watersheds", *Environmental Modelling & Software*, **20**(4), pp 381-400.

Beck, M B, and Cummings, R G (1996), "Wastewater Infrastructure: Challenges for the Sustainable City of the New Millennium", *Habitat International*, **20**(3), pp 1-17.

Beck, M B, and Speers, A (eds) (2006), "*2nd IWA Leading-Edge Conference on Sustainability*", Water and Environmental Management Series, IWA Publishing, London.

Beck, M B, Chen, J, Saul, A J, and Butler, D (1994), "Urban Drainage in the 21st Century: Assessment of New Technology on the Basis of Global Material Flows", *Water Science and Technology*, **30**(2), pp 1-12.

Beck, M B, Fath, B D, Parker, A K, Osidele, O O, Cowie, G M, Rasmussen, T C, Patten, B C, Norton, B G, Steinemann, A, Borrett, S R, Cox, D, Mayhew, M C, Zeng, X-Q and Zeng, W (2002b), "Developing a Concept of Adaptive Community Learning: Case Study of a Rapidly Urbanizing Watershed", *Integrated Assessment*, **3**(4), pp 299-307.

Beder, S (1999), "Beyond Technicalities: Expanding Engineering Thinking", *J Professional Issues in Engineering*, **125**(1), pp 12-18.

Benyus, J M (1997), "*Biomimicry: Innovations Inspired by Nature*", William Morrow, New York.

Brunner, N, and Starkl, M (2004), "Decision Aid Systems for Evaluating Sustainability: A Critical Survey", *Environmental Impact Assessment Review*, **24**, pp 441-469.

Chen, J, and Beck, M B (1997), "Towards Designing Sustainable Urban Wastewater Infrastructures: A Screening Analysis", *Water Science and Technology*, **35**(9), pp 99-112.

Darier, E, Gough, C, De Marchi, B, Funtowicz, S, Grove-White, R, Kitchener, D, Guimarães-Pereira, Â, Shackley, S and Wynne, B (1999), "Between Democracy and Expertise? Citizens' Participation and Environmental Integrated Assessment in Venice (Italy) and St Helens (UK)", *J Environmental Policy & Planning*, **1**, pp 103-120.

Davis, C K (2006a), "Ethical Dilemmas in Water Recycling", in "*Water Recycling*" (B Jimenez, ed), IWA Publishing, London (to appear)

Davis, C K (2006b), Personal Communication.

European Chemical Industry Council (CEFIC) (2001), "Recovery of Phosphorus from Sewage and Animal Wastes", *Conference Summary*, Second International Conference, Noordwijkerhout, the Netherlands, March, 2001, CEFIC, Brussels [available on-line at www.nhm.ac.uk/mineralogy/phos].

Færge, J, Magid, J, and Penning de Vries, F W T (2001), "Urban Nutrient Balance for Bangkok", *Ecological Modelling*, **139**, pp 63-74.

Falkenmark, M (2005), "Towards Hydrosolidarity: Ample Opportunities for Human Ingenuity", *Report*, Stockholm International Water Institute, Stockholm, Sweden [available on-line at www.siwi.org].

Florman, S C (1994), "*The Existential Pleasures of Engineering*", St Martin's Press, New York.

Galloway, J N (2003), "Acid Deposition: S and N Cascades and Elemental Interactions", in *Inter-element Interactions of the Major Biogeochemical Cycles* (J Melillo, C B Field, and B Moldan, eds), Island Press.

Galloway, J N, and Cowling, E B (2002), "Reactive Nitrogen and the World: 200 Years of Change", *Ambio*, **31**(2), pp 64-71.

Galloway, J N, Aber, J D, and Erisman, J W (2003), "The Nitrogen Cascade", *BioScience*, **53**, pp 341-356.

Gibbons, M (1999), "Science's New Social Contract with Society", *Nature*, **402** (Supplement), pp C81-C84 (2 December).

Grandin, T (2005), "*Animals in Translation: Using the Mysteries of Autism to Decode Animal Behavior*", Scribner.

Grote, U, Craswell, E, and Vlek, P L G (2005), "Nutrient Flows in International Trade: Ecology and Policy Issues", *Environmental Science and Policy*, **8**(5), pp 439-451.

Gyawali, D (2001), "Rivers, Technology and Society", Himal Books, Kathmandu.

Hawken, P (1993), "*The Ecology of Commerce: A Declaration of Sustainability*", Harper Business, New York.

Hawken, P, Lovins, A, and Lovins, L H (1999), "*Natural Capitalism: The Next Industrial Revolution,* Rocky Mountain Institute, Snowmass, Colorado.

Holling, C S (ed) (1978), "*Adaptive Environmental Assessment and Management*", Wiley, Chichester.

Jansson, Å Å, Folke, C, Rockström, J, and Gordon, L (1999), "Linking Freshwater Flows and Ecosystem Services Appropriated by People: The Case of the Baltic Sea Drainage Basin", *Ecosystems*, **2**, pp 351-366.

Jenerette, G D, Wu, W, Goldsmith, S, Marussich, W A, and Roach, W J (2006), "Contrasting Water Footprints of Cities in China and the United States", *Ecological Economics*, **57**, pp 346-358.

Jiang, F (2006), "Nutrient Removal In Wastewater Treatment: Control, Costs, Trading, and Sustainability", *PhD Dissertation*, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, Georgia.

Kates, R W, Clark, W C, Corell, R, Hall J M, Jaeger, C C, Lowe, I, McCarthy, J J, Schellnhuber, H J, Bolin, B, Dickson, N M, Faucheux, S, Gallopin, G C, Grübler, A, Huntley, B, Jäger, J, Jodha, N S, Kasperson, R E, Mabogunje, A, Matson, P, Mooney, H, Moore, B, O'Riordan, T and Svedin, U (2001), "Sustainability Science", *Science,* **292**, pp 641-642 (27 April).

Larsen, T A, Peters, I, Alder, A, Eggen, R, Maurer, M and Muncke, J (2001), "Re-engineering the Toilet for Sustainable Waste Water Management", *Environmental Science and Technology*, 1 May, pp 192A-197A.

Lenzen, M, Lundie S, Bransgrove G, Charet, L, and Sack, F (2003), "Assessing the Ecological Footprint of a Large Metropolitan Water Supplier: Lessons for Water Management and Planning Towards Sustainability", *J Environmental Planning and Management*, **46**(1), pp 113-141.

Little, R G (2002), "Controlling Cascading Failure: Understanding the Vulnerabilities of Interconnected Infrastructures", *J Urban Technology*, **9**(1), pp 109-123.

Loucks, D P, and Gladwell, J S (eds) (1999), "*Sustainability Criteria for Water Resource Systems*", International Hydrological Series (UNESCO), Cambridge University Press, Cambridge.

Malle, K-G (1994), "Accidental Spills – Frequency, Importance, Control, Countermeasures", *Water Science and Technology*, **29**(3), pp 149-163.

Mara, D (2005), "Ecological Sanitation – An Unaffordable Option", sidebar material, *Water21*, p 29 (April).

Matsui, S, Harada, H, Utsumi, H, Matsuda T, and Shimizu, Y (2006), "Advanced Sanitation with Vacuum Truck Collection System of Human Excreta", in *2nd IWA Leading-Edge Conference on Sustainability* (M B Beck and A Speers, eds), Water and Environmental Management Series, IWA Publishing, London, pp 136-144.

McCann, W (2005), "The Sanity of Ecosan", *Water21*, pp 28-30 (April).

McDonough, W, and Braungart, M (2002), "*Cradle to Cradle: Remaking the Way We Make Things*", North Point Press, New York.

Morimoto, R, and Hope, C (2004), "Applying a Cost-Benefit Analysis Model to the Three Gorges Project in China", *Impact Assessment and Project Appraisal*, **22**(3), pp 205-220.

Mulder, K (ed) (2006), "*Sustainable Development for Engineers: A Handbook and Resource Guide*", Greenleaf, Sheffield.

National Science Foundation (2006), "Simulation-Based Engineering Science: Revolutionaizing Engineering Science Through Simulation", *Blue Ribbon Panel Report*, National Science Foundation, Washington DC.

Niemczynowicz, J (1993), "New Aspects of Sewerage and Water Technology", *Ambio*, **22**(7), pp 449-455.

Norton, B G and Steinemann, A (2001), "Environmental Values and Adaptive Management", *Environmental Values*, **10**(4), pp 473-506.

Nowotny, H, Scott, P, and Gibbons, M (2001), "*Re-Thinking Science. Knowledge and the Public in an Age of Uncertainty*", Polity/Blackwell, Malden, Massachusetts.

Otterpohl, R, Albold, A, and Oldenburg, M (1999), "Source Control in Urban Sanitation and Waste Management: Ten Systems with Reuse of Resources", *Water Science and Technology*, **39**(5), pp 153-160.

Pearce, F (2006), "*The Parched Planet*",

Poff, N L, Allan, J D, Palmer, M A, Hart, D D, Richter, B D, Arthington, A H, Rogers, K H, Meyer, J L, and Stanford, J A (2003), "River Flows and Water Wars: Emerging Science for Environmental Decision Making", *Frontiers in Ecology and Environment*, **1**(6), pp 298-306.

Price, M F and Thompson, M (1997), "The Complex Life: Human Land Uses in Mountain Ecosystems", *Global Ecology and Biogeography Letters*, **6**, pp 77-90.

Rees, W E (1996), "Revisiting Carrying Capacity: Area-Based Indicators of Sustainability," *Population and Environment*, **17**(3), pp 195-215.

Rinaldi, S M, Peerenboom, J P, Kelly, T K (2001), "Identifying, Understanding, and Analyzing Critical Infrastructure Dependencies", *IEEE Control Systems Magazine*, December, pp 11-25.

Ringuest, J L, Graves, S B, and Case, R H (1999), "Formulating R&D Portfolios that Account for Risk", *Research Technology Management*, **42**(6), pp 40-43.

Schlesinger, W H (1991), "*Biogeochemistry: An Analysis of Global Change*", Academic Press, San Diego, California.

SIWI-IWMI (2004), "*Water – More Nutrition Per Drop. Towards Sustainable Food Production and Consumption Patterns in a Rapidly Changing World*", Policy Paper, Stockholm International Water Institute (SIWI) and International Water Management Institute (IWMI), Stockholm, Sweden, 35pp.

Solow, R M (1991), "Sustainability: An Economist's Perspective", 18th J Seward Johnson Lecture, Marine Policy Center, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

Thompson, M (1989), "Postscript: Engineering and Anthropology: Is There a Difference", in *Environmental Threats: Perception, Analysis and Management* (J Brown, ed), Belhaven, New York, pp 138-150.

Thompson, M (1996) "Unsiteability: What Should It Tell Us?", *Risk, Health, Safety and Environment*, **169**, 169-179.

Thompson, M, Ellis, R and Wildavsky, A (1990), "*Cultural Theory*", Westview, Boulder, Colorado.

Tsai, J C C, Chen, V C P, Beck, M B, and Chen, J (2004), "Stochastic Dynamic Programming Formulation for a Wastewater Treatment Decision-making Framework", *Annals of Operations Research*, **132**, pp 207-221.

Uhlmann, V (2006), "Sustainability Management by Water Utilities: Views Across Australia, Europe and the USA", in *2nd IWA Leading-Edge Conference on Sustainability* (M B Beck and A Speers, eds), Water and Environmental Management Series, IWA Publishing, London, pp 67-72.

Unesco (2006), "*Water: A Shared Responsibility*", World Water Development Report 2, United Nations, Berghahn, New York.

van der Vleuten-Balkema, A (2003), "Sustainable Wastewater Treatment: Developing a Methodology and Selecting Promising Systems", *PhD Dissertation*, Technical University of Eindhoven, The Netherlands.

Wackernagel, M, and Rees, W (1995), "*Our Ecological Footprint: Reducing Human Impact on the Earth*", New Society Publishers, Philadelphia, Pennsylvania.

Zehnder, A J B, Yang, H, and Schertenlieb, R (2003), "Water Issues: The Need for Actions at Different Levels", *Aquatic Sciences*, **65**, pp 1-20.

Zimmerman, R (2001), "Social Implications of Infrastructure Network Interactions", *J Urban Technology*, **8**(3), pp 97-119.

Current Specific Criteria (Figure 2)	**Program of Research** To proceed from "Current Specific" to "Future Strategic" criteria (To be determined)	**Future Strategic Criteria** (Main discussion of paper)
	Socially Legitimate	
! Public awareness ! Cultural acceptance ! Local development		! Legitimate under the prevailing local, cultural diversity and forms of public debate/discourse amongst the community's various social solidarities
	Economically Feasible	
! Capital cost ! O & M cost ! Total Annualized Economic Cost (TAEC)		! Bequest to future generations: of natural capital and attaching ecosystem services
	Environmentally Benign	
! Resource consumption (chemicals and energy) ! Resource recovery (nutrients, energy, water) ! Environmental impact, water: COD, NH_4-N, TP, TSS ! Environmental impact, soil: sludge volume and mass ! Environmental impact, air: CO_2 and CH_4		! Ecological footprint ("appetite") ! Connectedness in web of global material cycles ("metabolism") ! Spectrum of frequencies of dynamics ("pulse")

Table 1: Point of departure for a program of research intended to provide logical and systematic links for assessment of sustainability against the kinds of grand, macroscopic criteria set out in the paper, relative to the *status quo* of indicator sets typified by Figure 2.

(a)
(b)
(c)

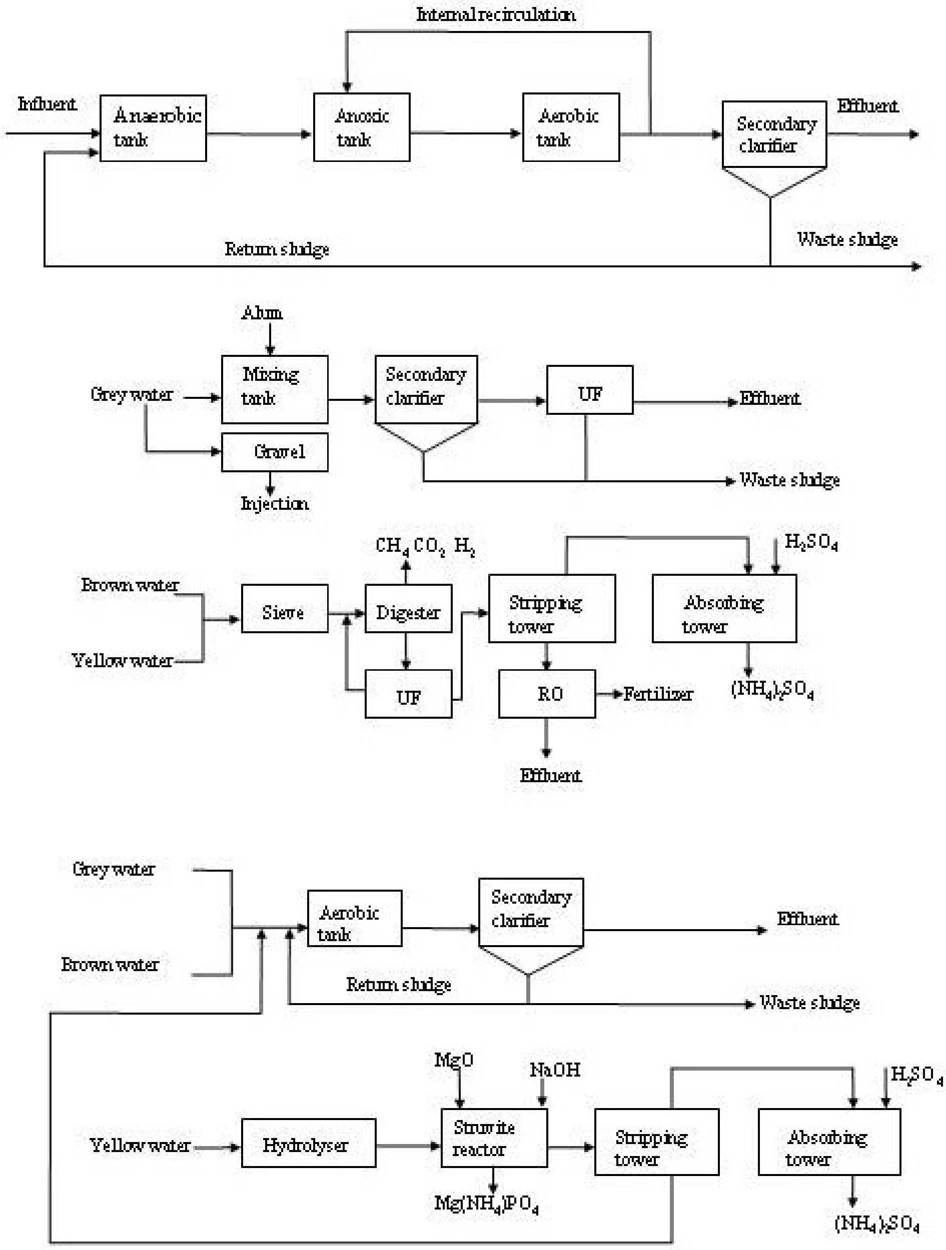

Figure 1: Schematic flow charts for various configurations of the wastewater treatment part of a metropolitan wastewater infrastructure: (a) current Business-as-Usual arrangement, with no upstream separations (referred to cryptically as Mixing); (b) current Business-as-Usual arrangement, with presumed upstream separation in each household of wash waters, i.e., grey water (referred to cryptically as ANS-AHP-separation); and (c) "Yellow Wave" arrangement, with presumed broadscale implementation upstream (in households) of urine-separating toilets (referred to cryptically as ANS-separation; a separate pipe for conveyance of the yellow water through an existing combined sewer system is not necessarily in place).

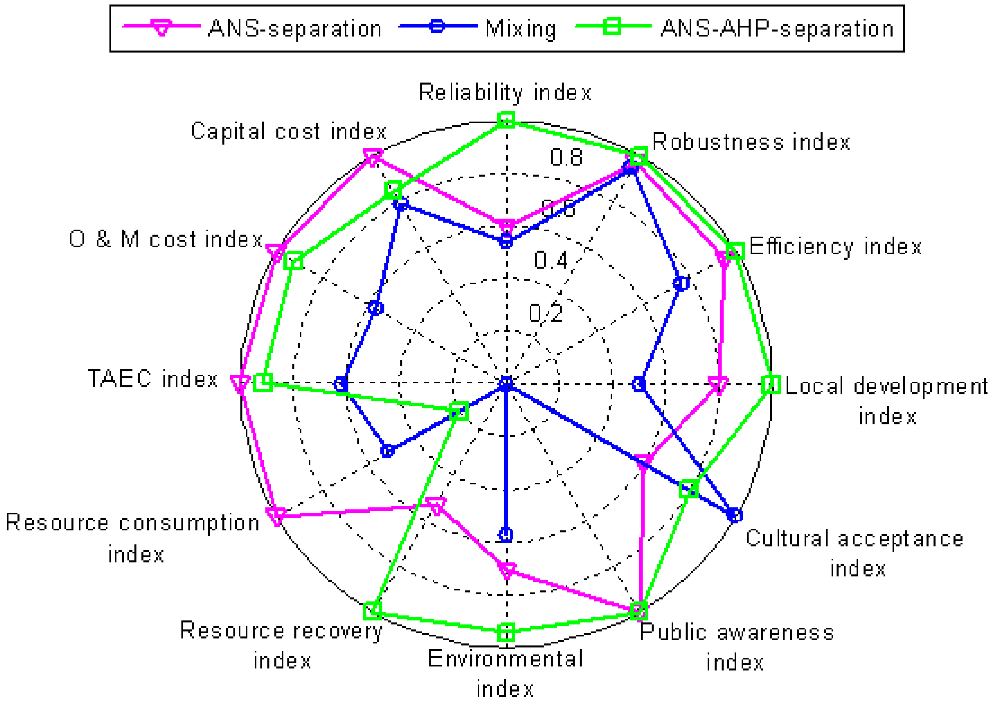

Figure 2: Sustainability assessment of the three designs of Figure 1 according to a typical set of (composite) indicators, spanning the functional, socially legitimate, economically feasible, and environmentally benign facets of infrastructure performance.