Chapter 3: The Triple Bottom Line

> "[W]hat is sound about the idea of a Triple Bottom Line is not novel ... and ... what is novel is not sound" (Norman and MacDonald, 2004).

To each and every force, such as that propelling our discussion strategically towards the merits of the Triple Bottom Line, there is an equal and opposite reaction. Such healthy skepticism is just as apparent in respect of IWRM (Jeffrey and Geary, 2006). That likewise there could be archly opposed schools of thought on the engineering of IUWM, however, has essentially been anathema to our profession in modern times, at least until the "revolutions" of the 1990s already noted. A multiplicity of alternative, even controversial, technological paths leading away from unsustainability may abound, as much as a discomforting multiplicity of inter-generational community aspirations, towards which distant futures those paths should broadly be heading.

Our journey through the Triple Bottom Line may therefore be bewildering for some readers, especially in the now approaching first stage of considering what might constitute {social legitimacy}. For this will not be the stuff of everyday practice in environmental engineering. But we shall still need to take every opportunity to ponder how our ensuring there is optimal flocculation in the clarifier of a potable water treatment facility, for example, fits into this bigger picture.

Plurality: The Absence of Conformity and Convergence to a Singularity

To guide us on our journey, let us consider Figure 2 and, for the moment, confine our discussion of it to just the following, stretching out first to the distant future and subsequently returning in two steps to the present.

Where Society wishes to be generations hence (25-75 years from today) is expressed in Figure 2 as the green oval domains to the upper right of the picture. They are plural, of course. And it would be surprising indeed were the situation to be anything other than this. In a healthy society, with good governance, such expressions of people's aspirations for the longer-term futures of their cherished facets of their environments are highly unlikely to converge on the singularity of a consensus, or shared vision. Significantly too, these aspirations for the distant future should unmistakably be here the views of the lay stakeholders in the given community or city: that which *they* imagine, in *their* terms, to be what we technical experts are calling "IUWM nested within IWRM". Achieving social legitimacy would seem to call for nothing less than that the several distant aspirations of Figure 2 be recognized as "owned" by the different solidarities amongst the stakeholders, bearing thereby the authenticity of *their* authorship, untainted by any signs of manipulation as a result of some carefully crafted process orchestrated by professional experts.[10]

Developing the alternative technological trajectories enabling policy to attain society's more distant aspirations is very much the responsibility of Engineering and engineers. These various paths are symbolized by the red rectangles in Figure 2. Courtesy of the paradigm-breaking thinking provoked by the approach of the new millennium, they too are decidedly multiple. They will not be confined solely to that "business-as-usual" which dominated affairs for the final several decades of the twentieth century. A second school of thought, for example, was hammered out in the very struggle to break — or break free from — that paradigm (Hunt, 2010). It is recognized today as ecological engineering (McCutcheon *et al*, 1994; Odum, 1994), hence distinguished from (traditional) environmental engineering, if not also from Green Chemistry, itself arguably a third relevant school of thought, which also emerged in the early 1990s (Anastas and Warner, 1998; Wikipedia, accessed 8 November, 2008; Warner Babcock Institute for Green Chemistry; www.warnerbabcock.com; accessed 10

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[10] However, the green oval domains of Figure 2 spring from my imagination — I, the technical expert writing this *Concepts Paper* — and those of my professional colleagues (for instance, Beck and Chen, 1999; Beck *et al*, 2011a). If things are thus tainted and unauthentic, alas, so must be it for the purposes of this *Paper.* Nevertheless, I am a stakeholder and a member of Society, not some detached value-free agent, somehow set well apart from Society, as my own personal experience with the origins of what is to come later in Box 4 (of Chapter 4) has clearly shown me (Hare *et al*, 2006).

March, 2010) and subsequently broadened to enfold Green Engineering (Anastas and Zimmerman, 2003).

Extrapolations of future infrastructure components — from whatever school of thought — might reasonably extend anywhere between 5 and 20 years ahead in time.

Taking now a second step back from the distant future to the present, at the lower left in Figure 2, to within the next couple of years or so, some socially legitimate institution or process is obliged to fashion "one routine step" into the future; which step must be most mindful of both the plurality of distant future aspirations and of stimulating expansion in the palette of alternative technological trajectories. In moving from the locked-in initial conditions of the paradigm of water infrastructure in cities of the Global North (those of Figures 1(a) and 1(b)), each routine, incremental technological change should promote a burgeoning of options for subsequent, incremental adaptation.

But how are we to fashion that first, one routine step, for tomorrow? How should we move forward under all the plurality of Figure 2?

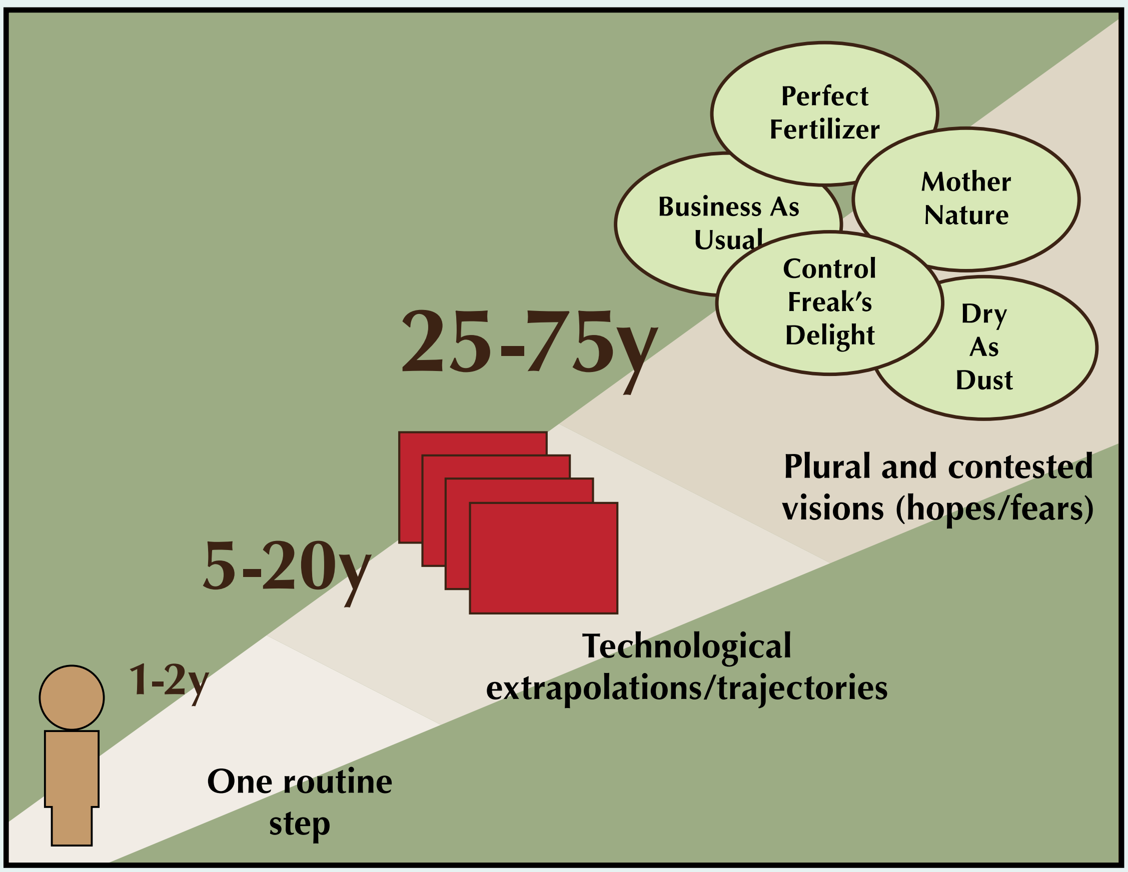

Figure 2:
Framing the "big picture" of how the city might evolve to become a force for good in its environment with, first, the plural (and contested) visions of the distant, inter-generational futures for the city's water infrastructure (green oval domains), second, the technological alternatives (red rectangles) as possible paths towards those futures from, third, the determination and implementation of one routine step "tomorrow".

3.1 Social and Political Legitimacy

> If the challenges we face today — of too great an unsustainability in the water sector — were ones of engineering and technology, they would already have been fixed, years ago. Today's problems are those of achieving good governance.

Simply and succinctly put, we assume governance has everything to do with the healthy debate surrounding the plurality of perspectives held by various stakeholders on any issue of environmental stewardship affecting and within their community. We need to understand something about how this plurality can arise, hence be expressed as the alternative green oval domains in Figure 2, and how the tortuous complexity of community politics and negotiations — as they surround the formation of policy/action — can be grasped through the workings of a relatively uncomplicated typology.

Myths of Nature and Social Bonds

In *Sustainable Development of the Biosphere* (Clark and Munn, 1986), Holling posited four "Myths of Nature" (Holling, 1986; and Figure 3).

Let us begin with his myth of "Nature benign", in the lower left panel of Figure 3. In that outlook, though subject to all manner of insults and injury, Nature is imagined supremely resilient, able to return to the "equilibrium" Man has come to know and cherish over the generations. The state of nature — as the ball-bearing on the basin-shaped potential surface in Figure 3, or as the state variable ($\boldsymbol{x}$) in a mathematical model ($\boldsymbol{M}$) — may be buffeted this way and that, but will always come to rest at the bottom of the basin.

The myth of "Nature tolerant but perverse" (upper right panel; Figure 3), holds instead that — up to a point — Nature will indeed return to the favored equilibrium following disturbance by Man, but if struck too forcefully may be dislodged into quite another equilibrium, and one that may not be at all to Man's liking.

Then there is the myth of "Nature ephemeral" (lower right panel; Figure 3). Those who adhere to this view believe that any perturbation, no matter how small, may cause the behavior of Nature to descend into unmitigated disaster.

For many — and here is the rub, for so many of the world's poor and disadvantaged — Nature must appear as "Nature capricious", behaving without rhyme or reason, beyond their conception of what counts to survive in life (the fourth, upper left panel of Figure 3).

Onto these Myths of Nature can be mapped characteristics of the social solidarities of Cultural Theory (Thompson *et al*, 1990). These are characteristics of how individuals bind one to another to form like-minded groups, with a shared outlook, in particular on the Man-Environment or Man-Nature relationship. Their mapping onto Figure 3 is literally so (Thompson, 2002)[11].

For upholders of the individualist solidarity, typically associated with markets and corporations, Man is regarded as inherently self-seeking and atomistic, while Nature is well able to recover from any exploitation, in other words, "Nature benign". Here, in the lower left quadrant of Figure 3, competition between individuals tends towards being unfettered.

Members of the egalitarian solidarity, for whom Nature is almost the exact opposite — "Nature ephemeral", fragile, and intricately inter-connected — consider Man as essentially caring and sharing (in the lower right quadrant of Figure 3). To them, unfettered competition in the affairs of Man (if not Nature) has very little appeal indeed.

A third social grouping, the hierarchist solidarity, aligns itself with the myth of "Nature tolerant but perverse", in the upper right quadrant of Figure 3. It stands somewhere between the individualists and egalitarians and their favored myths of Nature. For it views Man as malleable, deeply flawed, but redeemable by firm, long-lasting and trustworthy institutions. Egalitarians, being themselves in a rightward quadrant of Figure 3, sympathize with the fettering of competition implied by the hierarchy, but abhor the layered forms of social interactions and differences of unequal status, the very essence of which hierarchy comprises.

[11] We offer this particular anthropological perspective not because we believe it fits all social contexts, but because it offers the most straightforward insights. These insights, moreover, are especially well suited to the setting of water and engineering (see, for example, Dixit, 2002; Gyawali, 2004).

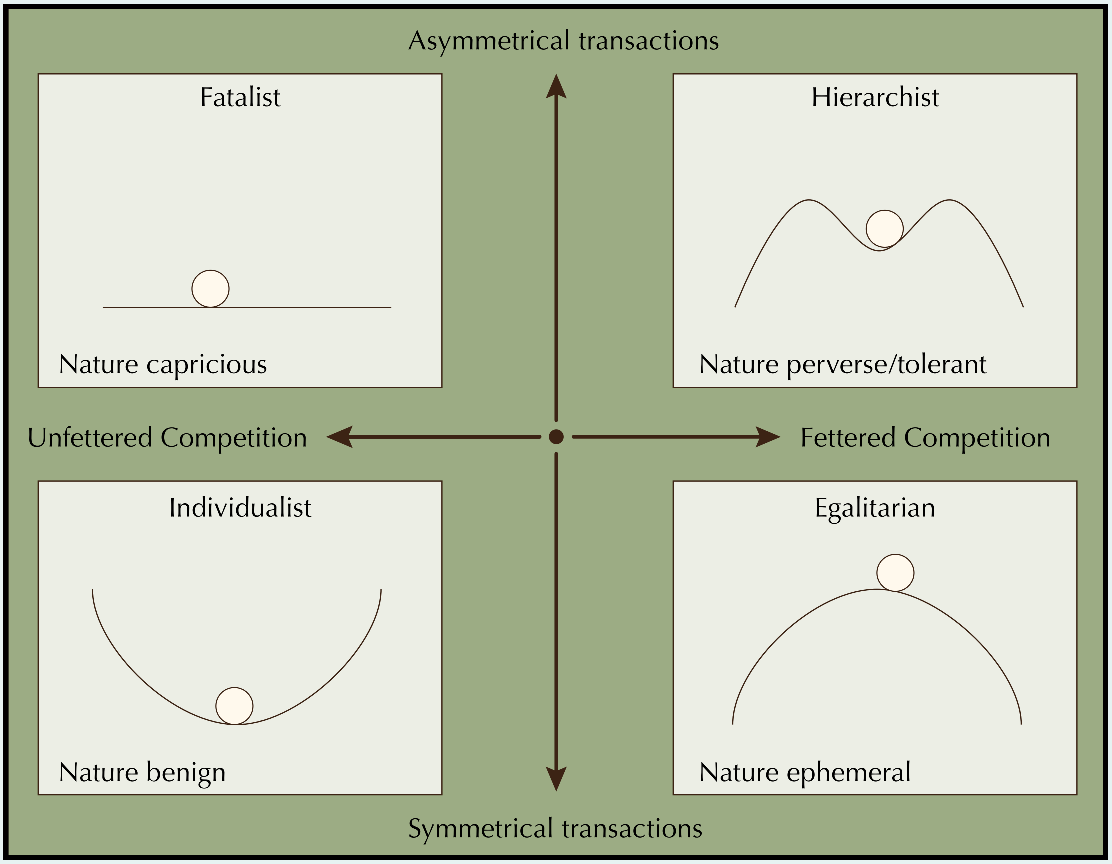

Figure 3:
Thompson's "solidarities", and their respective Myths of Nature (from Holling). The metaphor is that of a ball-bearing (the state of the system) rolling about on a surface (of potential energy), where local stability and stasis are defined by any points on the surface with (locally) a zero gradient (from Thompson, 2002; redrawn).

Standing apart from social and community governance, in the upper left quadrant of Figure 3, the fatalist solidarity gathers around the myth of "Nature capricious", for it knows that Man is fickle and untrustworthy. No member of this solidarity has power or influence in the affairs of Man and Society — why bother to vote, the government is always elected!

Viewed through the prism of this typology of social solidarities, it could be argued that sustainable development is itself essentially an outlook of the hierarchists alone, and one which risks excluding the other "voices" in society: those of the individualist, for whom all development is sustainable; the egalitarian, for whom no development is sustainable; and the fatalist, for whom nothing makes much difference at all.

Styles of Management

Of the five social solidarities recognized in Cultural Theory,[12] but three — individualist, egalitarian, and hierarchist (for the fatalist has, by definition, no voice) — reaffirm the essence of democracy in the affairs of Man and Environment, through their contestation in the policy debate (Thompson, 2000):

> [T]hough each solidarity has its distinctive model of democracy (and is thus able to claim that its solution will strengthen democracy, and that those professed by the others will weaken it) no one of them has the "right" model ...

[12] A fifth solidarity is recognized beyond the four of Figure 3: that of the hermit, who lives out an autonomous existence (Thompson *et al*, 1990).

The three comprise an irreducible, triangular policy space, defined at its vertices by the three policy prescriptions of the three solidarities for solving the ills of the world — a three-legged "contested terrain", as pictured by Gyawali (2004). An orthodox insistence on there having to be a *single agreed* definition of the problem, and the struggles then to decide which policy prescription and attaching model of democracy are right, may not in fact be helpful. Endless, but punctuated, contestation, played out amongst the *enduring plurality* of perspectives, diagnoses, and prescriptions, might rather be the essence of the democracy that is needed.

For the individualist solidarity, therefore, managing institutions that work "with the grain of the market", free of environmentally harmful subsidies, for instance, are what are needed. This is the voice in the debate that calls for de-regulation, for the freedom to innovate and take risks, and for the internalization of environmental costs so as to "get the prices right".

We must all tread lightly on the Earth, argue egalitarians. Trust and leveling go hand-in-hand, while institutions that distribute unequally are distrusted. This is the voice in the debate for whom voluntary simplicity is the only solution to our environmental problems, with the "precautionary principle" being strictly enforced on those who are tempted not to share the simple life. It argues for zero-growth and calls urgently for major shifts in our behavior, so as to bring our profligate consumption down within the limits that have been set by Mother Nature.

Environmental management requires certified experts — assert the hierarchists in contrast — not least because determining the precise locations of Nature's limits, hence statutory regulation, calls for a good scientific grasp of where the boundaries of stability lie in their myth of Nature (in the upper right quadrant of Figure 3). All economic activity must then be kept within those limits. Fair distribution is by rank and station. Theirs is the voice that talks of "global stewardship".

Fatalist actors do not really have a voice in the debate. If they had, they would not be fatalistic! Nevertheless, since time and money that are spent on something about which nothing can be done is time and money wasted, there is some wisdom here that should not be ignored.

Such sentiments — of a constructively contested space of sharply juxtaposed outlooks and prognoses, which essentially should not be rendered down to just a single prescription for managing from one perspective — are widespread in the contemporary sustainability debate. They appear in the *Local Politics of Global Sustainability* (of Prugh *et al*, 2000), the *Panarchy* of Gunderson and Holling (2002), the design space of *Remaking the Way We Make Things* (McDonough and Braungart, 2002), the Public-Government-Science Trialogue of Ashton *et al* (2006), the four world views essential to growing the successful businesses of *The Next Industrial Revolution* (Hawken *et al*, 1999), and the five strategic "rationales" for the restoration of ecosystems (Clewell and Aronson, 2006). Their point is to crystallize out the pluralism of perspective necessary for the birth of policies and designs respectful of diversity — and thereby having a greater potential to succeed.

Styles of Environmental Science, Engineering, and Technology

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, which entail differing attitudes towards risk: 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, skepticism (about technology), and risk-avoidance. Engineers and scientists working in a given context — government department, private-sector consultancy, voluntary organization — will generally tend to frame the "problem", hence the nature of the "solution", in ways sympathetic to the capabilities and influence of that context. This would be no surprise to the authors of IWA's *Sanitation 21* document (IWA, 2006).[13] It was Gyawali's experience too, fired in the crucible of having been Minister for Water Resources in Nepal (Gyawali, 2004):

> The very sciences of different solidarities, their framing of problems, the questions they ask and the areas they look into for answers are different.

[13] And Boxes 2 and 4 will make this quite apparent in due course.

There can, and arguably should, be a plurality of environmental sciences *and*, we add here (again), a plurality of schools of thought on IUWM nested within IWRM. They are set out in Box 1.

In matters of re-engineering and technological innovation, the archetypal hierarchist actor favors high-tech virtuosity and large-scale engineering projects, whereas the egalitarian would celebrate "small is beautiful", as well as small being frugal, empowering, and environmentally benign (Thompson and Gyawali, 2001). The latter ignores any economies of scale, in contrast to the former, who overlooks any dis-economies of scale, such that big is always best. At a scale somewhere in between, where the minimum of the curve of net economic production lies, the individualist will plump for (economically) appropriate technologies — as "cheap and cheerful" as possible. The individualist's challenge, however, is that the minimum is inherently both uncertain and shifting, hence the need for careful judgement and risk-taking. The fatalist instead simply has better things to worry about, such as "getting by from day to day", so that economic productivity is diversified, but not in any systematic or strategically reasoned way — "very cheap, but not so cheerful".

Yet it seems that any murmurs about the merits of engineering and technology innovations in IUWM within IWRM are being drowned out by the calls for "good governance".

Governance Over Technology: The Urge Towards Participation

> The Global Water Partnership (GWP, 2000b, 2002) and the UN's World Water Assessment Program (WWAP, 2006) recognize the current water crisis as a crisis of water governance.

Indeed, we should all doubtless want better governance. And surely a very great deal has been written and discussed of such better governance in the water sector (GWP, 2000b, 2002; EC, 2000, 2001; Barreira, 2003; WWAP, 2006; Ashton *et al*, 2006; Mostert, 2006a; Pahl-Wostl *et al*, 2007a,b, 2008; Pahl-Wostl and Toonen, 2009; Termeer, 2009; Franks and Cleaver, 2009). From this derives that sense of engineering and technology being cast aside, that they are not the issue: a kind of hegemony of "governance over technology", in other words. But how might we now understand governance through the lens of the foregoing discussion of plural Myths of Nature, styles of management, styles of engineering for sustainable development, and so on? For of great concern eventually will be to have a sound appreciation of which elements of governance are enabling (and which disabling) of the kinds of re-engineering interventions and technological innovations deemed attractive for attaining CFG (our challenge from Chapter 2.4; Beck *et al*, 2011b).

History records that most developed nations introduced urban water and sewerage services in the mid-1800s through privately owned companies or private operators. It was not long, however, before these utilities were taken into public (municipal) ownership, with the notable exception of those in France (Juuti and Katko, 2005). The public-sector voice comes across with clarity in the moniker "social municipalism", even reinforced in the accusation — presumably from opposed former private-sector actors — of this being "water and gas socialism" (Barraqué *et al*, 2006). Hooper (2006) tends towards endorsing the same, since he interprets the GWP's call for good governance as emphasizing the involvement and leadership of public-sector actors.

Mondello (2006) appears otherwise convinced, and for reasons likely to confirm those fears persuading Massarutto (2006) to place professionals, experts, and engineers "on probation" (as already observed). Mondello's vision is of the General Agreement on Trade and Services (GATS) of the World Trade Organization (WTO) ushering in more privatization of water services, including in the urban sector of greatest interest to us herein.

Yet others, in particular Mostert (2006a), note the significance of civil-society (non-governmental) actors. If public participation is a very good thing, it would culminate according to Mostert (2006a) in "self control" at the top of Arnstein's (1969) "ladder of citizen participation", wherein "the public performs tasks independently, for example, through water users' associations". Western-style public participation, Mostert goes on to note, has been articulated by government. In promoting and achieving such participation elsewhere, however, non-governmental users' associations have been prominent (and

BOX 1

Schools of Thought: Styles of Engineering Sustainability

Center-span in Figure 2 is a portfolio of several red rectangles. It symbolizes the set of alternative paths of technological transitions, leading away from the current unsustainable pattern of urban water infrastructure (today) towards something judged more sustainable (generations hence). These options for re-engineering the city, we assert, may also reflect alternative schools of engineering thought, or alternative styles of engineering sustainability into an unsustainable system.

We set out these alternatives herein. Our sketches of them are inevitably colored by the subjective perspective of a life-time's experience.[1] History, appropriately therefore, provides both context and a starting point.

S1: 20th-Century Technocratic Paradigm (20CTP)

This is essentially the style of Civil Engineering, with hitherto a modicum of input from Chemical Engineering and, more recently, from Green Chemistry and contemporary, hi-tech Biomolecular and Biochemical Engineering. By reflection — in the eyes of ecologists, in particular — this is all about shovels, bulldozers, earth-moving, bricks, concrete, steel and so on: man, materials, and intrusive engineering structures. "Big is best." It is the infrastructure we have predominantly in cities of the Global North. This is how we have come to know the basic structural configuration of Figure 1(a) for the city's intimately coupled water and nutrient infrastructures. Its future, one might suppose, may continue along much the same lines, as Figure 1(b), with increasing rates of innovation from disciplines other than traditional Civil Engineering.

From the standpoint of Control Engineering, the 20th-Century Technocratic Paradigm would not be described as impressively hi-tech, but rather mid-tech. It struggles to exploit Information and Communications Technologies (ICT) to the full. Its style of re-engineering over the generations can be caricatured as one instinctively of "100% reconstruction": build, demolish, and build entirely anew. The style has a high propensity for technological (and institutional) lock-in, according to Collingridge's four technical indicators of inflexibility in technological systems (Collingridge, 1981; Thompson, 1996): large scale (of the production unit); long lead time; capital intensity; and major infrastructure needs, for example, where a large, remotely located dam (water infrastructure) requires yet other infrastructure as a pre-requisite, such as transport for access (Gyawali, 2004).

The risk of failure is self-evidently low. By definition, 20CTP uses tried-and-tested technologies; it is the custom we have come to expect. In the unfolding of this paradigm over the decades, nonetheless, the system of urban wastewater infrastructure — and the watershed whose integrity it is intended to protect — can be argued to have become ever more fragile and vulnerable (Beck, 2005; Beck *et al*, 2010a). In the absence of ICT, there is no capacity to detect and respond to significant, fast disturbances in real, operational time. The deleterious consequences of any associated upsets will appear all the more amplified, the more the watershed has been restored towards a pre-city status — by the very introduction of this customary (20CTP) sewerage and wastewater treatment in the first place.

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[1] Lest there be any doubt, I declare myself to have been steeped in what will come to be described as the outlook of Dynamics and Control (D&C).

BOX 1

S2: Dynamics and Control (D&C)

Anything having an operational stage in its life-cycle should be the subject of Dynamics and Control. D&C supposes a world in which there has been wholesale incorporation of ICT into engineering systems. "Very smart indeed", its proponents would say. In this ideal world, such thoroughgoing application of ICT would enable full advantage to be taken of the (theoretical) sophistication of Control Engineering — a generic style of engineering, yet not generally taught to Civil Engineers (alone amongst all the primary branches of Engineering). Under D&C, operational management in real-time of each of the constituent unit processes of any of the structural arrangements of Figure 1 ought to be highly responsive to any untoward disturbance or change of operational objective. Pushing this to its logical limit, D&C should be the epitome of a strategy of "0% reconstruction" for re-engineering of the city's infrastructure so that it may become a force for good (a CFG). In the sense of constructive, argumentative debate, D&C could be set to oppose 20CTP (as indeed it is, in Box 3). It should exemplify the spirit of adapting the existing built environment to the maximum extent possible. It is all about sensors, electronics, communication, the internet, computers, buttons, switches, actuators, touch screens, and so on. To the professional engineer, D&C could appear as the "soft" alternative to the "hard" path of 20CTP. To the ecologist it could be seen as his/her nemesis, the apotheosis of all that s/he abhors in the engineering turn of mind: Man's supreme control of Nature; his dominion over it.

D&C looks as if it ought to be low risk. It is merely a matter of applying ICT to otherwise tried-and-tested Civil Engineering works. It should fare well in respect of minimizing operational failure, being fully capable of swift, quasi-subliminal reactions in suppressing damage propagation and accelerating system recovery in the event of any process upset or failure. And yet there is the well-known argument (rehearsed in Beck, 2005): that increasing any system's reliance on ICT merely makes that system even more vulnerable to failure in the supervisory ICT sub-system itself. Altogether "Too clever by half" might be the view of those who are suspicious of D&C's style. D&C, moreover, would be precisely that school of engineering thought promoting Holling's "brittleness" of behavior in any technological system (Holling, 1996). For it is largely born of a belief in being able to control the system according to the Myth of "Nature benign" (in Figure 3; lower left panel). In this view, devoting ever more ICT and automation to confining movement of the ball-bearing of Figure 3 to an ever narrower trough on the potential surface, renders the system ever more prone to abrupt failure — worse still, with no means of maintaining any kind of useful service under the then ensuing radically changed operating conditions.

At its core, the Control Engineering of D&C is about re-engineering the dynamics of a system's behavior. It is about changing the spectrum of perturbations and variations to which our lives should otherwise naturally be subject, through our participation in the water and nutrient metabolisms of the city, so that they might become more to our liking and comfort. But what is liked and comfortable for one individual or solidarity may be very different from that for another, exactly as conceived of in Figure 3.

S3: Ecological Engineering with Self-Organizing Systems (SOS)

To the extent that any specific realization of any of the basic arrangements of Figure 1 is intrinsically lower-tech (in the mind of the archetypal engineer), so SOS will be pre-disposed towards application thereto. This might primarily be the case for Figure 1(c), where aquatic ecosystems may predominate,

BOX 1

or Figure 1(d) in which terrestrial ecosystems may be better attuned to an infrastructure gathered around the technologies of dry sanitation.

For those who view D&C as the culmination of the heavy-handed, technocratic paradigm of Engineering — surpassing even 20CTP in its most extreme form — SOS would have none of all that ICT. It would have none of any *externally* imposed control. Control should much rather be encouraged to derive from within the system, as it does *par excellence* in the self-organization of natural ecosystems. Advocates of SOS, therefore, argue for a system of urban wastewater infrastructure thoroughly rid of the controlling, un-natural hand of the engineer. They argue for the natural-ness of flora, fauna, soils, and the unit processes of wetlands, reed-ponds and so on — not the manufactured-ness of steel and concrete, nor the engineered intensity of the unit processes contained within the structures made of such materials. SOS is Ecological Engineering writ large, in spite of a recognition of this very title being (highly) debatably an oxymoron (Hunt, 2010).

SOS suffers from two strategic difficulties. First, it is difficult to make the unit processes of SOS work intensively in the compressed and confined spaces of dense cities. Second, because of their intrinsic *self*-organization and nonlinear ecological complexity — *and* our inevitably substantial lack of understanding thereof — their behavior must be replete with latent "tipping points", hence full of "systemic risks". Just as much as control and stability derive from *within* the self-organizing system, so may the seeds of its instability, with no apparent, *external*, causative disturbance. We may not know well on which potential surface of Figure 3 things are operating. Furthermore, the system itself may be evolving, or re-organizing internally the way it organizes itself. The shape of the potential surface is migrating, in effect, through the four archetypes of Figure 3, such that the previously innocuous, minor, external perturbation may push the system's dynamics over the edge into instability. If we imagine technologies to have life-cycles, these processes of Ecological Engineering — when somehow softly re-engineered to work more intensively in cities — could "grow up" to be the "wayward teenagers" we all know of only too well. Absent ICT, moreover, we would have no idea of passage past the latent tipping points, until there was teenage messiness all over the place.

When city-focused, therefore, SOS should be considered potentially high-risk. Yet being tried and tested, hence low-risk, is precisely what SOS could be claimed to be. For there are decades and centuries of experience of SOS designs in the rural and pre-industrial societies of China and Indo-China. But here too lurk significant latent risks. SOS's origins in the intensely close cycling of the excreta of humans, pigs, ducks, and fish amongst the houses, pens, and ponds of south-east Asia might make it a most effective engine of pathogen evolution and propagation. Perhaps SOS seeks to realize just a bit too much of the mantra of eco-effectiveness, of "waste equals food" (McDonough and Braungart, 2002).

S4: Decentralization: Small is Beautiful (SiB)

This, now, strikes one as a most democratic style of engineering sustainability. SiB's inspiration is that of placing "control" back in the hands of the ordinary people in the local street. Things will become beautiful through the increasing smallness wrought by systematic decentralization of the currently massively centralized — *ergo* brutal — configuration of 20CTP. Small could be beautiful for any of the structural arrangements of Figures 1(a), (c), or (d): from the residuals of our daily bread and water being utterly mixed, to their separation respectively under wet and dry sanitation systems. Imagine thousands of miniature replicates of these arrangements of Figure 1 eventually blooming across the

BOX 1

city. With the beauty of such local empowerment comes responsibility for technical failure. As the form of infrastructure migrates away from the single, centralized wastewater treatment plant, owned and operated by the municipal government (or private utility), logic would require responsibility to rest increasingly in the hands of the individual head-of-household.[2]

SiB bears a risk. Its logical thrust is that of returning the water and nutrient infrastructures of the city to where they were, in their close spatial proximity, prior to the invention and introduction of the WC. The risk is therefore that of undermining the security of urban public health. "Small" might be too "intimate". The lesson has been comprehensively learned: the supply of drinking water should remain technically remote from the disposal of human excreta. In the denseness of the cities of the Global North, and in the light of increasingly innovative approaches to urban agriculture at various scales (Dagerskog *et al*, 2010; Drechsel and Erni, 2010), questions of concern arise. How much of the city's daily bread and daily water might best still come from afar on the upside of the city, to reach each of the "internal" miniature replicates progressively breaking away from the city's originally centralized wastewater infrastructure? How much might *safely* be the share of the internally re-generated nutrients and water (and rainwater) supplies, recovered from the downside residuals of the growing throng of internal replicates? The thrust of SiB, towards (in principle) ever tighter water and nutrient cycles, conveys the risk of compressing the coiled spring — to the point where it snaps back.

The risk, lesser or greater, surely depends on one's perspective. "Ever more local needs ever more automated control", it has been said (Olsson, 2006); or, to paraphrase, "Ever more local needs ever more of the generic style of D&C's school of engineering thought". Yet, as we have said, one may be no more secure with such use of ICT in this context (see Zimmerman, 2001) — of its doing the right thing unfailingly, automaton-like ("Too clever by half") — than with either ill-trained professional personnel, or untrained, "unpoliced", technically lay members of the public, who fail to do the right thing at the right time. To put this in a nutshell: is a single, large failure in the professionally supervised and policed municipal government's (remote, river-side) centralized treatment plant better or worse than a lot of small failures in lots of unprofessionally supervised (and unpoliced) households, including one's own, in the heart of the city?

S5: Earth Closet (EC)

Where neither the WC has been introduced, nor the entire water-based paradigm for removing human excreta from one's very personal space — 20CTP, in effect — some would say they should better *never* be introduced. Thus would we have an infrastructure of dry sanitation, gathered around the Earth Closet (EC), or composting toilet, or some other variation on this basic theme, hence the designation of EC for this style of engineering sustainability. Human waste would thus never be introduced so conspicuously and directly into the water cycle.[3]

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[2] Survey data on the introduction of urine-separating toilets indicate a clear preference for having such devices installed and maintained in *public*, institutional spaces (such as a library) as opposed to the *private* space of the household (Lienert and Larsen, 2009). Bearing responsibility *personally* — for maintenance of this form of "technological individualization" — is significant.

[3] Except *via* groundwater systems, as precipitation drains through the earth-compost deposited on the land (Drechsel and Erni, 2010). Or, if "dry" is sufficiently dusty to be whipped up by a wind, via the atmosphere, with subsequent deposition on the land (or the skin of citizens). Everything is related to everything else, in one way or another.

BOX 1

If, in the cities of the Global North, we were to take the belt-tightening of eco-efficiency to the possible absurdity of its logical end-point, the water metabolism of the city would be cut to an absolute minimum, with effectively zero-discharge of water on the downside of the city, hence the prime motivation for drawing the third structural arrangement of the urban metabolism according to Figure 1(d).

The essential dryness of EC, with its appeal to terrestrial ecosystems as opposed to the aquatic ecosystems of SOS, ought at least to be able to circumvent the risk-prone syndrome of the "pathogen-factory" of SOS's historical origins. It should thus be deemed low risk in that particular respect, except where (i) flooding is a serious prospect, hence mobilization of the pathogens and nutrients temporarily immobilized by EC, or (ii) pathogen inactivation chemicals (such as lime) may be carried aloft as dust, with insufficiently inactivated pathogen spores ready to take advantage of any skin irritation created by that chemical treatment.

S6: Separation at Source (S@S)

Like the preceding style of EC, this last school of thought is defined by its own basic structural configuration of the city's water and nutrient infrastructures. Figure 1(c) is its embodiment. This is how the essential challenge of Cities as Forces for Good was originally conceived (Chapter 2.4), although it would not then (*circa* 1998) have been considered what is here styled the Separation at Source (S@S) school of thought. S@S is distinguished by a path of technological transitions inducing structural change in the conventional configuration of the city's water infrastructure (Figure 1(a)). In its pursuit, the various fluxes of residuals from the city's notional households are not mixed (Figures 1(a) or 1(b)), but separated at source, hence the progressive transition from Figure 1(a) to 1(c), and even beyond to Figure 1(d) — attached, as it is, to EC above.

One might argue that S@S is not another school of thought, since it calls for the same kinds of Civil Engineering interventions as 20CTP. Yet 20CTP was driven by an utterly dedicated, single-minded "water-centric" goal of pollution control. Water-borne substances, including nutrients, were to be removed as environmental "bads", in order to generate a single product, namely, progressively less polluted water. *Removal* of nutrients from wastewater remains a most active domain of engineering invention and design; and it may well remain so for many years to come. Before there was the challenge of Cities as Forces for Good (Chapter 2.4), there was the more specific challenge of producing a "perfect fertilizer", through re-engineering of the city's wastewater infrastructure. The intent was therefore quite other than that of the water-centric 20CTP. Nutrient recovery and the production of a perfect fertilizer (as an environmental good) were to become the single-minded purpose of (re-) design, deliberately to turn the previous intent on its head, with crystal-clear water relegated to the status of mere by-product.

There are three segments to the S@S strategy, each distinguished in respect of space-scale: what happens locally in the household (L), i.e., source separation of feces from urine (and from water, as the means of residuals transport); what happens, if necessary, by way of transporting (T) the separated fluxes to somewhere else, possibly somewhere remote (R); and what happens at the possibly remote "somewhere else" (R), in terms of resource recovery (nutrients, energy, water), typically at the centralized wastewater treatment plant of 20CTP. It is hard to imagine the household urine-separating toilet (UST) — and like sanitation devices applicable at the very local and personal scale (L) — as *not* being key to an S@S style of engineering sustainability (Larsen *et al*, 2009; Larsen, 2011).

BOX 1

The intensely local segment (L) of S@S may inherit some of the risky features of the individually empowering style of SiB. Siting and operation of the machinery and facilities for resource recovery may create the potential for too much of the "wrong" materials — incompletely recovered nutrients; the chemical additives and microbial communities of recovery; and incompletely inactivated pathogens — to be in the "wrong" place in the event of failure. Transport of the wrong materials to the right place (*via* T) may also be risk-prone, in particular, if (T) must rely on the legacy infrastructure of 20CTP, i.e., through adaptations of the existing, combined city sewer network. Separation in time — of a sequence of pulses of water, yellow water (urine), black water, or whatever water, through the network — will be prone to the chance occurrence of precipitation triggering the combined sewer overflow.

Nothing is without risk, however, not S@S, EC, SiB, SOS, D&C, or 20CTP. Rectifying the always re-emerging Achilles heel of each is what drives innovation — in perpetuity.

Engineering and its Anthropology: Orthodoxy, Rebels, and Cranks

Writing on "*Uncertainty and Quality in Science for Policy*", Funtowicz and Ravetz (1990) introduced what they called a "research-pedigree matrix". As a field of enquiry matures, they argued, colleague consensus passes from "no opinion", to "embryonic field", "competing schools", to "all but rebels" and "all but cranks". The inference in this progression is that "competing schools" will — or should — eventually yield to the orthodoxy of a single school of thought. It could be, therefore, that "sustainability engineering" for IUWM within IWRM has presently progressed from an embryonic field to the several competing schools of thought set out in this Box.

This, of course, is not exactly our argument here. For we assert throughout this *Concepts Paper* that a state of competing schools of thought is (and should be) enduring. In the spirit of Cultural Theory, whose seminal text was also published in 1990 (Thompson *et al*, 1990), if there is an orthodoxy, then even the voices of the rebels and cranks should not be entirely ignored. After all, whence derives the anomaly and its irritant advocate that motivates the paradigm shift (Kuhn, 1962)? How is the flagship enterprise of SOS — the "Living Machines" of Todd *et al* (2003) — working its way within or without 20CTP? Cultural Theory inherently permits the notion of each school of thought asserting its orthodoxy, hence its hegemony over the other fervently held orthodoxies — all thus being rendered mutually contradictory "certainties". Hunt (2010) records the anthropology of the struggle of the "irritant" ecological engineering and eco-technologies to be acknowledged in the (over-bearing) presence of environmental engineering (the 20th Century Technocratic *Paradigm*, in effect).

Evidence of similar struggles is recorded elsewhere (McCann, 2005; Chapter 3.2 in the main body of the text; and Box 2). An "eco-san" toilet, for instance, seeks nutrient recovery as a priority, along the lines of SOS, or EC, or S@S. The professional (engineering) sub-group within the International Water Association (IWA) who are promoting thinking about this kind of device/technology used to call themselves the Ecological Sanitation (Eco-San) group. They now associate under the rubric of Resources Oriented Sanitation (ROSA) — a change chronicled between the 2006 and 2008 editions of the IWA Yearbook. The motivation for the change may have been to better convey the intended (transformative) message to an audience populated by adherents of other schools of engineering thought, most probably (in their view) that of 20CTP. Yet the re-branding may have been precipitated by some fairly aggressive criticism of the term "ecosan" in McCann's 2005 article in the magazine *Water21* (see also Box 2). The headline jibe was of "eco-insanity" (McCann, 2005). The essence of

BOX 1

the argument against the eco-san toilet, in this particular instance, was that those yet to attain access to basic, rudimentary sanitation for survival should not be asked to consider a more expensive alternative dedicated to the luxury of recovering resources.

As with the manner in which ROSA may have grown uncomfortably out of a reaction to strident criticism of ecosan, what is now CFG was born in part of a reaction to the vituperative heaped by the establishment of the 20CTP school of thought upon the notion of producing perfect fertilizer from the conventional wastewater infrastructure of cities of the Global North. In the spirit of Funtowicz and Ravetz (1990), such a turning on its head of the motivation of 20CTP must have appeared then (a decade ago) as the doings of a rebel or, worse still, a crank.

Things do indeed change. With the benefit of the long view (1870-2000), the analysis of Neset *et al* (2008) for the phosphorus metabolism of Linköping reveals how the symbiosis amongst agriculture, diet, the city, and its wastewater infrastructure has waned over the centuries and decades — but that there is a hint it might now be on the cusp of waxing. Our (human) nutrient residuals are once again to be seen as resources instead of pollutants. They are already, as we know from the city of Ouagadougou, the capital of Burkina Faso (Dagerskog *et al*, 2010).

successful), notably in the rural, irrigation sectors of developing countries.[14]

Like so many things that appear new, this urge towards greater and better "participation" has been growing for quite some time (Reed, 2008). And like IWRM and the TBL, a degree of jaundice may soon set in (Reed, 2008):

> [S]takeholder participation has been increasingly sought and embedded into national and international policy. Although many benefits have been claimed for participation, disillusionment has grown amongst practitioners and stakeholders who have felt let down when these claims are not realised.

Governance *is* complicated. Reaching up to the heights of Dahl's (1989) classic theory of pluralist democracy, good governance has been defined as founded on the following (Ney, 2009; Thompson, 2008a):

(i) The voice of each of the three (active) solidarities should be heard in the debate, over choices in setting off "tomorrow" (in Figure 2) towards the collective set of distant aspirations;

(ii) Each solidarity should be responsive to each of the two other voices, i.e., not attempt to ignore or shout them down.

Drawing upon the phrasing of legal theorist Schapiro (1988), Thompson (2002) calls for a "clumsy institution" as the enabling mechanism of such good governance. Clumsy institutions would grant some recognition to each conviction as to how the world is, each Myth of Nature in Figure 3. They would be "messy, noisy, and argumentative" institutions. This, Thompson contends, would be (Thompson, 2002):

> ... in contrast to those more elegant, and more familiar, arrangements (tidy, quiet and suavely consensual) in which just one conviction holds sway.

It would be governance decidedly extolling the virtues of committed engagement (participatory, that is), if not seeking consensus. It would seek rather to harness contestation. So deeply defining may this be, some might want to change the aphorism "*Cogito, ergo sum* (I think, therefore I am)" to "*Dissentio, ergo sum* (I disagree, therefore I am)" (Nowacki *et al*, 2010).

Overcoming the Gravitational Pull of Consensus?

> "Simple systems are manageable in the sense that, once we understand enough about them, we can define some desirable state of affairs (sustainable development is the current favorite) and then steer the totality towards it." (Thompson, 2002)

Given consensus about the singular "it"— *the* shared vision, that is — policy preferences for the necessary "steering" ought to be all the more readily revealed.

If only we could agree on *one* choice of distant aspiration (one of the green oval domains in Figure 2, say that of the distant target of Perfect Fertilizer), we would know whither we should be headed, as well as the attaching technological path towards that destination from the present Business-as-Usual.[15] If we could only agree on an operational definition of "sustainability", or "sustainable development", we would know how to make progress away from unsustainability in the water sector and towards sustainability. If we could only agree on how to measure sustainable development, policy options for attaining it could be clearly ranked and the "best" extracted for implementation — rather along the lines of solving our caricature of the mathematical program of sustainability in Chapter 2.5.

Examining the manner in which communities and societies arrive at consensus — a shared vision of the future, or an agreed index of sustainable development — is thus important. For it lies at the heart of one of the deliberately contrarian postures of this *Paper*.

---

[14] Under the continuing migration of rural inhabitants into the city, it is not inconceivable that the institutional "culture" of rural water users associations could flow with these people into the institutional setting of urban water governance. It has happened before. At the time of industrialization and the growth of urban communities in Europe "migrants from the countryside imported their customs and requested free water of good quality from public taps" (Barraqué *et al*, 2006).

[15] We shall, in fact, choose the Perfect Fertilizer target — with its strong attachment to the challenge of CFG (Cities as Forces for Good) — as *the* anchoring device for much of the remainder of this *Concepts Paper*. Such a singular focus is necessary in the interests of specificity and clarity of exposition. It should not, of course, be read as any abandonment of the pluralities of stakeholder aspirations and styles of engineering sustainability so essential to the overall argument of the *Paper*.

According to Boulanger (2008), only the UNDP's Human Development Index (HDI) has achieved any real measure of success as an index of social well-being, and certainly more so than the Index of Sustainable Economic Welfare (ISEW) of Daly and Cobb (1990). Yet the HDI has been vehemently attacked by Baneth (1998), on the grounds that (as quoted in Boulanger, 2008):

> It was a vain, pretentious and slightly ridiculous endeavour to try and sum up human development in all its complexity and multiple dimensions with a single figure.
>
> A pilot flies an aircraft using data supplied by a large number of instruments and that data cannot be summed up in a single indicator.

For Boulanger himself, however (Boulanger, 2008):

> The aircraft metaphor is irrelevant ...
>
> In a human society, things are very different. All its citizens do not have, a priori, the same destination and perhaps most of them do not even know where they are going. Before even thinking about steering the social aircraft, its pilots must try to get everyone to agree on where they are headed.
>
> This is exactly where indicators for sustainable development come into play.

Now the struggles over which model of democracy is "right", which would threaten so severely to undermine the capacity to incorporate quantitative accounts of {social legitimacy} into any formal scheme of optimization (the mathematical program of Chapter 2.5), begin to matter.

Boulanger (2008) calls upon two such models of democracy: "aggregative" and "deliberative". Under the former, he does not expect his promotion of indexes of social well-being to come properly to pass, in liberal democracies which (Boulanger, 2008)

> ... see the political process as a simple choice, by voting, between a priori preferences which were generated before the electoral process.

Going to the heart of the dispute over all such indexes, their means of integrating indicators into indexes — through *aggregation* — he asks (Boulanger, 2008):

> [o]n what basis and using what procedure should the decision be made, for example, to give the economic pillar a 45% weighting, 35% to the social pillar and 20% to the environmental one?
>
> [Rather] ... there is another model for democracies, the "deliberative" model, in which the political process exists precisely for creating a common vision of what is good or just.
>
> It is deliberation which makes it possible to transform "pre-reflective" preferences, established ex ante, into ex post reflective preferences, capable of transcending personal opinions and taking the common good into consideration.

In other words, this is public participation of an active, not passively reactive, kind, underpinned by political theorist Dewey's strong preferences for such, as expressed in his 1927 text *The Public and Its Problems* (Dewey, 1927; as cited in Boulanger, 2008). The process is one of deliberately transforming and adapting prior preferences into posterior preferences: getting "everyone to agree on where they are headed", as Boulanger (2008) would have it, still seemingly captivated by the gravitational pull of consensus.

Thompson, however, writing here (above) about "*Man and Nature as a Single but Complex System*", would actively resist entrapment in the allure of achieving consensus (Thompson, 2002). He opens his piece with the subtitle "A Road Without End" — and one indeed whose eventual direction will only unfold as we travel along it, sometimes driven predominantly by the policy style of one solidarity, later by another, and so on.

Except that, to insist literally on consensus may be to be pedantic. Instead, a decent number of Boulanger's "everyone" might agree on where they are headed, for a while, with the others going along grudgingly (in Thompson's terms), until the disagreements — never banished, nor suppressed, nor entirely resolved — reassert themselves, bringing about a change of direction (Gyawali, 2004).

Referring to the mature regulatory context of environmental law and policy in the United States, Coglianese (2001a) says this:

> We are living, as some might have it, at the dawn of an age of consensus.

> This craving for consensus was institutionalized in 1990 with the passage of the Negotiated Rulemaking Act ...

His path-breaking — and hotly debated (Coglianese, 2001b) — analysis of the empirical evidence leads him to conclude that seeking consensus does not save time, does not lead to improved policy, and does not lower the rate of legal challenges to policies (Coglianese, 2001a). Consensus-seeking risks shifting policy-making away from serving the public interest, substituting the process with merely the design of policies people can "live with", by "lumping it" (Coglianese, 2001a), perhaps "going along grudgingly" (in other words).

Elsewhere, puncturing the notion of participant "satisfaction" as a measure of successful public policy-making, Coglianese (2003) observes that this is incomplete because "it excludes those who do not participate". As Thompson would say, all the voices have not had access to the process. Like Boulanger, Coglianese is not impressed by the aggregative model of democracy, which he characterizes as follows (Coglianese, 2003):

> According to one common conception of democratic theory, public decisionmaking is all about the aggregation of — and ultimately the satisfaction of — public preferences.

Such refinement of environmental governance, with ready recourse to an effective legal discourse, does not obtain everywhere, however.

What happens, moreover, in the *public* space of community debate and disputation may be quite unlike the view arrived at, hence the strictly personal decisions made (the acting very locally) in the *private* space of the individual in his/her dwelling or household.

Basic Instincts: Human Aspirations

Amidst the chaos and deprivation that are the enduring state of some cities in some parts of the world, sustainability must seem a luxury, if not an irrelevance. In the midst of an earnest academic debate of world views on the Man-Environment relationship — amongst the three myths of Nature "benign", "tolerant but perverse", or "ephemeral" — can dawn the realization: that so very, very many people in the world subscribe to none of these. For these three active voices in the debate around the community-environment-policy-design space are beyond conception of what it takes simply to survive in life, beyond comprehension of the advantages of a deliberative model over an aggregative model of democracy.

Writing well before any inkling of the HDI, Maslow (1943) — in his theory of human motivation — gave birth to what has since been summarized as his pyramid, or hierarchy, of needs. Other similar sets of "satiable needs" for achieving happiness can be found in Max-Neef (1991), whose elements include subsistence, protection, freedom, identity, participation, creation, idleness, affection, and understanding (see also Azar *et al*, 1996). In the prodigious four-volume treatise on "*Human Choice and Climate Change*" (Rayner and Malone, 1998), an entire chapter is devoted to a discussion of human needs and wants (Douglas *et al*, 1998). It reminds us of our commonplace experience: the attempts we all make to argue for this, that, or the other as a "need" *not* a "want", hence to justify its becoming *the* priority for policy action. "We" want what we assert to be "the" priority need, not someone else's want, which we seek to render inferior — as a want (not a need) — through the power of our voice. Seeking sustainability may just as reasonably be pursued as a need by some, while being perceived as a want or a luxury by others (as will become quite apparent shortly). There are those, then, who dispute whether needs and wants are in fact hierarchical. Maslow's metaphorical pyramid is to be flattened, as it were (Douglas *et al*, 1998).

Others, assuming still the hierarchy, have attempted since to give a more contemporary interpretation to the pyramid. They argue that those needs at its apex (values, beliefs, and aesthetic preferences) should *not* be considered the concern of seeking sustainability, if this is to become a more meaningful concept (Marshall and Toffel, 2005). Skeptics of sustainability, however, viewing it as a luxury of the Global North, would say it is unlikely to flourish below level 3 in Maslow's hierarchy (labeled "Love/Belonging"), where the over-riding, urgent priorities are: "Safety" (level 2), as in security of body, of employment, of morality, and so on; and — at bottom — sheer "Physiological" survival (level 1), i.e., matters of breathing, food, water, sex, sleep, homeostasis, excretion.

How, then, can investments specifically in water infrastructures promote individual and community development beyond raw survival towards meeting the aspiration of love/belonging — if at all they can? How can these engineering interventions be deployed expressly so that those at the bottom of the pyramid of dignified human development may be brought to such a state where they care to engage in any debate over the challenge and vision of Chapter 2.4 — of cities as forces for good in *their* environment — beyond their desperate needs of survival for just today and tomorrow?

IWA's *Sanitation 21* document asks a more rudimentary question: "Why Do 'Well-designed' Urban Sanitation Systems Fail?" (IWA, 2006). Its answer is failure through the mis-matching of types of sanitation services provided across the different scales of human agency — household, neighborhood, district, city, and "beyond" — to the types of demands for such services by each of these actors.

In its analysis, *Sanitation 21* reports that actors expressly aspire to "environmental protection" at larger scales (the city, and beyond-the-city). This aspiration disappears from people's agendas at progressively smaller scales of agency, falling behind the goals of social status and cleanliness, which are priorities for the neighborhood and household actors (IWA, 2006). When plotted in Figure 4, as sets of ranked aspirations versus scale/domain, one candidate answer to our own question might run as follows. That style of basic sanitation somehow enabling convergence and consistency of significant aspirations amongst the household, neighborhood, and ward/district scales of human agency would need to be in place as a prerequisite for debating sustainability in the water sector around the community-environment-policy-design space. In fact, all but the "Onsite Dry" technical option, of the eight or so set out in *Sanitation 21*, would seem to satisfy this requirement (IWA, 2006). The barrier to acquiring a stake in the "luxury" of sustainability appears thus hardly insurmountable.

It is *not* that the poor and disadvantaged in their desperate, unsanitary circumstances comprise solely the passive fatalist social solidarity of Figure 3. On the contrary, as Box 2 relates in small and encouraging ways, we might conclude that healthy community debate and entrepreneurship (not to mention hope) spring eternal, including around the technological design space of a form of sanitation potentially vital to attaining several of the distant, global visions of Figure 2 (those of Perfect Fertilizer, Mother Nature, and Dry as Dust). Thus report Dagerskog *et al* (2010):

> Since March 2009, there has been a "human fertiliser" market in Ouagadougou, the capital of Burkina Faso. Human urine and dried faeces are collected and taken to eco-stations, where they are sold to farmers after adequate storage. In this way they increase sanitation coverage, create jobs in the private sector and provide urban farmers with complete and efficient indigenous fertilisers.

Things are altogether more subtle and complex than the simplified Figure 4 might suggest. The purpose of Box 2 is to explore such subtlety and complexity in greater depth.

Long View: Engineering and Inter-generational Equity — Ever in a State of Change and Flux

There is a deeply rooted moral and ethical role for engineers in societies. In his book *The Existential Pleasures of Engineering*, Samuel Florman reminds us of the moral cause that engineers once attached to Engineering: to install works — our engineering interventions — that would lift the ordinary people out of the drudgery of their daily existence (Florman, 1987). So great was their commitment to this vision that engineer Gantt — he of the charts around which we gather today's project time-lines — founded an association called the "New Machine" in order to pursue his vision of what society should be. Unlike sustainability, that association passed rapidly into obscurity (Florman, 1987). But the wellspring of the vision — the moral and ethical commitment — endures, less perishable, more timeless. It finds its way into the outcome of Box 2, for instance.

Value systems and *Weltanschauungen* do indeed change. Most of us today, both within and without the engineering profession, would probably be aghast at Gantt's early 20th Century vision. In the 19th Century, medics, clerics, politicians — all technically lay persons from our contemporary perspective, as water professionals — opined pertinently on the subject of Victorian city infrastructure, and were heeded by the engineers of the day. For most of the 20th Century, following the rise of the profession of sanitary and then environmental engineering, we experts believed we alone knew what was best for the water sector (Beder, 1997). In just these last 10-20 years, such selfconfidence (if not arrogance) has been punctured. How today should members of the community of environmental engineering professionals learn from the *seeming* "amateurism" — when it comes to water — of the public and the politicians?

We have come to recognize that the water engineering of the second half of the 20th century was not "self-evidently doing good by the biosphere". And there will surely be changes yet to come.

In many countries eutrophication remains a significant problem. If, however, one is reasonably convinced of the likelihood of the nutrient-rich residuals of our daily bread coming to be seen as resources gainfully to be recovered, how should one view the headlong rush to remove these resources of tomorrow as pollutants of today — even spending significant amounts of energy to "burn" them up into the atmosphere (through microbial nitrification-denitrification)? Or there again, over the decades, precisely the opposite of eutrophication might become *the* problem — could we call it "oligotrophication"? — through some exotic species invasion, such as zebra mussels in the Great Lakes of North America (Schertzer and Lam, 2002). What was once considered a polluting action may become a restorative action.

Science evolves. Understanding how the Environment works, and how Man interacts with it through policy prescriptions and the technologies embedded therein, may change the very grounds on which such policies are founded. The basin-shaped potential surface underpinning the Myth of Nature Benign in Figure 3 may be evolving, rims turning downwards, to that of Nature Tolerant but Perverse, or something

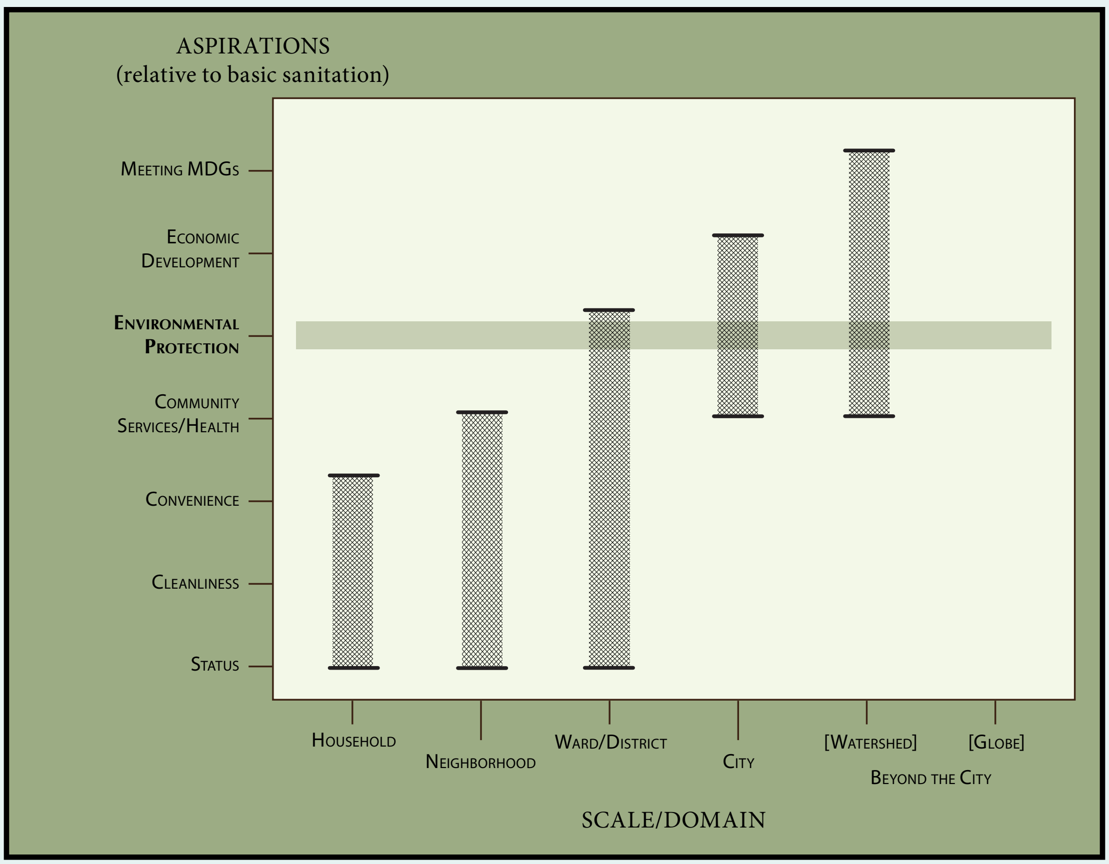


Figure 4:
Scale-dependent human aspirations relative to access to basic sanitation: a modest re-working and graphical portrayal of the hierarchy of preferences of *Sanitation 21* (IWA, 2006; Table 3 therein). In view of the discussion of the graphical (as opposed to tabulated) representation of this material in Box 2, the reader should note well this distinction. The intentions of *Sanitation 21* should not be confused with the present re-working herein of a small portion of its content.

else. The surface may in fact be co-evolving with the policy applied. At the moment of casting the policy action in stone, we simply cannot be aware of all that is happening — and may happen in the future — to the Environment (Beck, 2002; Dennis, 2002). Our "knowing" is not quite right, and will never be so. Policy originating from one style of management, involving technology from one school of engineering thought, may only come to pass in circumstances altogether alien to that conviction — that Myth of Nature; that school of thought — holding sway as the eventual policy was hammered out in the preceding disputatious debate.

Behavior, decisions, designs, and technologies that looked intrinsically "good" in their day can become "bad" in the eyes of a beholder generations later. Is then the young water professional of today, developing and applying software geared ever more efficiently to building an ever more successful, cost-effective infrastructure for nutrient removal, behaving inequitably by his/her children?

If we never asked such a question before, the fact of its being asked here and now is the consequence of seeking sustainability in the water sector.

No-one, of course, can presume to predict how our value systems (and fashions) might change over the generations, which is why it is so difficult to incorporate considerations of inter-generational equity into formal analyses of sustainability. Some core ethical attributes, such as the UN Convention on Human Rights (UNGA, 1948) are more "constant" or invariant than others. Even there, however, flux and change are in the air, in respect of the matter at the very heart of this paper, namely water: that access to it should become an inalienable human right; in response to a failing system of water supply in Jakarta (Bakker, 2006); through protest at the 2006 World Water Forum (Pahl-Wostl *et al*, 2007b); hence through the UN declaration of 28 July, 2010, to which nations are to sign up (BBC, 2010; www.bbc.co.uk/news; accessed 3 August, 2010).

A generation from now the concept of sustainability itself, with its triple bottom line and IUWM nested within IWRM, may leave our children and their children aghast; just as we are today looking back on Gantt's vision, or recoiling now at the caricature of a mathematical program in Chapter 2.5. Few technological systems are less capable of rapid adaptation and evolution than the water infrastructures of cities of the Global North (Collingridge,1981; and Box 1); to few others, therefore, can adoption of the inter-generational long view of sustainability be more fitting.

For the moment, however, aspiring to be less unsustainable is what still captures our imagination. Yet with the prospect now of our greatest hopes suffering the fate of Gantt's vision, with undertones of our vanity in contemplating the nature of our own legacy, are sustainable styles of IUWM nested within IWRM those designed for continual adaptation and evolution? Instinct would have us jump towards responding in the affirmative, perhaps. But was not much of Victorian engineering "built to last", in contrast — and largely, it has to be said, to our good fortune today, a century and more on?

BOX 2

A "Person-Centric" Perspective on the World of Water: Needs, Wants, Luxuries — and Motivations

Figure 4 conveys a simplified representation of how aspirations — needs, wants, luxuries — vary as a function of scale, from that of the individual household to that of the globe. It is based on tabulated material from IWA's *Sanitation 21* document (IWA 2006). Here, we reveal some of the subtleties and complexities masked by what is otherwise the benefit of Figure 4's graphical simplicity. Our argument will take us from the large (global) to the small (local), and back. En route, we shall be obliged to deal with a plurality of social perspectives, thus to bring some disorder (some deconstruction) to the neat, linear "correlation" of Figure 4.

Aspirations, Scale, and Agendas

Sanitation 21 was motivated by these questions:

> Just how important is the environment and how do decision makers value its protection when assessing a range of sanitation options? When, if ever, is it justified to expend energy created by the burning of fossil fuels on cleaning wastewater? Is it fair to charge very poor people the costs of wastewater treatment from which they experience no immediate private benefit? If this is not fair, how can utilities operate and who should pay them for the costs of running a system? How much can utilities be expected to promote environmentally optimum solutions if this results in no revenue for them?

Their collective point is this. In effect, ordinary urban dwellers — those unserved in respect of basic sanitation at the local household and neighborhood scale — are being asked to put in mind benefits and costs relevant to actors, agencies, and the environment at larger scales. But that is not how these individuals perceive their needs. Which immediate needs, if they are to be met for sanitation at the local scale, will not be driven by, or serve, any broader considerations of the environment. And that is the point of Figure 4. Citizens' preferences vary across scales (as observed elsewhere by Gatzweiler (2006)).

Sanitation 21 goes on to say:

> These questions are just a few of those which should be addressed by system planners when initiating or managing urban sanitation systems. Often they are not because the decision making process is dominated by one particular type of decision maker — perhaps an engineer with highly technical knowledge, or perhaps someone from a development agency with a strong social agenda or a strong home-industry export agenda, or again it may be the environment agency or a donor with a strong commitment to environmental protection. But in all these cases opportunities for exploring the whole range of potential solutions may be lost and the agenda may be 'hijacked' by one particular interest group.

These multiple decision-maker types we can now readily recognize in the archetypes of the social groupings and solidarities of Figure 3. They have their characteristic styles of management and they have their agendas: *their* solutions so well tailored to *their* specification of the problem. Whichever solidarity gets to rank and order the various aspirations up the vertical axis and within the bars of Figure 4, also gets to set the policy agenda and put "their" needs — as the policy priority — ahead of the thereby rendered (inferior) "wants" of others (whatever the others might argue!).

The voice of the ordinary people is not being heard; their needs are not being met. Another larger, louder voice holds sway in framing the problem, *ergo* its solution. "Why do 'well-designed' urban sanitation systems fail?" enquires the *Sanitation 21* report (IWA, 2006). Because what is 'well-designed' in the eyes

BOX 2

of one beholder is ill-designed in those of another.

The "Luxury" of a More Sustainable Toilet— the "Needs" of Basic Sanitation and Shelter

This too is asked in the *Sanitation 21* document (IWA, 2006):

> Can people who have no previous experience of recycling human wastes be persuaded to adopt such practices and who pays for the promotion of the approach?

The ecosan dry toilet is one such means of recycling. In particular, it is one already the subject of vigorous debate in professional circles, with accusations in the air of its epitomizing the expensive luxury of sustainability — for the multitudes of the poor and unserved, that is (Box 1; McCann, 2005; also Chapter 3.2). Kwame's recent field study (2007) of the social acceptability of ecosan dry toilets — amidst the tough realities of life on the ground in peri-urban Accra, Ghana — could hardly have been more timely (Kwame, 2007).

Adoption there of the new technology promised not just sanitation but the benefit of nutrient recovery (instead of environmental pollution) and the personal and community obligation to confront the actuality and proximity of our very human biological residuals. Those in the community with a strong individualist flare wanted to know whether a market for the sale of personal, composted residues could be created, not least to compensate them for the waste of their own personal time in achieving the composting. Hierarchical types, if they could not have the status symbol of a WC, preferred legislation — for punishing non-compliant members of the community — and trusted, certified experts, such as community health nurses and sanitary inspectors, as the bases of their scheme for managing the introduction and operation of the new ecosan technology. Egalitarian participants meanwhile, understood the benefits (without further expert endorsement), would allocate land to collective, community composting, even in favor of land for individual shelter, and stood ready to overcome the single obstacle to adoption. Their agenda was to change the perceptions of the individualists and hierarchists who had yet to be persuaded of the benefits of recycling human wastes through introduction of the ecosan toilet (Kwame, 2007).

The need of the community for basic sanitation had still to be met. Yet there were those within that self-same, unserved community, who argued for the seeming luxury — to others — of a more sustainable style of toilet. Indeed, this was a luxury needed by some over and above the want of others of a roof over their heads.

The simplicity of Figure 4 conveys part of the message, in particular, that of how aspirations vary with scale and domain. It implies however — as does the *Sanitation 21* document on which it is based (IWA, 2006) — that one nominal set of aspirations can be expressed (if not its elements ranked) at each scale, as though there is a single, homogeneous "actor" in that domain. Kwame's (2007) empirical evidence suggests quite otherwise. What is more, the tidily organized and coherent bars reaching up the vertical axis of Figure 4 might in practice be shot along the entire axis, fragmented and incoherent (but not necessarily at all vague).

BOX 2

The Small and the Big Things in Life

We are urged to eat less meat (by Lord Stern), entreated to generate a designer sewage (by Watts, 1993) and, better still, give house-space to an ecosan toilet.[1] Higher technology, in the form of the Information and Communication Technology (ICT) of the D&C style of engineering sustainability in Box 1, can be brought to bear on warning us of our imminent transgressions in excessive consumption of water (and energy) in the bathroom shower (Willis *et al*, 2010).[2] To these small and personal things of life can now be added the avoidance of divorce. For it is not environmentally sustainable, argue Yu and Liu (2007). It leads to more households, fewer people per household, less efficient use of the rooms in a house, and consistently so across 12 countries from both the Global North and South. As they report (Yu and Liu, 2007):

> 627 billion gallons of water could have been saved in the U.S. in 2005 if the efficiency per person in divorced households had been the same as that in married households.

Yet breaking down such lumped consequences and aggregated numbers into the very small and highly personal — and motivated by the empirical findings of what happens when cities *shrink* (for example, Leipzig in eastern Germany) — Skirbekk (2009) challenges the arguments of Yu and Liu (2007). Divorced individuals tend to live in more centralized settings, in apartments as opposed to free-standing houses, and their child-bearing patterns differ from those who remain married. These things also matter, as do the particular spatial arrangements of housing types *vis à vis* the specific spatial configuration of the attaching urban water supply network (not to mention its sewerage).

Lord Stern may have come upon the small and the personal from the bigness of global climate change and the high carbon-footprint of global fertilizer and food production. Would any of us chance upon the big and the global, departing from the intensely personal and intimate matter of choosing whether to divorce? What, then, far less stressful, but still close to home, might bring to mind the cumulative, outward propagating ramifications of such small and local actions in the bigger picture?

Motivation: Scale and a Person-centric Perspective

As water professionals, we have always asked ourselves: "What can environmental engineering do for public health in the city?". Driven by the big issues in the world (sustainability and climate change), we peer into the city from the outside, much as in Figure 1: "Thinking globally; acting locally"; posterior action flowing from prior debate.

We should ask this too, of the small (but vital) things in life: "What can my personal health and well-being do for (re)engineering of the water and nutrient infrastructures and metabolisms of the

---

[1] But this last would be a hard sell in some countries. For if even "water use is often overlooked" in building codes for sustainable homes in a water-centric world (the UK, in this instance; Gaze and McKeown, 2009), what chance is there for the sustainability of the nutrient metabolisms of those homes to be taken into account? However, one might find that in the round — in the big scheme of things — eating meat is not all that bad, if somehow downstream of the home it enables relatively easier recovery of nutrients in forms more readily and beneficially recyclable than those deriving from a vegetarian diet. The question should at least be raised.

[2] National building codes derived from the deliberations of large (national) institutions may stimulate the re-design of household water-consuming (hence energy-consuming) appliances for maximum eco-efficiency. But it is local, individual human behavior in respect of their deployment and operation that is crucial (Kenway, 2010).

BOX 2

city, as well as the global cycling of nutrients (and water) beyond?". Our concern could — perhaps should — be the fashioning of policy interventions with scope *primarily* for broadening people's perceptions. Our circumstances change. Individuals in the city find their circumstances shifting back and forth along the continuum: from survival; to having then a life with less health, and then more health; to a sense of well-being, including the well-being of a dawning awareness of the more distant, remote facets of the natural and global environment. If we, as professionals, are so convinced of the universal "good" of our all being less unsustainable, what devices, technologies, and styles of water-nutrient infrastructure should be invented and installed, deliberately to create a yearning within the community for a sense of the bigger picture, hence for disputing and debating that universal good itself?

What if, as engineers — yet motivated by the small and personal things in life (of our personal health and well-being) — we were to adopt the person-centric view of the world of Figure B2.1? If we understood how people reason outwards, from themselves, in their own strictly personal, local circumstances, to grasp the big issues; and if we could associate specific engineering and technological interventions with each element of such reasoning; could we then prioritize those interventions nudging the community faster — rather than more slowly — towards the desired apprehension of those big issues? Having thus divined some key "pressure points" in the logic of the beliefs of that person-centric perspective, what might we propose as promising and specific, professional engineering interventions intended deliberately to make the remote and the global palpable to the local and personal? Would this, in the present century, be a coming to pass of "environmental conservation ... as a core state interest", in succession to that of social welfare in the last century and economic success in the 19th Century (as hoped for by Dryzek *et al*, 2002; see also Chapter 3.2)?

"What makes people care?" asks the psychologist. "What evokes empathy within the individual?" These days, with the technological advances of Imaging Neuroscience (Schmitt *et al*, 1998), we can observe the minuscule of those neural networks in the brain that are activated when we, as individuals, are confronted with the experiences of others: their physical/cognitive circumstances; their psychological/social circumstances; their hunger, their poverty, their lack of sanitation. Our brains respond to such things, it appears (Immordino Yang *et al*, 2009), not through activation of any higher-level, culturally acquired neural networks, but through the profoundly existential, subliminal, visceral bits of brain function. These are primal drives of survival. With monumental significance, we know that "people will kill for ideas". And yet we also know that under evolution, from the beginnings of solely the "selfish gene" (of popular book titles; Dawkins, 1976), can emerge cooperation: beyond the gene, the cell, the organ, and the organism (as we climb up the scales), amongst human individuals, expressed and acted out within their society (at a yet larger scale).[3] In 1943, when Maslow published his seminal "Theory of Human Motivation", he could not have imagined how the minuscule of that motivation might today be empirically observed (Davidson, 2004; Davidson and Lutz, 2007).

What then might engender empathy for the big (remote) issues in Figure B2.1, in particular, of sustainability and climate change (Chiao and Mathur, 2010)? Might engineers have an ethical role in

[3] This synthesis is based on a presentation of Terrence Deacon at a workshop on "The Human Brain and the Social Bond" (Konrad Lorenz Institute and International Institute for Applied Systems Analysis, Altenberg-Laxenburg, Austria, September, 2010). The merest hint of how such grand synthesis might be assembled can be found in Deacon's published work on the evolution of language capacity (Deacon, 2010).

BOX 2

this? For this would be a case of:

"[Engineers] Acting Locally, [as deliberate stimulus to community yearning for] Thinking Globally"!

Now the goal would be to promote posterior debate through prior action. In turn, of course, further (posterior) action should emanate from what would by then have become that prior debate.

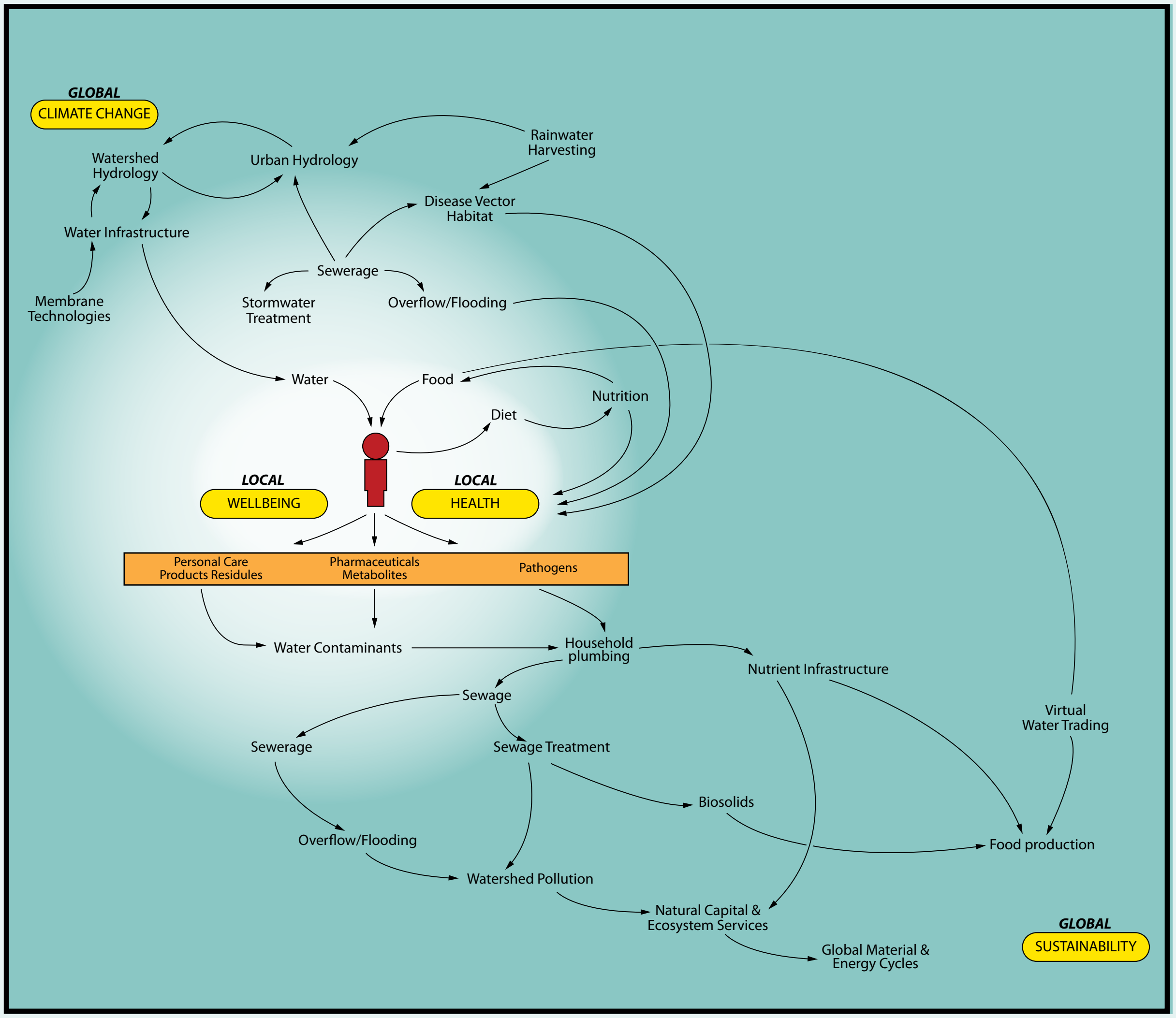


Figure B2.1:
A person-centric network of conceptual associations among entities in the ever-widening perception of the individual citizen (urban dweller). In other words, scale ranges from the local and most intimate of personal choices outwards to the global, whole perspective of Earth Systems Analysis, including thoughts of Sustainability and Global Change. "Think (ever more) globally, while continuing to act (very) locally".

3.2 Economic Feasibility

Our goal in this *Paper* is to strike a balance between a sense of "knowing broadly what to do" and our remaining unsettled in the knowledge that "that 'knowing' is itself not quite right". Our goal is also to facilitate an effective balance between the routine and the uncommonly innovative.

In the introduction of Chapter 1, a commitment was made to adopting a contrarian stance: not to heed the siren calls to convergence on some settled, crystalline, immutable, unquestioned, operational definition or procedure for sustainability (at least, not to heed these calls for the moment); and to insist on taking the long view. Writing from the disciplinary standpoint of Engineering, we could readily admit to the discomfort and difficulty of dealing with all the plurality of perspective that has now burst out of the foregoing discussion of {social legitimacy}. As engineers too, we can look back to the mathematical program caricatured in Chapter 2.5 and readily appreciate the impossibility of pouring the contents of Chapter 3.1 into some crisply shaped mold of quantitative, mathematical representation. As for the long view, we have turned this back onto our own discipline, almost as shock therapy, to emphasize the way in which the very foundations of our science, technologies, styles of management, and outlooks on the world are continually evolving in the longer term — of today looking back aghast at Gantt's aspirations.

Inasmuch as we may have horrified social scientists with the crudeness of our appreciation of what it may take to achieve {social legitimacy} in IUWM within IWRM, so we now risk offending economists.

In the Language of Business: Natural Capital, Ecosystem Services, and Service Providers

According to Hawken *et al* (1999; p 4), an economy needs four types of capital — its factors of production — to function properly:

> human capital, in the form of labor and intelligence, culture, and organization
>
> financial capital, consisting of cash, investments, and monetary instruments
>
> manufactured capital, including infrastructure, machines, tools, and factories
>
> natural capital, made up of resources, living systems, and ecosystem services

This last is the newcomer. Its significance for Hawken *et al* (1999) is not in doubt, for their book is entitled *Natural Capitalism: The Next Industrial Revolution.* At the beginning of the first industrial revolution, they relate, human capital was the scarce variety of capital and therefore the limiting factor in the economy. Natural capital, conceived of as "resources", as opposed to the more modern interpretation of resources *and* "ecosystem services", was abundant — indeed, so much so, it was not even granted the significance of being considered a form of capital. At the close of the first industrial revolution, human capital has become abundant, while natural capital is threatened with being driven towards scarcity.

It is clearly still a titanic, polemical struggle to gain recognition of this, as the title of another recent book makes clear — *Natural Capital and Human Economic Survival* (Prugh, 1999) wherein we can read (Prugh, 1999; p 19):

> The fundamental error of the dominant economic worldview is to treat land (the environment) as merely a factor of production (and one of declining importance, at that). In effect, this outlook locates the environment within, and subordinates it to, the human economy ...

We have inherited from neo-classical economics (Prugh would argue) the profoundly wrong-headed view that the environment is enfolded within human economy; human economy is not enfolded within the environment, as it should be.

In 1963, Barnett and Morse wrote a classic text on *Scarcity and Growth: The Economics of Natural Resource Availability* (Barnett and Morse, 1963). The subject was addressed again in 1979, in *Scarcity and Growth Reconsidered* (Smith, 1979); and then revisited in 2004, with the publication of *Scarcity and Growth Revisited: Natural Resources and the Environment in the New Millennium* (Simpson *et al*, 2004a). Over these four decades, scarcity has come to be reclassified as an "Old Scarcity", of fossil fuels, minerals, agricultural products (Pearce, 2004), and the "New Scarcity" (Simpson *et al*, 2004b), as in the

> sky, water, and land ... employed for waste disposal with [previously] little thought about

> the consequences

or (Pearce, 2004)

> [the Earth's] life support assets, such as biological diversity, the global atmosphere, ocean resources, tropical and boreal forests, coral reefs, and wetlands.

The difference between old and new is as that between how the environment was viewed in the *Limits to Growth* of the early 1970s (Meadows *et al*, 1972), as stocks of resources, and how in the contemporary *Natural Capitalism* (Hawken *et al*, 1999), as stocks and flows of services provided by those stocks.

While some elements of the legacy of neo-classical economics are clearly contentious, others are apparently not (Ayres (1998), as cited in Hawken *et al* (1999; p 165)):

> If there is any implication of neo-classical economics that seems to be beyond challenge it is that shifting the relative prices of factors of production (i.e. labor, capital resources) will eventually induce the economy to substitute the cheaper factor (labor) for the more expensive one (resources). For the same reason, I want to increase the tax burden on activities that damage the social or natural environment, so as to discourage such activities and reduce the resulting damage.

Environmental taxes, or pricing a polluter's use of the environment to receive his/her waste, and tradable permits to discharge a given quantity of pollutant, are both forms of market-based instruments of environmental policy (Pearce, 2004).

Given the four forms of capital, sustainability can be interpreted as a matter of passing on to future generations an undiminished aggregate of capital stock, summed across its four types. Thus, if substitution is possible — if forms of capital are entirely fungible (interchangeable) — sustainable behavior in the present could embrace replacing, say, some natural capital with at least as much equivalent manufactured capital (Figure 5(a)). Human economy could thereby continue untroubled on its path into the future.

Economists would call this meeting the conditions of "weak sustainability" (Pezzey and Toman, 2004). No-one would argue there would be no trouble should this notion of fungibility be pushed to the logical absurdity of all natural capital being replaced by manufactured capital. The trouble with the notion, however, is that natural capital, especially in the dimensions of ecosystem services and living systems (as opposed to non-renewable resources), is essentially not substitutable (as Dyllick and Hockerts (2002) reiterate). The survival of the human economy, as Prugh (1999) has put it, cannot be ensured without the passing on to future generations of some minimum stock of natural capital.

Still, if forms of capital are fungible — an assertion Norton and Toman (1997) ascribe primarily to Solow (1993) — inter-generational obligations reduce to a concern for a "fair investment policy". There are no particular things that we owe to the future. Hence, the present generation will pass an "unstructured bequest package" on to future generations (Norton and Toman, 1997; as recorded in Figure 5(a)).

If fungibility does not obtain, however, so that a minimum stock of natural capital must be passed on, then arrangements must be made for a "highly structured bequest package". This now is as represented in Figure 5(b), and qualified by the term "strong sustainability".

Ecosystem Services

Figure 6 (Aronson *et al*, 2006) encapsulates this same history — from first to subsequent industrial revolutions — although it chooses to focus on the correlation between declining natural capital and rising manufactured capital (as opposed to human capital). At the same time, it confirms the growing appreciation of the significant difference between natural capital and ecosystem goods and *services*, the historic fall in whose quality and diversity is matched — according to Aronson *et al* (2006) — by the increasing cost and difficulty of their restoration, if not its impossibility (Dyllick and Hockerts, 2002).

We do indeed work in an inter-disciplinary setting. Aronson *et al* (2006) would probably not baulk at being labeled ecological *restorationists*; their paper was composed expressly for the purpose of engaging in a cross-disciplinary dialog with ecological *economists* Farley and Daly (2006); and that dialog takes place in the journal of Ecological *Engineering*. Figure 6 (Aronson *et al*, 2006) is a carefully thought-through adaptation of an earlier diagram composed by Daly and Farley (2004). In opening the dialog, Aronson *et al*

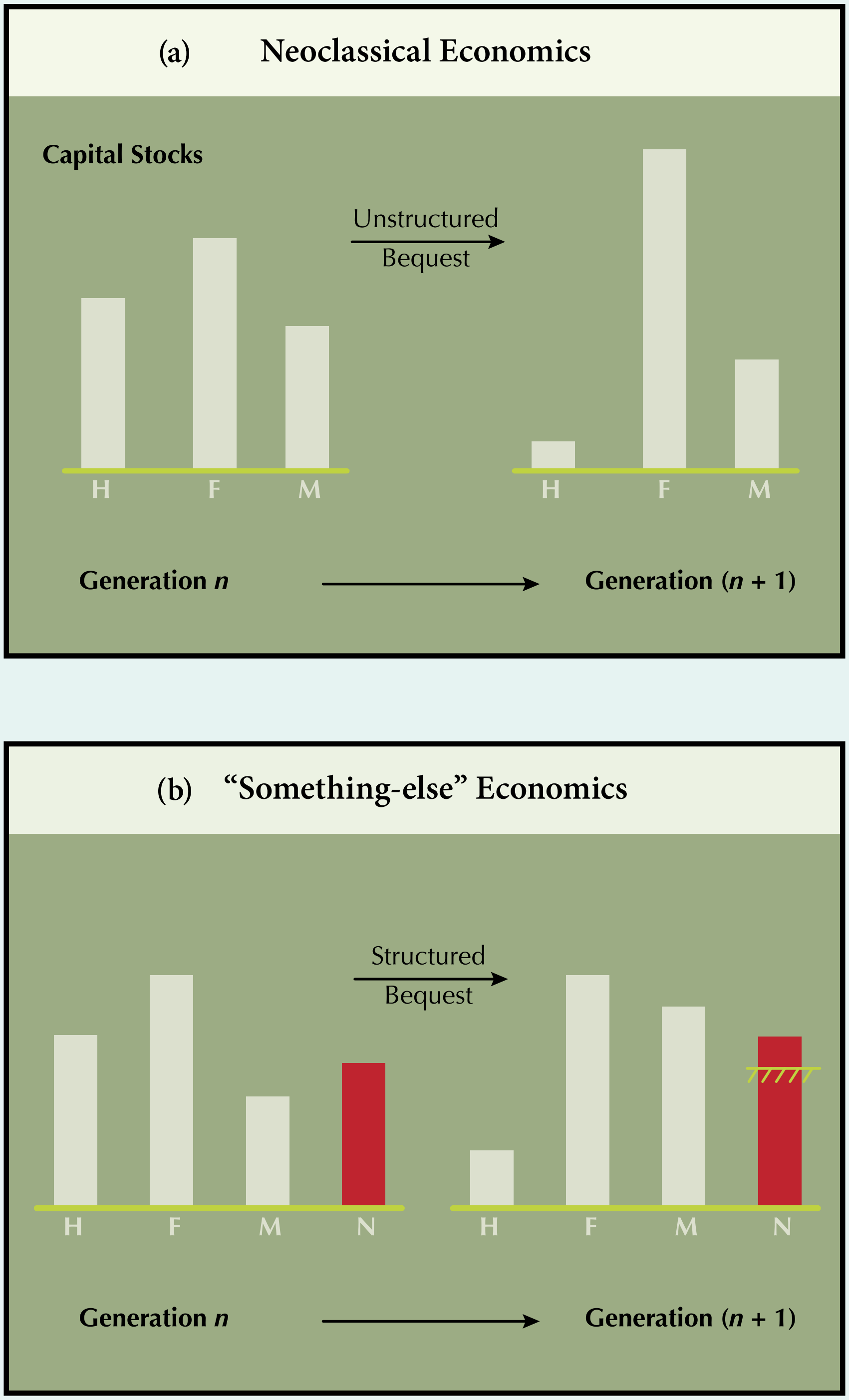


Figure 5:
An engineer's caricature of capital stocks and Solow's notion of bequests to the future: (a) an "unstructured bequest", nominally attached to neoclassical Economics; and (b) a "structured bequest", nominally attached to "something else" Economics. H is human capital; F is financial capital; M is manufactured capital; and N is natural capital.

(2006) quote a personal (prior) communication from Daly:

> More and more, the complementary factor in short supply (limiting factor) is remaining natural capital, not manmade capital as it used to be. For example, populations of fish, not fishing boats, limit fish catch worldwide. Economic logic says to invest in the limiting factor. That logic has not changed, but the identity of the limiting factor has.

In their response, Farley and Daly (2006) begin by pointing to what they see as inadequacy in the scope of ecosystem services portrayed by Aronson *et al* (2006), who overlook "one of the most important roles of natural capital", i.e., "the ability of natural systems to absorb and recycle waste", which "may prove more limiting than [natural capital's] role as a source of raw materials" (the "New Scarcity", in other words, of Simpson *et al*, 2004b). Farley and Daly proceed then to help us ground our thinking in neo-classical economics, as a subsequent point of intellectual departure (though doubtless this was not their original intention; Farley and Daly, 2006):

> The problem is that humans, like all other species, rely for their survival and economic welfare on intangible, non-marketed ecosystem services such as climate stabilization, water regulation, waste absorption and so on. Though increasingly scarce, the majority of these ecosystem services have no price, and therefore no feedback from markets signaling their scarcity and no market incentive to produce them.

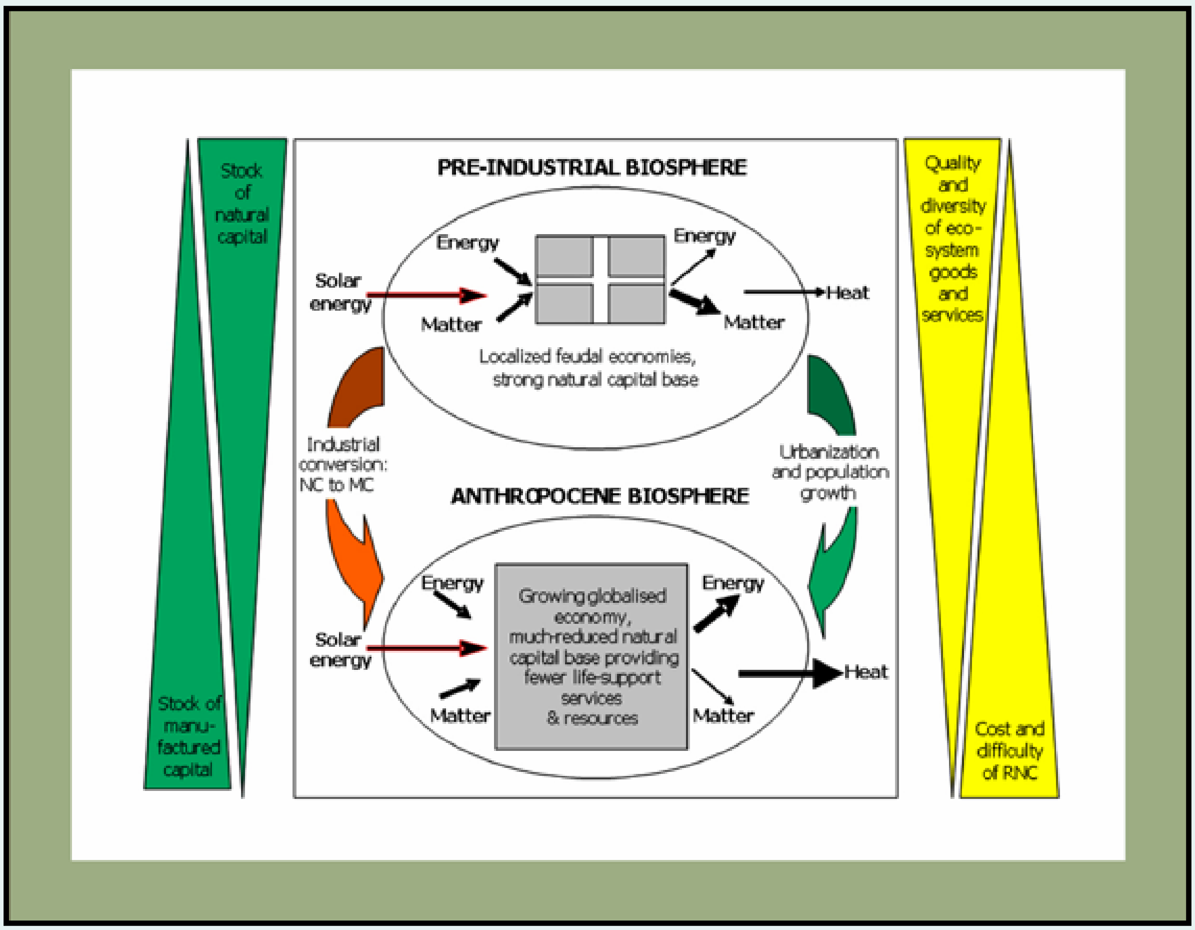


Figure 6:
Figure 2 from Aronson *et al* (2006), whose caption for this figure reads: "Pre-industrial and anthropocene biospheres diagram. Note that in the anthropocene biosphere a relatively lower proportion of energy is contained in matter on earth (e.g., forests) with the balance leaving earth as heat or accumulating in the atmosphere as carbon dioxide. RNC stands for Restoring Natural Capital." (Reproduced with permission).

Service Providers

Building upon the platform established through this dialog, with now, in particular, a more complete appreciation of the nature of ecosystem services, we can approach the concept of an "ecosystem service *provider*" (Kremen, 2005). We may talk easily of the supply and demand for such services. In respect of the threats to their continuing provision, however, even estimates of their economic values, Kremen suggests we understand but little of the role of biodiversity in providing these ecosystem services. She employs an oft-cited case study in water supply to make her point (Kremen, 2005; see also Heal, 2000):

> When New York City decided to protect the Catskill Watershed rather than build an expensive water filtration plant, ... it vindicated the economic potential of ecosystem services. It is remarkable, however, how little ecological information went into this decision. Planners reasoned that even if they underestimated the area required by half, it would still be far cheaper than building the water filtration plant. Numerous urban centres around the world depend on natural water purification mechanisms to provide safe drinking water for hundreds of millions of people, yet we have little ability to predict how much land must be protected and nearby land use must be restricted to provide water of sufficient quantity and quality.

In the service of "purification of water", vegetation, soil micro-organisms, aquatic micro-organisms, and aquatic invertebrates are identified as the ecosystem service providers (Kremen, 2005). Choices in engineering a more sustainable IUWM within IWRM, therefore, should be guided by the extent to which they direct investment towards the prosperity (or otherwise) of these entities — collectively, the natural capital — in order to ensure lasting streams of high quality ecosystem services therefrom (see also Tilman *et al*, 2002).

Yet how exactly might the classical technology of the activated sludge process of wastewater treatment be reworked so that the city could contribute to restoring natural capital and enhancing the watershed's ecosystem services? The question is neither fanciful nor rhetorical. It arises from Kremen (2005) herself, albeit in a mere footnote to her tabulation of (global) ecosystem services classified according to the Millennium Ecosystem Assessment, no less (Carpenter and Folke, 2006; www.MAweb.org). The question ranks thus as but the "smallness" of a footnote to a tabulation of the "largeness" of global ecosystem services. And in that sense, "thinking globally, acting locally" — an awareness of the "tele-connections" in things — is epitomized.

The activated sludge process exemplifies an engineered microbial ecosystem. Emerging from the quasi-rural, quasi-natural setting of the sewage farm of the 19th-Century, the activated sludge process has become the culmination of engineering intensification: enabling what Nature does for herself, but of necessity in the increasingly confined urban spaces of the 20th-Century wastewater treatment works.[16] At the heart of the 20th-Century Technocratic Paradigm (20CTP) of Box 1 resides thus much of the style of those who might most implacably oppose the paradigm; those who espouse the principles of engineering sustainability through the Self-Organizing Systems (SOS) of ecology — specifically here, a microbial ecosystem. Indeed, precisely because of its *engineering* over the decades into well-confined industrial, *ergo* quasi-laboratory settings, the activated sludge process provides a remarkably apt microcosm for the experimentation characteristic of the *science* of ecology. And in those settings, Graham and Smith (2004) seek to promote the idea of "designed ecosystem services".[17] Moreover, they look to the development and application of models (***M***) as the means to articulate and realize this idea (Saikaly and Oerther, 2004), rekindling the youthful exuberance, as it were, of systems ecology from the 1960s and 1970s (Curds, 1973a,b). In turn, this image of experimentation with the "heavy" concrete, steel, pumps, and blowers of the activated sludge process, giving rise eventually to its own re-invention in the

[16] Historical changes in phrasing over the decades and centuries — from sewage farm to sewage works, then wastewater treatment works, and water reclamation plant — tell us much about the motivation attaching to our various schools of engineering thought (in Box 1). The contemporary water-centric system, born of the WC and today labeled "water resources facility", is free of any connotations of the manures, nutrients, and fertilizers customarily associated with the long-since forgotten sewage *farm*.

[17] This may be different from, or fall short of, the notion of restoring the pre-city ecosystem services implied in Aronson *et al* (2006). But it is something resonant with our vision and challenge in Chapter 2.4, as much as with comments also expressed in Grimm *et al* (2008) in their work on "Global Change and the Ecology of Cities".

"lighter" form of much better understood ecosystem services, echoes the notion of a dematerializing economy (Kander, 2005).[18]

Here, then, we see the role of Engineering and engineers in re-working (re-engineering) the palette of alternative technological trajectories — the red rectangles in Figure 2 — for moving away from the present conditions towards the distant aspirations of society, in response to the challenge and vision set out in Chapter 2.4.

Plurality of Economic Valuations

The problems in all of this increasingly complete invasion of "business speak", of course, are profound and several. They are ones of how

> to put a number on that minimum stock of natural capital;
>
> to assign tangible prices to those ecosystem services;
>
> to assess the risks of business failures amongst the ecosystem service providers; and
>
> to devise a system of valuation so that, amongst the other factors of production in the economy, things are steered away from depleting that of which there is deemed to be too little and towards exploiting that of which there appears to be too much.

To provide perspective on what this might entail, let us paraphrase an illustration given by Prugh (1999; p 95) of three alternatives for assessing the value (V) of having "entities" such as oysters, as service providers in Chesapeake Bay (on the east coast of the USA):

(i) *Classical Economics:* V_C is the sum of the monetary values of all dock-side sales of oysters harvested and of the transactions of oyster-related commerce thereafter.

(ii) *Environmental Economics:* V_E is the foregoing (V_C), plus the value to the present human population of knowing the oysters are there in the bay and knowing too that future generations will likewise appreciate this knowledge.

(iii) *Ecological Economics:* V_X is all of the above, i.e., V_E, plus the value of the services of the oysters in filtering, and thereby cleansing, the bay's waters to the benefit of their (the oysters') ecosystem and the members of the human population that appreciate the benefits of a healthy, integral environment — with some of its clearest origins in Leopold's land ethic (Meine and Knight, 1999; Rosenblum, 2005).

Mindful of the stunning abundance of species, ecologies, and environments, it should not take much to imagine an equally vast and labor-intensive industry devoted to producing just the valuations themselves implied in V_E and V_X.

Key, however, are these two points. First, there is the unmistakable and unsurprising *plurality* of these three economic perspectives. This will manifest itself in working back through the commercial framework — from failing service providers, to service streams, hence to stocks of natural capital — to evaluations of the {economic feasibility} of re-engineering the elemental technology and policy components of IUWM within IWRM. Second, conspicuous by its absence is a sense of the long view in the classical economic valuation of V_C, perhaps by design for the purposes of the original argumentation (Prugh, 1999).

In Söderbaum's recent book, *Understanding Sustainability Economics: Towards Pluralism in Economics*, the pluralism for which he pleads would be that in which there is a viable and acknowledged school of economic thought *other* than that of neo-classical economics, which he labels "Business as Usual" (Söderbaum, 2008). What he then calls "Social and ecological modernization" (see also Hunt, 2010), we here would approximate as the school of environmental economics. That to which Söderbaum himself would be inclined to subscribe, he calls a "Radical interpretation of SD [Sustainable Development]". We surmise this would be closely aligned with what we refer to above as ecological economics.

Spun a slightly different way, economic "goods" come in more than just a single form. Pearce (2004) equates those of the Old Scarcity of *Scarcity and Growth*

[18] Not necessarily to be confused with a service economy (Stahel, 1997) or a performance economy (Stahel, 2006) or with the impacts of "digital technologies" on the dematerializing and/or re-materializing of economies (Berkhout and Hertin, 2004) or, more specifically, cities such as Singapore (Schulz, 2007).

(Barnett and Morse, 1963) with "private goods" and those of the New Scarcity as "public goods". The two imply their differing respective styles of valuation and management. Since "scarcity" has been inextricably conjoined with "growth" — for four decades — Pearce goes on to acknowledge that there are (and long have been) "[a]nti-growth protagonists". They argue for "no growth", because of the very "scarcity" itself, be it new or old (Pearce, 2004). This "vocal force" (Pearce's phrase), we observe, might well be arguing against resource depletion, hence to conserve "common-pool goods" for a more equitable caring and sharing by all. Thus should we have private, public, and common-pool economic goods (and their attaching styles of preferred policy).

Long View: Inter-generational Discounting

Looking out over the marine fisheries industry, Sumaila and Walters (2005) ask:

> [H]ow much in 'current generation discounted dollars' do we need to give up in order to ensure that future generations have the benefit of inheriting 'healthy' natural and environmental resources[?]

To answer their own question, they, as ecologists translating material from decades of economic thinking (Peña, 2009) — as we in our turn are now transcribing that material into terms familiar to water and environmental engineers — must cycle through almost all of the facets of seeking {social legitimacy} set out in the foregoing Chapter 3.1. They do so as follows.

They propose an equation for discounting to a net present value (NPV) future streams of (annual) net benefits to flow from ecosystem services and natural capital. In their words (Sumaila and Walters, 2005; p 138):

> For each simulated future year, we treat the benefits as accruing to the current generation (at standard discount rates) plus to each of the annual 1/(generation time) increments of new stakeholders who will have entered the stakeholder population by that future year. Each incremental group of new stakeholders is assumed to discount future benefits at the standard or normal rate after entering the stakeholder population.

"Generation time" here is taken as 20 years, for the sake of illustration, such that after 20 years those of our children born in the present year will have joined the body politic and will then (20 years on) have a basic democratic right: that government should reflect only the preferences of the individuals who are members of that enfranchised body and able, therefore, to participate (at the least) in Boulanger's (2008) aggregative model of democracy.

The Sumaila-Walters scheme straddles the values and preferences of *current* and *future* generations. It straddles the difference, therefore, between *standard* and *inter-generational* approaches to discounting. And in this dichotomy it reflects choices they label *empirical*, or indicative of *personal* tastes — we and you acting individually as consumers (largely in our "private spaces") — and choices they call *ethical*, or indicative of *social tastes* — you and we acting collectively as citizens (in the "public space" of community and society debate). To these alignments, can be added this, from Prager and Shertzer (2006), who commend the Sumaila-Walters scheme:

> [I]f one believes that a major goal of economics is to quantify *human preferences* (and the corresponding goal of resource economics is to quantify *societal preferences*) ... the use of conventional discounting is logically inconsistent ... [emphasis added]

In short, if the discounting equation of Sumaila and Walters (2005) is adopted, future streams of net benefits flowing from ecosystem services and natural capital will be valued more highly in the present than they would were a conventional rate of discounting applied.

In the face of the social and community diversity suffusing our discussion throughout this *Paper*, their approach assigns to all stakeholders (present and future) but a single, uniform outlook on the Man-Environment relationship, and one that is not only *invariant* over time but *singularly* egalitarian in spirit. Or as Gatzweiler (2006) has put it, in writing about governance for a public ecosystem service economy:

> [T]he choice of the discount rate strongly reflects a certain ethical standpoint, which is not necessarily the one held by people concerned about or affected by biodiversity conservation measures.

This invariance and singularity of perspective in the Sumaila-Walters scheme seems at odds with our discussion of ever-evolving "fashions", in respect of how considerations of inter-generational equity contribute to achieving {social legitimacy} (witness the changing perception of engineer Gantt's motivations in Chapter 3.1). In assessing now the {economic feasibility} of a given technology or policy, it is not all that difficult to imagine the following kind of logical inconsistency: an invariant, inter-generational discounting procedure conditioned upon the myth of "Nature benign"; which is applied under a valuation scheme (such as V_C, V_E, or V_X) originating in the myth of "Nature tolerant but perverse"; in the design of a policy now whose consequences will be inherited in the future by those eventually convinced quite otherwise by, say, the myth of "Nature ephemeral". Simply put, our utopian vision of today may come to be inherited as dystopia in the eyes of our children.

Even without reaching for such diversity, economists of apparently the same broad persuasion — those adhering to valuations V_C, it seems — may be pitted one against the other, as Godard (2008) notes in his review of the reviews of the "Stern Review" (Stern, 2006) on the economics of climate change:

> Paradoxically, the much-attacked choice of a low discount rate chosen to ensure an equal treatment of the utility of all generations is best grounded in the utilitarian philosophy that underpins the type of economics that both the Stern Review and most of its critics share.

Once was the time when Engineers might have been rather smug about such highly contested variations on but one basic economic theme amongst the thoroughly disputatious plurality of schools of economic thought. Not amongst our profession would such diversity hold — the accounts of Box 1 notwithstanding — nor our outlooks change with time. But many of us today *are* ruffled by what Gantt had in mind a century ago; while conversely just as many might be comforted by what seems to have moved the first three Presidents of the (UK) Institution of Civil Engineers a century or so before Gantt (Wynn, 2009). We are not all uniformly in the same boat — or aircraft, as Baneth (1998) and Boulanger (2008) would have this — heading in the same direction, without deviation, across the generations. Smugness about uniformity may come to be (constructively) substituted by the "disputatious plurality" formerly perceived as the weakness of Economics.

Economists, in return, are not above calling into question the style of Engineering. When Söderbaum (2008) suggests as further reading beyond his own book that of Nobel-laureate Sen — *On Ethics and Economics* (Sen, 1987) — he does so on the basis that Sen is critical of neo-classical economics for its

> almost exclusive reliance on an 'engineering tradition' where ethical aspects more or less disappear.

Sen, says Söderbaum,

> recommends a development path for economics where ethics is taken seriously.

Plurality of outlooks, variability therein over time (if not sea-changes), hence uncertainty in respect of the discount rate (if not mutual contradictions), can all exert an influence over the composition of the longer-term technological trajectories (the red rectangles of Figure 2) towards less unsustainable forms of IUWM within IWRM. Facets of this significance have just begun to surface in our own technology and policy sector, in studies of inter-generational stewardship of lakes prone to eutrophication (Ludwig *et al*, 2005). They are considerably more mature in the much more prominent policy sector of shaping strategic public- and private-sector investments in energy technologies for mitigating global climate change (Ringuest *et al*, 1999; Lempert, 2002; Lasry, 2008; Peña, 2009; Lemoine *et al*, 2010). Yet despite all the debate ensuing in the wake of publication of the Stern Review (Godard, 2008; Lasry and Fessler, 2008), including over the shape of the discount function — that it might better be hyperbolic instead of the customary exponential (Sumaila, 2008)[19] — the choice of a single, time-invariant value for the discount rate-constant seems somehow to be a matter of tinkering at the fringes of a deeply intractable problem of social debate and

[19] This is notably a discount function proposed by psychologist George Ainslie (Ainslie, 2001), and presciently so for us under the prospect of climate change. Ainslie's goal, hence his choice of the hyperbolic discount function, was to understand how addicts continue to make decisions in the here and now that they know full well to be harmful to their future well-being and survival.

democracy.[20] As with the fine line in the archetypal mathematical program of Chapter 2.5, there is only so far one can penetrate effectively with quantification and numerical analysis.

Bequests to the Future and Grand Social Programs

As reported by Boulanger (2008), Sen

> ... was the first recognized economist to propose a multidimensional vision of development, focused, not on economic growth or an increase in monetary income but rather on an extension of the real freedom of people to achieve their goals.

The body politic of the modern state, we are told, acquired such *economic growth* as a core state interest — one of its "imperatives" — in the 19th Century and *social legitimacy* in the 20th Century (Dryzek *et al*, 2002).[21] Simple extrapolation suggests *environmental benignity* will take this present century to become a third imperative of the state.

As in ascending the steps of the seeming hierarchy of economic valuations (V_C, V_E, or V_X), or Maslow's much disputed pyramidal form of human motivation, or the ranked aspirations of Figure 4 (which places economic growth above all else, except notably achievement of the Millennium Development Goals), one has a sense of scaling the heights of some lofty social program, just as Gantt had contemplated. What is the environmental engineer, busying him- or her-self with the nuts and bolts of urban water infrastructure, to make of such high-minded notions of {economic feasibility}? Their sweeping scope must seem a far cry from the engineering economics of Total Annual Economic Cost (TAEC): employed to discriminate amongst alternatives for upgrading infrastructure performance (Jiang *et al*, 2005); where the upgrading aspires to nothing grander than simply lowering the phosphorus content of an effluent; with horizons spreading little beyond the fence-line of the wastewater treatment plant; hence a style of valuation (V_0) subsumed under those of V_C and the others?

What then, in the light of contemporary pragmatism, might be our bequest to Brundtland's next generation? For things can be altogether undignified, rather desperately personal, and far from grand.

Ecological sanitation systems — the ecosan we now know from Boxes 1 and 2 — 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 (themselves already touched upon in Boxes 1 and 2):

> 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 [feces] 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 lofty vision, the "luxury" of earnest debate about collective, global sustainability, and hard — brutally hard, and very immediate — local, personal pragmatism.[22]

In her analysis of the companion matter of connecting the poor of Jakarta, Indonesia, to a formal, networked supply of potable water, Bakker (2006) concludes that abject failure was likewise a function of economic disincentives, and at every turn: as public sector gave way to public-private sector partnership, bringing forth in turn an audible civil-society voice; and with all this unfolding across the local, municipal, and national

[20] One current view is that the discount rate-constant should in any case better be time-variable (Obersteiner, 2010).

[21] Their work was confined to nation-states of the Global North, however: Germany, Norway, the USA, and the UK.

[22] With the rest of that particular debate being played out in McCann's (2005) article in *Water21*.

scales of governance in a specific, and specifically important, cultural context.[23]

Lofty Principle and the Little Things in Life

How now indeed should we contemplate the high-minded principle of our bequest to the 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? How too then could we resolve Solow's moral dilemma (Solow, 1991), or respond to the challenge put to (now) Lord Stern by Landau (2008): 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 today's poor? For they need something to be done right now about their water situation — and something Solow would assert is inevitably consumptive of current natural capital, quite the opposite of a constructive bequest to some distant future.

Scale, in its various manifestations, is yet again important here. On the one hand, there is a need to consider accounting for the time preferences exhibited in *individual* behavior with respect to the future, as those individuals aspire to local social status and cleanliness in their households (according to Figure 4 and IWA's *Sanitation 21* document; IWA, 2006). On the other, account must be taken of society's *collective* and changing preferences over inter-generational time, especially if, say, *large-scale* ecosystem services are in danger of degradation (Norton and Toman, 1997). Aspirations vary across these vastly different scales. And the ranking of policy-critical needs ahead of mere wants, let alone luxuries, may often be a function of s/he who can shout the loudest (as we have seen in Box 2). In this resides the hugely complex compound of {environmental benignity}, {economic feasibility}, and {social legitimacy}, making it so tortuous for us to engineer our way out of unsustainability in IUWM.

Besides basic physiological survival and security of body (ranked elsewhere at levels 1 and 2 in Maslow's hierarchy), and before aspiring to "Think globally, act locally", the individual contemplating investment in a single-pit pour-flush toilet might best be brought to a position where "Debating somewhere *districtly*, acting locally" has been facilitated, if Figure 4 holds true. To that end, the engineer might thus ponder how to design and install forms of household, neighborhood, and ward/district supplies of potable water and sanitation infrastructure, deliberately to initiate debate about sustainability, and as soon as possible. This is just such a change in perspective as that related in Box 2: from peering in on the problems of IUWM within IWRM, from a professionally detached distance (Figure 1; and Figure 2, as well); to looking outwards and upwards from the individual and the self (from Figure B2.1 embedded in the detail of Box 2). After all, we know that slum-dwellers in some of the cities of South America place dwellings in their neighborhoods in a rectilinear, grid pattern (Thompson, 1979); one that is all the more conducive to any subsequent introduction of basic water infrastructure by the powers that be, in anticipation of this community moving on to its next aspiration.

[23] A context suffused with corruption and mafia-style control of water-vending operations, as if there were not already enough impediments to network connections for the poor (Bakker, 2006).

3.3 Environmental Benignity

We began in Chapter 2.4 with a challenge and a vision, grounded, as sustainability is itself, in the perception of Man bumping up against the limits of the Environment. The charge to the engineer is to come up with technological (and policy) trajectories tending towards a contemporary vision of what should be good for the Environment, i.e., first and foremost, promote movement positively along the dimension of {environmental benignity}. That "goodness", nevertheless, will be subject to a plurality of fervently held interpretations, which interpretations will surely manifest themselves in what constitutes {economic feasibility}, in what grants {social legitimacy} of action and innovation, and — perhaps more contentiously — in a plurality of schools of thought on environmental and sustainability engineering (in Box 1).

Scale, both in space and time, is yet again important. In the preceding discussion of economic valuations the reader was being invited to expand his or her horizons successively outwards (from V_C, through V_E, and on to V_X): from me and you acting as consumers (literally of the oysters) to you and me thinking more as citizens. Not at all apparent there was the reverse, of thinking being pushed backwards and ever more inwards: through the urban water and wastewater infrastructure; to the intimacy of our personal dietary preferences and their consequences for sewage; hence to the choices in those private, inner circles that enable the oysters to survive and prosper in the estuary, in spite of the city. With "lofty principle and the little things in life" was how Chapter 3.2 was closed.

That was a matter of space: the tele-connections between the relative smallness of personal choice and engineering economics and the big picture of natural capital, ecosystem services, and service providers. It was a matter of thinking through the strings of reasoning flowing outwards to climate change and sustainability from the person-centric perspective of Figure B2.1 in Box 2.

What, then, might be the companion tele-connections along the dimension of time? For time, like space, has the same intuitively separated spans. They are manifest in the many commonplaces we have already encountered:

> in the great debate in economics over the choice of a discount rate that could run from now until the next generation (in Chapter 3.2);
>
> in our behaving as consumers for today, yet as citizens for the sake of our grandchildren (also in Chapter 3.2);
>
> in Solow's dilemma of the need to be consumptive now of natural capital, in the interests of attaining a greater stock of such capital in the more remote future (again in Chapter 3.2);
>
> in looking back, from what may inspire the engineers of tomorrow, to Gantt's motivation of a century ago, and that of the early Presidents of the (UK) Institution of Civil Engineers, a century or so before Gantt (in Chapters 3.1 and 3.2);
>
> and here last (but there first, in Chapter 2.3), in the life-cycle of any technological system of infrastructure.

We know — from Crandall Hollick's (2007) account of the city of Kanpur in India (at the very beginning of Chapter 2) — that it might just be so much more convenient (and surely much simpler) to ditch considerations of what may happen over one span of time in order to focus on another. We might (and surely do) overlook the seeming minutiae of what may happen over the short term of operations (minutes, hours, days, weeks) in favor of attending to the strategic "bigs" of planning, designing, and constructing a future wastewater treatment facility (over months, years, and into distant decades). Now we know the adverse consequences of *not* paying sufficient attention to cross-scale influences along the dimension of time: of being insufficiently mindful of the *interactions* amongst the "here and now" and the (possibly) "there and then". In particular, the "here and now" may come to *dominate* the system's behavior from time to time in some remote "there and then", when having to deal in real-time with a sudden crisis in the distant future.

Interactions Across Time: "The Long and the Short of it All"

We begin by recalling Figure 1. And for the moment, let us put aside considerations of the daily bread and nutrient metabolism of the city, to focus solely on its daily water and water metabolism.

As the city lands down on the ground over geological time (a long view indeed), it alters the spectrum of hydrological fluctuations in the flows of water through the watershed, i.e., the watershed's hydrological regime. It does so in various ways, most obviously through:

(i) the diversion and accelerated transfer of precipitation-induced flows from the city's surfaces to the receiving streams, *via* the storm sewer network;

(ii) the creation of artificial storage, such as reservoirs — or the exploitation of other naturally highly-damped, slowly-changing systems, such as groundwater in aquifers — in order to lower the vulnerability of the city's supply of daily water to the vagaries of natural fluctuations in precipitation; and

(iii) the supply/removal of water flows to/from the city, to suit the city's economic and social metabolisms, with their emphatic diurnal and weekly oscillatory components.

Tuning the infrastructure of the city to those specific rhythms and routines that are so much to our liking, as we go about our urban economic and social lives, distorts the spectrum of fluctuations in the watershed's hydrological regime.

Construction and operation of a reservoir will tend to transfer some of the power in the higher-frequency components of the regime (fluctuating over minutes, hours, days, and weeks) to the lower-frequency components (with periods of years, decades, centuries, and millennia). Installing the city's sewer network has the opposite effect. Once the city has arrived, it is then as though all the variety of periodic fluctuations in the behavior of the environment are ever thereafter progressively subjugated to the predominant 24-hour and 7-day cycles of steadily intensifying city life. This historic process, moreover, increases the vulnerability of the city-watershed couple to very fast, aperiodic crises on the scale of hours, minutes, and even the seconds of abrupt failure. In sum, what happens at the frenetic pitch of minutes is by no means utterly independent of the lugubrious undulations and rumblings over the decades — and perhaps quite the opposite.

Thus it is that we write of "the *long* and the *short* of it *all*": hence the frustrating inevitability — for we always knew it — of the inseparability of the parts from the whole, as much in time as in space. Expressed somewhat lyrically (Holling, 1996):

> Not only do the large and the slow variables control small and fast ones, the latter occasionally "revolt" to affect the former.

The ecosystems we encounter in the streams and rivers of the city's watershed, and therefore what we today recognize as their services, evolved over geological time in sympathy with that pre-existing, pre-city hydrological regime (Odum *et al*, 1995; Grossman *et al*, 1990, 1998; Reice *et al*, 1990; Naiman *et al*, 2002; Poff *et al*, 1997, 2003, 2010).

For Holling, it is the semi-arid grasslands of east and south Africa that best reveal this role of the spectrum of perturbations in understanding the impact of man on the environment (Holling, 1996):

> Under natural conditions ... the grasslands were periodically pulsed by episodes of intense grazing by various species of large herbivores [not quite our bull in any kind of shop!]. Directly as a result, a dynamic balance was maintained between two groups of grasses.

But then such ecological resilience was lost with the advent of man and the modernity of arranging things — in time — to his liking (Holling, 1996):

> When such grasslands are converted to cattle ranching, ... the cattle have been typically stocked at a sustained [always present], moderate level, so that grazing shifts from the natural pattern of intense pulses separated by periods of recovery, to a more modest but persistent impact. Natural variability is replaced by constancy of production.

Taking our lead from Odum *et al* (1995), who write of Nature's pulsating paradigm in respect of aquatic environments, the pulse of the imposed city could be said to have quickened the pulse of its surrounding watershed (Beck, 1996). The notion of a system's frequency spectrum illuminates succinctly such cross-scale influences (Beck and Cummings, 1996; Beck, 1996, 2005; Beck *et al*, 2010a).[24] It is as pictured in

[24] The discussion of Grimm *et al* (2008) on "Global Change and the Ecology of Cities" hints at the same benefits of this particular means of describing the behavior of a system.

Figure 7 (Beck, 2005); its supporting narrative is as follows.

At the outset, there is the spectrum for the environment without the city. A first snapshot is then taken (in Figure 7(a)) of the spectrum for a mature city with an infrastructure for urban drainage and foul sewerage, but no treatment of any wastewater. Some of the "power" in the slower, lower-frequency components of the natural drainage of water over the pristine, pre-city land surface (over months, years, decades) has been shifted and concentrated into the faster, higher-frequency fluctuations in city behavior (the weekly and daily patterns of life). Impervious surfaces, pipes, and large engineered conduits simply focus volumes of water and speed them on their way from one place to another.

The spectrum for the second stage of infrastructure evolution is drawn for the subsequent installation of the kind of comprehensive wastewater treatment facilities presently the custom in cities of the Global North (Figure 1(a), in other words). We suppose it transforms the spectrum of Figure 7(a) yet again (Beck, 2005). Some of the power in the weekly and daily rhythms is attenuated, through the elimination of significant amounts of pollutants previously imposed on the city's environment (under the first stage of urban development). This success of the infrastructure of wastewater treatment, however, merely separates the city's undiminished and continuing potential for issuing polluting disturbances from a now visibly restored aquatic environment. Things can go dramatically wrong — they fail — in hours and minutes, hence the piling up of the second-stage frequency spectrum towards the yet higher-frequency components of Figure 7(a) (Beck, 1981, 2005; and Box 1). The more the effort invested in maintaining the barrier of the city's wastewater treatment, so grows the vulnerability of the city's progressively restored watershed.

While post-city ecosystems and services might be able to remain intact under an enhanced, even predominant diurnal component, they doubtless did not evolve in the presence of a prominent weekly (societal) cycle in the hydrological spectrum, nor the shock of the city suddenly breaking free of the restraining padding, as it were, of its comprehensive wastewater infrastructure.

We already know well enough what it may take to reverse some of the alterations in the post-city hydrological spectrum: programs such as those of constructed wetlands, restoration of canalized urban streams, low-impact residential development (Dietz, 2007), and sustainable urban drainage systems (cast in the framework of the triple bottom line by Jacobs (2008)). All of these strategies are capable of attenuating the exaggerated powers of the high-frequency components of urban water flow fluctuations (and the influence they exert over the spectra of Figure 7(a)). Almost certainly they were not presented hitherto as frequency-spectrum manipulations, or the means to lower the pulse-rate of the city-watershed. But that is what they are. Stream ecologists recognize them expressly as such: in their wrestling with how to compensate for the effects of dams and impoundments, within the broader context of IWRM (as opposed to IUWM). Their efforts have come to be known as providing for "environmental flows" (Arthington *et al*, 2006; Richter, 2010). Their goal, however, is reversal of the changes in the spectrum sketched in Figure 7(b), i.e., the complement of restoring the city-induced distortions of the spectra in Figure 7(a).[25]

The impact of the "large animal" of the city "grazing in its pasture" can be gauged not only by its footprint (Rees and Wackernagel, 1996) and metabolism (Wolman, 1968), but also its pulse-rate. Yet the foregoing illustrations of pulse-rate manipulations are essentially just restorative. Further, they are confined to mitigating the impact merely of the city, as opposed to the rest of man's interventions in the watershed (for the purposes of irrigating agriculture, for instance); and they are confined to the goal of adjusting the city's water metabolism alone, uncoupled somehow from its nutrient metabolism.

It is time to re-introduce considerations of the daily bread of the city, and build through the analogies of

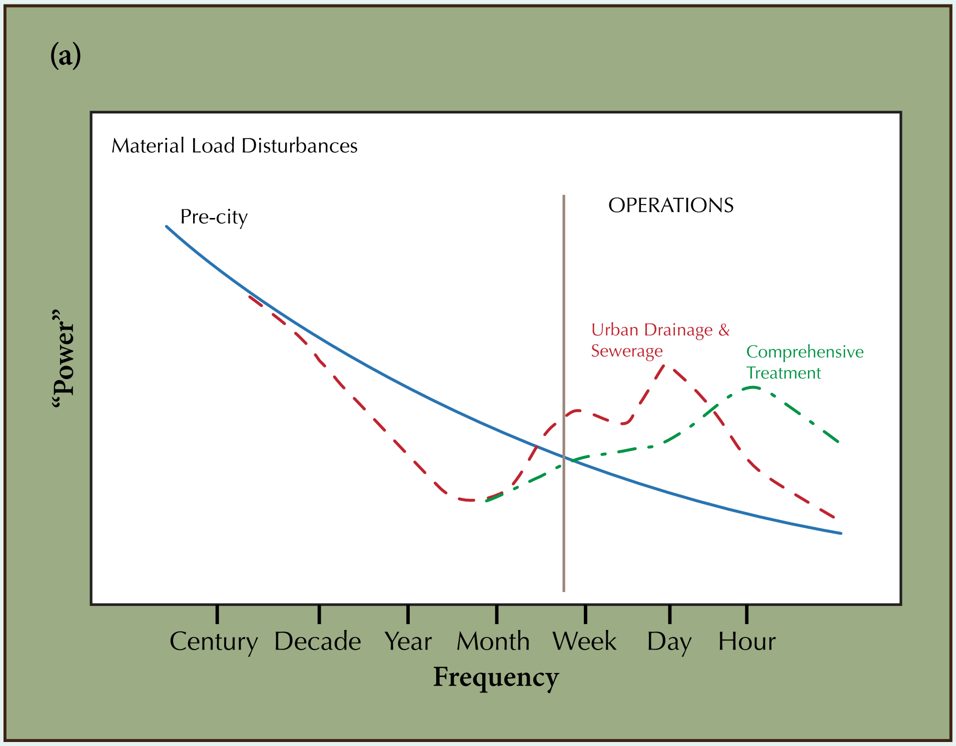
[25] Intuitively, one might think the respective changes wrought over time in the two (Figures 7(a) and 7(b)) should cancel each other out. The evidence of contemporary ecosystem impacts in watersheds so modified by man's interventions indicates quite otherwise. The "long and short of it all" are entangled in complicated, non-additive, nonlinear ways (see also Holling, 1996).

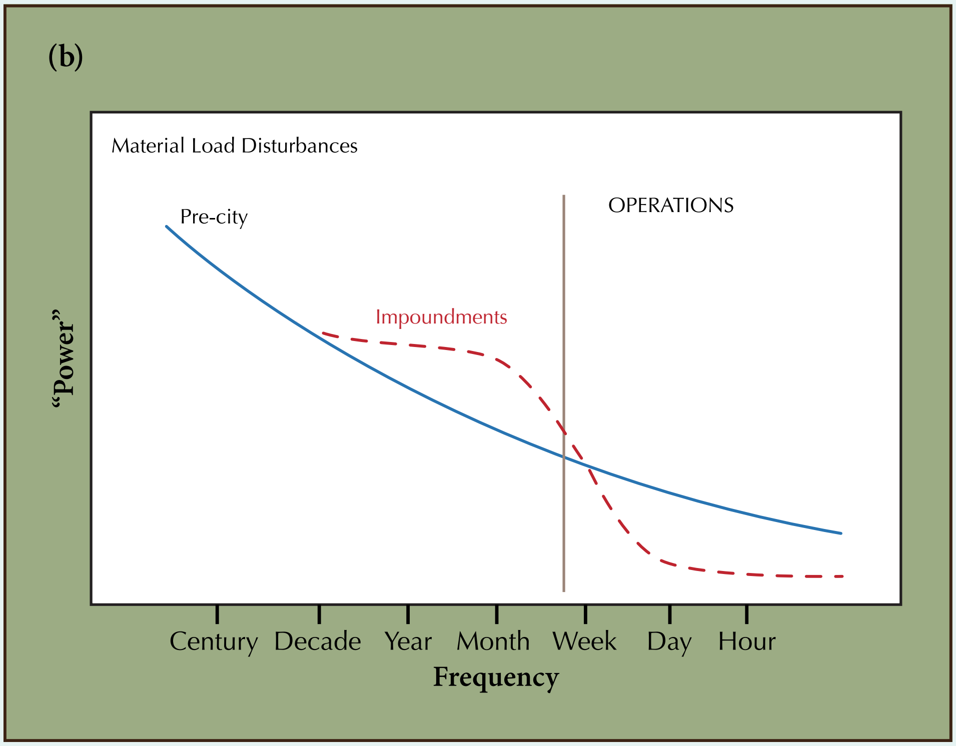
Figure 7:
Visualization of the notion of pulse-spectrum.

(a) City-watershed pulse, or spectra summarizing perturbation regimes for three successive stages of city water and wastewater infrastructure. In other words, these are the spectra of material load disturbances to which the surface water environment of the city is subject: continuous line represents the pre-city condition; dashed line represents the situation with urban drainage and sewerage installed as infrastructure (but not wastewater treatment); and dashed-dotted line represents conditions under a comprehensive system of urban wastewater infrastructure.

The vertical line separating out the higher frequencies of primary concern to assessing and managing behavior under "Operations" is redolent of the fixation of Beck (1981) and the historic oversight of such great concern to Crandall Hollick (2007).

(b) Companion historical change in the pulse-spectrum of watershed hydrological behavior brought about by the installation of impounded reservoirs along the river (dashed line).





appetite, metabolism, and (now) pulse — as entailed in {environmental benignity} — towards possible responses to the challenge and vision of Chapter 2.4: of the city-infrastructure couple as a force for good (CFG) in the environment.

Appetite and Ecological Footprint

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 (just as in Figure 1). 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 an areal 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, whether technical expert or technically lay person. Wikipedia, for example (accessed 14 January, 2010), reports humanity's total Ecological Footprint to have been some 1.3 times the (biologically productive) area of planet Earth in 2005 (see also Hoekstra, 2009).[26] Projections elsewhere suggest that by 2050, with a world population of nine billion people, our collective global appetite could consume planet Earth more than twice, if not several times over.

Like Integrated Water Resources Management, or the Triple Bottom Line, the Ecological Footprint (EF) has its critics. For what such analysis gains through its clarity and intuitively understandable quality, it loses in other ways through being perhaps too simple and unsubtle. Newman (2006) has gone further, beginning by saying this:

> Policy is largely about what cities need to do — not what they should try to stop doing.

The admonishing tone that comes with the EF is somewhat at odds with our sense of searching for expression of the "force for good" in CFG. Newman (2006) continues:

> The Ecological Footprint model is used largely as a symbolic parameter representing the problem of resource consumption.

The plain phrases of the footprint are indeed so easily understood. Bidden to "tighten our belts" through ever enhanced efficiency, the exhortation to reduce the city's footprint speaks simply, loudly, and clearly. It speaks to the debate, moreover, in the voice of the egalitarian solidarity: "Salute frugality, especially in the profligate Global North". That we are in danger otherwise of consuming the planet several times over is a quite unpalatable, apocalyptic vision.

But now we stand at odds with Newman (2006), when he concludes:

> Analysis from this perspective [of the EF] can help a city frame a variety of policies to begin reducing global ecological impact. However, it does little else.

Specific policies can be framed and acted upon, with a practical impact on the ground. There is a detailed calculus that works, below the arresting headline figures: to select alternative, candidate items of technology; to follow the principles of the EF to compute their respective consequences; hence to make choices to reduce the city's footprint. Technological alternatives for wastewater treatment facilities for the city of Petaluma, California, USA, were just so evaluated (already in 2000) — under the customary coupled and centralized paradigm of wastewater infrastructure of Figure 1(a) (Davis, 2008).

Availing ourselves of the calculus, we can embark on building a response to the challenge and vision of Chapter 2.4. Our work-space is composed as follows.

Case Study

In our social setting, we shall act as though quite convinced of the merits of "Perfect Fertilizer" (PeFe) as our target vision. This will be our favored, specific green oval domain of Figure 2. In addition, we shall pick out essentially the Separation at Source (S@S) style of engineering sustainability, from the portfolio of red rectangles of technological

[26] The ecological footprint has a younger sibling: the water footprint (Hoekstra, 2009). It was born of a reaction to the fixation of classical water resources management on "supply" and the "local". Matters of "consumption" and the "global" — Hoekstra tells us — are just as important (if not more so). Our global water footprint, however, is not yet quite as dramatically bad as our global ecological footprint (Hoekstra, 2009).

paths in Figure 2 (and Box 1). These choices, however, presume nothing about their superiority over any other convictions others may hold about either the green ovals or red rectangles of Figure 2. For that would be to go against everything said hitherto about the nature of {social legitimacy} and {economic feasibility} in the challenges we face.[27]

To be computationally and numerically specific, we shall further take the particular case of re-engineering the wastewater infrastructure of Atlanta, within the watershed of the Upper Chattahoochee (Figure 8), so that that city might become a force for good in this environment (our CFG, in short; Beck *et al*, 2010a, 2011a).[28] Sitting in the headwaters of the Chattahoochee watershed in the south-eastern US, even the literal areal significance of Atlanta is unmistakable (Figure 8(a)). Comparing Figures 8(a) and 8(b), Metro Atlanta is significantly more extensive than the portion of it lying strictly within the Upper Chattahoochee watershed. The population estimate for Metro Atlanta is 5.4M, of whom just 1.3M inhabitants reside in the Upper Chattahoochee watershed.

Our primary observing point in the affairs of this city-watershed couple will be that where the largest of Atlanta's wastewater treatment plants, the R M Clayton facility (Mines *et al*, 2004), discharges its treated effluent to the Chattahoochee River (the yellow dot in Figure 8(b)).

The inset of Figure 8(a) shows that the Chattahoochee watershed (as a whole) straddles three states, Georgia, Alabama, and Florida. Access to its water resources has been the subject of "water wars" amongst the three since the early 1990s. These remain as yet unresolved (in 2011). At one stage, in the early 2000s, a treaty seemed possible. It was not. It unraveled into failure because downstream Florida insisted on a spectrum of environmental flows being maintained in the river as it crossed the Georgia-Florida state line. Yet further downstream, the cumulative impact of all the various engineering interventions along the Chattahoochee is known to be affecting the well-being of shell-fish populations in Apalachicola Bay, in the Gulf of Mexico (Wilber, 1992; Figure 8(a)). This impact is encapsulated in the altered relative strengths of fluctuations in tidal salt- and fresh-water exchanges. And it was precisely at these coastal interfaces in Georgia, Florida, and the south-eastern US seaboard generally, where members of the Odum family found the inspiration for developing their ideas on Nature's pulsating paradigm (Odum *et al*, 1995).

Assembling our response will take a total of four steps forward, together with a step backwards into a salutary case history of the city of Paris and eventually a companion reflection into the future, beyond the discussion of this *Concepts Paper*. We begin thus.

Step (1)

Customary sources of household wastewater can be distinguished crudely as yellow water (urine), black water (feces), and grey water (wash waters). In the conventional wastewater infrastructure of today's cities of the Global North, all are mixed and collectively removed in a single flux from the household (or office block, etc). From there they are conveyed by the added water of WC flushing through a centralized sewer network to a distant wastewater treatment plant. This is essentially the present arrangement in Atlanta. It is conceptually the structural configuration of Figures 1(a) and 1(b). It is the reference base-case all such assessments require. It is accordingly the (green oval) vision of "Business as Usual" in Figure 2, shaped by the 20th Century Technocratic Paradigm (20CTP) school of thought (Box 1) and its attaching portfolio of technological trajectories in Figure 2 (its red rectangle).

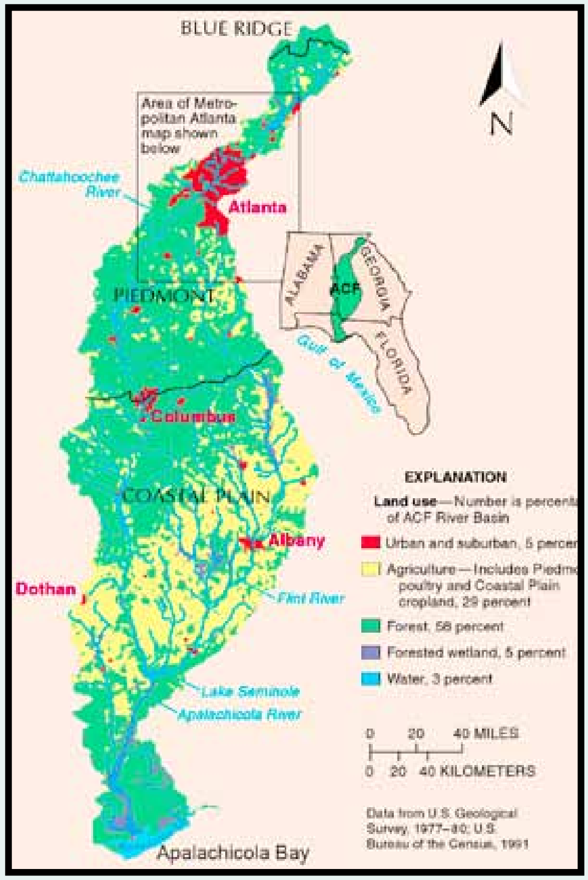
We assume that our preferred alternative style of engineering sustainability, Separation at Source (S@S; Box 1), can be implemented in two ways (Jiang, 2010). In the first, to which we shall refer as S@S(1), yellow water is separated at source through a urine-separating toilet (UST) (Hellström and Johansson, 1999; Lienert and Larsen, 2006, 2007, 2009; Larsen,

[27] In any case, things are always so much more combinatorially complex. PeFe itself might need to be produced in a variety of grades, contingent upon subsequent, downstream outlets and processing. By reflection, there is also greater variety than solely S@S, and several minor variations on that basic technological theme of source separation, in the means by which to migrate towards the target PeFe.

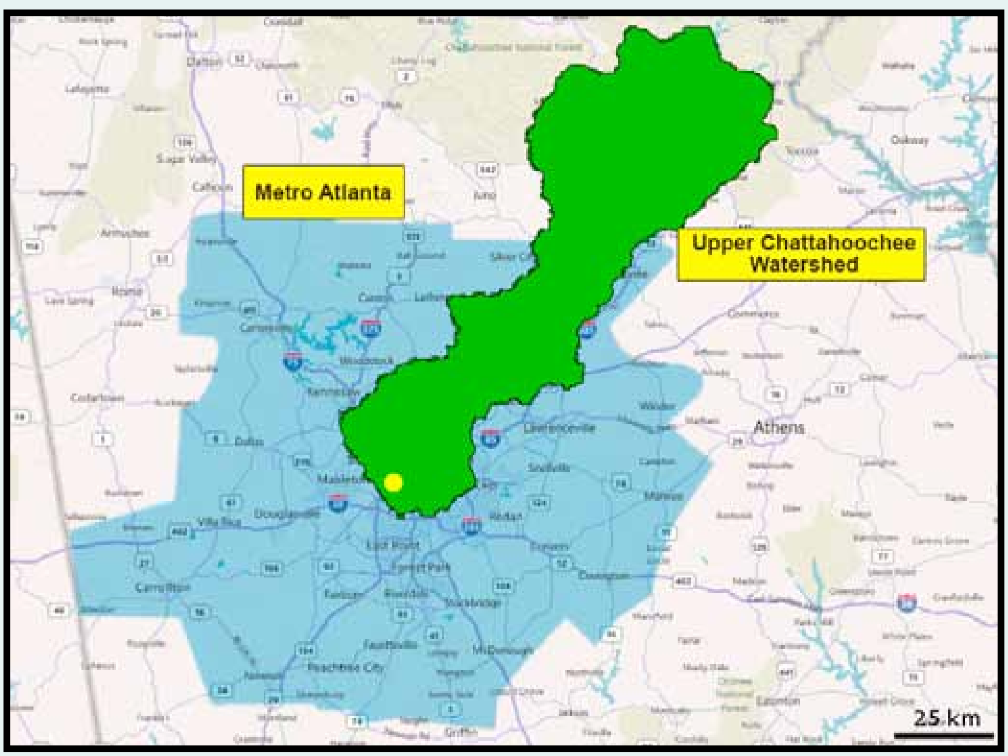
[28] This is one of the roles of Engineering, after all. For without the use of formal mathematical models (***M***), our attempts at grasping and debating the options for the distant future will remain vague and inconsistent.

Figure 8
Geographical location of the case study of the city of Atlanta and the Chattahoochee watershed: (a) entire Chattahoochee watershed, showing the river eventually discharging into Apalachicola Bay (Gulf of Mexico); (b) Upper Chattahoochee watershed (green area), with location of the R M Clayton wastewater treatment plant (yellow dot) as the largest of Metro Atlanta's (blue area) treatment facilities

(a)



(b)



2011) and thereafter conveyed separately out of the household — by truck transport — to the R M Clayton wastewater treatment plant. There, as imagined at some point in the distant future, the yellow water is simulated as being processed strictly separately to produce fertilizer materials. Hence we have a specific realization of PeFe; the applicable unit processes of treatment can be found in Beck *et al* (2011a). In the second alternative (S@S(2)), the combination of yellow and black waters is separated from the grey water and then removed by a vacuum-pipe system to the treatment plant, where it receives strictly separate processing to generate fertilizer products (again, see Beck *et al*, 2011a). The presently existing sewer network is used (unchanged) to convey the combined grey water and black water to the treatment plant in S@S(1); it likewise conveys just the remaining grey water to the plant in S@S(2). Of the two variations on the basic theme of source separation, S@S(2) is the more complete realization of the structural arrangement for the city's water and nutrient metabolisms in Figure 1(c). It is a matter of fact that the majority of the nutrient material (nitrogen, phosphorus, potassium) resides in urine, whereas feces are richer in their carbon content.[29]

By implementing these separations at source, for a typical, large city of the Global North (such as Atlanta), the ecological footprint (EF) of the related infrastructure — household, conveyance (sewer, vacuum, truck), and treatment — could be reduced to roughly 75% (for S@S(1)) and 66% (for S@S(2)) of its value under present (unseparated) arrangements (Jiang, 2010). That is to say, these reductions follow from proceeding from the structural arrangement of Figure 1(a) to that of Figure 1(c). They are driven significantly by reductions in the equivalent areas of land required to assimilate the diminished nutrient residuals (of N and P) under the strategies of separation at source. Such reductions, however, can vary significantly as a function of the applied process operating strategies: down just to 87% and as much as down to nearly 50% (Jiang, 2010). The changes of infrastructure include the re-plumbing of households. Reductions in the footprint of S@S(2) might be yet greater still, absent vacuum conveyance and the innovation of some accompanying re-design of the toilet.

Thus would we have begun to unweave a good deal of what today is seen by some as the "bad" of coupling the city's metabolism of its daily bread with that of its daily water. Our footprint calculations provisionally confirm our prejudice (in favor of an S@S strategy), although the numerical differences are not that substantial.

Taking stock, we have the image of the city as an organism with an appetite, but the simplicity of its mere footprint is a rather lifeless form. It is as though just a snapshot of its 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" — the stock of natural capital, that is — required to keep us going, like the bulk of the inanimate mineral resources of conventional economic production.

We have now an appreciation of the inputs to, and the outputs from, the city. Its footprint clearly calls for us to think of these within the dimension of space, as in area (and volume). But this assessment of the footprint yields no insight into how the one bundle (of inputs) is transcribed into the other (outputs). How then is all this stuff circulated through the body of the city and around the Earth? Portrayal of a sense of the processing and transformation of materials in variegated space (and time) is missing. Additional, complementary ways are needed for judging the {environmental benignity} of innovations, policies, and actions intended to achieve less unsustainability of IUWM, not least within the wider context of IWRM. We must also think in terms of the dimension of biogeochemistry.

Metabolism: Webs of Interaction and Material Cycles

Let us again adopt the perspective of the big picture.

Our species inhabits today 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 planet Earth as a whole, natural behavior of the system — as it evolves over the millennia — can be understood in the terms

[29] About 80% of the nitrogen and 50% of the phosphorus in domestic sewage derives from urine (Larsen *et al*, 2009).

of conceptual models of global material (element) cycles (Schlesinger, 1991; Galloway and Cowling, 2002; Galloway, 2003; Galloway *et al*, 2003). It is these 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 Environment. But the city, as it lands down on the ground in geological time, induces distortions rippling through the pre-existing cycles of water, C, N, P, and other materials (Beck *et al*, 1994; Beck and Cummings, 1996).

The hydrological cycle is most familiar to us; the global carbon cycle too. Nitrogen, however, is "the very stuff of life" according to Galloway and Cowling (2002). Invention of the Haber-Bosch process just before the First World War accelerated and expanded the production of ammonia (NH_3) from atmospheric N_2 (and not without a sizeable energy and carbon footprint, as we now appreciate). It changed the course of 20th-Century history — argue Erisman *et al* (2008) — and will bring about a global "nitrogen economy" in the present century. Thus, we observe, have Erisman *et al* (2008) done their bit to promote a "nitrogen-centric" perspective on the world (if not the metabolism of cities), while Elser and White (2010) have done theirs for "Peak Phosphorus". We, in our turn, have used the anthropogenic distortions in the global cycling of nitrogen to cast a sharp and critical light (in Chapter 2.3) on why the water-based paradigm of the city's *nutrient* (*ergo* nitrogen) infrastructure might reasonably be considered "broken" — at least in part.

Galloway and Cowling tell us further that in the late 20th Century anthropogenic (Haber-Bosch) N fixation from the atmosphere overtook natural terrestrial N fixation. 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? Or, as the challenge has been put in Chapter 2.4, should we rather strive to uncouple human development, not only from rising water and energy usage, but also from the growing industrial fixation of N?

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 and to "optimize" their diets — as Erisman *et al* (2008) advocate[30] — the focus on managing its fate thereafter should be all the sharper. 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 atmosphere. In recycling paper and textiles, the recovered material may spiral downwards (its quality being degraded at each turn) eventually to reach the landfill, albeit after more than just one rotation of the recycle. That would not be the objective. It would be so much better here, 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).[31]

[30] Their figures indicate that of all the reactive nitrogen produced industrially from the Haber-Bosch process in 2005, just 17% was consumed by humans in crop, dairy, and meat products, as their dietary N (Erisman *et al*, 2008).

[31] The complement of seeking to achieve upcycling of natural nutrients is the goal of cleaving into strictly separate cycles the circulation of natural nutrients and the circulation of technical nutrients, or quite unnatural substances, such as our legacy of industrial and xenobiotic materials, including the residuals of pharmaceutical metabolites and personal care products.

A Step Back: Case History of Paris[32]

Well before Haber filed his patent in 1908 on the "synthesis of ammonia from its elements" — and well before the British WC had been introduced to Parisian households half a century or so earlier — Bridet had acquired a patent in 1796 for making *poudrette* (a fertilizer) from human urine and excrement (Barles, 2007b). More were to follow. During the 1850s and 1860s, patents for manufacturing related chemicals on an industrial scale came "thick and fast". And until that time, those reactive species of N we would now have upcycled were largely *not* present in wastewater — because Paris had no wastewater as we know it today. 150 years ago, the city had already attained a decent measure of our contemporary vision of PeFe. Entrepreneurs were making good businesses out of urine and human excrement, as today might members of the individualist solidarity in a peri-urban community in Accra, Ghana, for example (Kwame, 2007; Box 2). This, then (the 1790s through the 1850s) was for Paris "the age of no waste" according to Barles. In 1817, she records, 20% of the dietary N of Paris's (human) population was returned to agriculture. "From today's daily bread unto tomorrow's", we might conclude.

These too were the times of predominantly dry sanitation in Paris. Its (nutrient) infrastructure, for dealing with the residuals of the city's metabolism of essentially just its daily bread, was that of Figure 1(d). The city's intake of daily water was employed primarily for street fountains and road cleansing. Attaining (and maintaining) such a good measure of PeFe was achieved over time in two waves: first, the rise to market penetration of the dry, *poudrette* form of fertilizer, across the first half of the 19th Century; and then the growth in liquid forms of fertilizer during the second half of the century. Hence came Barles' (2007b) second era, of the "1860s-1910s: liquid fertilization". The second wave somewhat undermined the commercial success of the first. The raw material was being weakened in strength at its source. The contents of cesspools were being diluted, not initially with the flushing of WCs, but through the grey waters of the growing water metabolism of households following in the wake of the increasing appeal of the household bath for cleansing oneself.

Demise of both the dry (*poudrette*) and liquid forms of fertilizer was to follow the First World War. Both the war and this demise owed something to Haber's patent (Erisman *et al*, 2008). The one would have been associated with the consequent expansion in industrial production of new explosives, the other with that of fertilizers. There was a growing sense of distaste and disgust amongst Parisians at the unpleasant, unhygienic nature of the infrastructure for collecting cesspool contents and their transport through the city's streets to the centralized sites of subsequent chemical transformation. Eventually, by the 1920s, Paris's "nightsoil" had become worthless. It was being generated at source in progressively wetter form, hence the increasing cost of its greater bulk (for transport) and likewise the increasing cost of recovering its valuable nutrients and other chemicals from its inevitably less concentrated character. Barles (2007b) has dubbed this era the "1920s-1970s: the birth of wastewaters".

To summarize, the symbiosis between Paris and its rural surrounds rose, from the return to agriculture of 20% of its (human) dietary N in 1817, to 24% in 1869, and 40% in 1913 — with population growing substantially all this time — only then to fall. The symbiosis was severed by the advent of today's conventional water-based paradigm of wastewater infrastructure, marked by a tripling of the re-direction of the city's dietary N into the Seine River by 1931, when it had reached 36%. From the basic configuration of Figure 1(d) in the 1850s, with dry latrines (and the manufacture of *poudrette*), Paris had thus passed through Figure 1(c) (from the 1860s until the 1910s), with a progressive "wetting" of the source-separation arrangement, to end up (from the 1920s onwards) with today's comprehensively mixed paradigm of Figure 1(a).

We now — in our case study (our work space) — want to reverse this historic progression, without in any way turning back the clock, and most emphatically not so in undermining maintenance of the high standards of public health we have come to enjoy in cities of the Global North. In order to fashion our second step towards CFG, the boundaries of what constitutes

[32] The following has drawn extensively on the work of Barles (2007a,b), especially Barles (2007b) (see also Billen *et al*, 2009). However, in the interests of not being repetitious — if nevertheless punctilious about giving due recognition to one's sources — the formalities of citation are kept to a minimum.

the "system" to be analyzed must be cast much more completely over the city-watershed couple of Figure 8(b).

As water professionals, we enquire into what can be done about the water metabolism of a city. And to find answers we usually define the system as that of the aquatic environment, the water infrastructure, and the aqueous effluent discharged back to a body of water. Classical systems analysis tells us that a richer set of answers — of options albeit for *water*-sector policies and technologies — should follow from adopting a wider purview: of accounting formally for the interactions amongst the water sector and some of the other sectors participating in the metabolism of the city-watershed couple. Our vision remains steadfastly fixed on PeFe. But it is informed now by the obvious symbiosis that once obtained in the Paris-Seine system, amongst the city, its waste-resource handling facilities, and the proximate (surrounding) agriculture.

Step (2)

A multi-sectoral, materials-flow model has been constructed to account for the interactions within the green (watershed) and blue (city) areas of Figure 8(b) and amongst the five sectors of water, food, energy, forestry and waste-(fertilizer)-resource management (Villarroel Walker, 2010; Villarroel Walker and Beck, 2011a,b). Five state variables — nitrogen, phosphorus, carbon, energy, and water — are tracked in the various flows through and around the web of multi-sectoral interactions. Given this bigger picture, we ask: how would the flows of materials constituting the metabolism of the city be changed by inserting this or that technology into the existing hull of Atlanta's infrastructure, inextricable, as it is, from the metabolism of the whole city-watershed couple (and, in truth, the rest of the world)? In particular, holding here to our chosen technological path of S@S, how much fertilizing material might be recovered on the downside of the city — and re-directed away from "polluting" the atmospheric and aquatic environments — were we to drop urine-separating technologies (USTs; Lienert and Larsen, 2006, 2007; Larsen *et al*, 2009) into all of Atlanta's households, office blocks, other work-places, public facilities, and so forth? What, moreover, might this achieve for the city's water metabolism?[33]

It turns out that replacing the kernel of why we have the water-based paradigm of today's Business-as-Usual — the household WC — with the UST (or like devices), and the associated changes to household plumbing, has the following illustrative consequences within the city and beyond. Water use, and therefore the water metabolism of the city, is attenuated by 5% (in terms of overall crude sewage flow). Beyond the water sector, 4,000 tonnes of N can be recovered annually, this being about 40% of the N content of fertilizer currently imported into the Atlanta-Chattahoochee system (Villarroel Walker, 2010). Its value as a fertilizer would be about \$4.3M per annum.[34] Alternatively, if used as feedstock for the production of algae (possibly on-site at the R M Clayton facility) with subsequent conversion into a biofuel, roughly $3(10^6)$ litres of that fuel, with a value of \$1.2M, could be generated on a yearly basis (Villarroel Walker, 2011). Concomitant with these illustrative rates of recovery of resources — from within the water sector, but to the benefit of the food and energy sectors — about 58% less N and 65% less P would be destined for disposal in landfills as municipal sewage sludge (within, therefore, the waste-handling sector; Villarroel Walker, 2010).[35] The prospect of uncoupling human development

[33] In order to eliminate nitrogen as a pollutant, wastewater treatment plants are by convention constructed with larger capacities than would otherwise be the case. Estimates show that some 60% diversion of urine away from the sewerage and (conventional) centralized wastewater treatment system, i.e., at 60% substitution of USTs in the city's household/office plumbing, the treatment plant could achieve complete removal of the remaining nitrogen without being "over-sized" and possibly with the bonus of net energy production (Wilsenach and van Loosdrecht, 2006; Larsen *et al*, 2009).

[34] Numerical estimates refer to that portion of the city of Atlanta within just the Upper Chattahoochee watershed, with a population of 1.3M. Much of metropolitan Atlanta and its population (currently 5.4M) resides in adjacent watersheds, as already noted. Recovered amounts of resources and their economic worth would be proportionately greater.

[35] This is equivalent to 7% less N and 20% less P disposed of to landfills as fractions of all the organic waste from all sectors in the entire Upper Chattahoochee watershed.

from industrial N fixation, if not the quarrying of P-containing ores, has appeared on the horizon.[36]

Put another way around, for comparison with the ecological footprint analyses of *Step (1),* the present assessment of Atlanta's metabolism indicates that comprehensive separation of material fluxes at source might enable these kinds of gains (Jiang and Beck, 2007): recovery of up to as much as 75% of the N as ammonium-N in the currently generated volumes of raw sewage (somewhat under 60% for P recovery). In addition, less than 3% of the N entering the re-engineered treatment plant of the (source-separated) future would be lost as a gaseous N-species emissions (Jiang and Beck, 2007), compared to a two-thirds loss under present arrangements in Finland (Sokka *et al*, 2004).

It took some 120 years — four or five generations — for Paris to realize a measure of PeFe, peaking at a "metabolic rate" of 40% of the dietary N of its citizens being returned to agriculture by 1913. Looking to the future, Neset *et al* (2008) estimate that about 25% of the P required in the average diet of a citizen of Linköping, Sweden, could be recovered from the sewage of that city. Phrased slightly differently, Mihelcic *et al* (2011) calculate that, if fully recovered, the P available in human urine and feces could amount to as much as 22% of total global P demand. The prospect is sufficiently "mainstream" to have become the stuff of headlines in the popular news services: "Where Sewage Meets 'Peak Phosphorus'" (Burkart, 2010). *Step (2)* suggests now that en route to a CFG over coming generations (two or three, very roughly, in Figure 2), just above 40% of the dietary N of Atlanta's citizens might become available as a conceptual PeFe fit for some further purpose, other than pollution (Villarroel Walker, 2010).

The "systems thinking" of *Step (2)* has drawn out and revealed our possibilities, well beyond the confines of the water sector. The complexities of the webs of intricate interactions in the city-watershed's metabolism have been brought home to us. They are echoed and illustrated in Moddemeyer (2010).

In contrast to *Step (1)*, the significance of not severing all the ties between the city and the watershed has become apparent (here in contemporary times, as previously for Paris). The metabolism of the body of the "bull" of a city is far more subtle than the crude footprint impressed upon the watershed. It is as if there has been an explosion of opportunities, with some ricocheting even into the transport sector. In a bygone era, nutrients were needed in fodder for horses as the means of transport; today they might serve as the basis of generating biofuels for the modern internal combustion engine. There are possibilities not only for policy, but also for entrepreneurship for innovation. This obviously once thrived in Paris. It may today seemingly spring from just about anywhere. Consider this cluster of now revealed logical and economic links. Renewable fuels are sought (for the energy and transport sectors), while recognizing Nature's provision of solar radiation and Man's deleterious contributions to atmospheric CO_2. In our pursuit of PeFe through a policy of separation at source enabled by urine-separating toilets, matching nutrients can be recovered (from the water and waste-handling sectors). Blooms of algae — to be avoided at all costs in the pollution of lake and coastal eutrophication (driven by the water-based paradigm of sewerage in the water sector) — are instead decisively to be welcomed. Climate change might conceivably drive the market for urine-separating toilets. That will be unsurprising to some.

A Step Ahead: Inter-mingling of the "Doings" of the City and the "Doings" of its Watershed

The grander sweep of the case history of Paris reminds us of how the modernity of the 20th Century, and the technocracy of its second half, have only relatively recently established habits of mind that in many ways blind us to what existed long before. Having forgotten the history of Paris, or never having known it, cities have come to be associated with the intensification of industrial production and the deliberate construction of infrastructure, both to sustain that production and contain the ills of its unwanted side-effects. We have come to think of the watershed and the rural surrounds of the city as the locus of agriculture.

[36] "The city of Ghent in Belgium will declare every Thursday a vegetarian day in an attempt to fight climate change" reported the *Daily Telegraph* of London on 14 May, 2009. Doubtless the global water and nitrogen metabolisms would benefit too. On 15 April, 2010, Wageningen University and Research Centre and the Dutch Ministry of Agriculture, Nature & Food Quality jointly announced a €1M program of research into "Sustainable production of insects as food" (www.fbr.wur.nl; accessed 19 March, 2011). The announcement noted that "Europe and North America are the only parts of the world that do not share [the] taste for insects". Any impacts on global water and nutrient metabolisms were not disclosed.

Yet poultry production in the Chattahoochee watershed surely qualifies as the intensified industrialization of Confined Animal Feeding Operations (CAFOs). Having a CAFO calls for a deliberate (ex-urban) infrastructure to "contain the ills of its unwanted side-effects". This very concentration of the CAFO, however, creates scope for entrepreneurial business and technological innovations. Pyrolysis of the chicken litter (the unwanted side-effect) can yield the goods of a gas fuel, a diesel-like fuel, and a pelletized fertilizer (Das *et al*, 2008). If this single piece of technology were to be incorporated wholesale into the CAFO (food) sector, hence the nutrient infrastructure of the Atlanta-Chattahoochee system, it could regenerate some 900 tonnes of N as fertilizer, 2100 tonnes of P as fertilizer, and 270 GWh of energy each year, i.e., an annual value stream of some $21M (in total) for the regional economy (Villarroel Walker, 2010).

Reminded of this exchange and intermingling of the "conventional" roles of the city and the watershed, an impertinent question has surfaced — and cannot be banished. What are cities, if they are not Confined Human Feeding Operations (CHFOs)? What then would spark the interest of the sustainability-minded CAFO entrepreneur, coming from outside the water sector, in any such business opportunities for fertilizer (PeFe) and energy recovery from the CHFOs of cities? Through what forms of social, sectoral, and institutional lock-in would that entrepreneur have to break, to gain access to the market, perhaps to create one? Is his/her voice not even gaining access to the debate — about IU*Water*M within I*Water*RM — let alone being acknowledged and responded to by the other "voices"? Where there is money to be made and a favorable regime of governance, one suspects, so there will be a way to break into the process.[37] And when it comes to making money (on the downside of the city), so much of this stems not from the residuals of the city's daily water, but its daily bread.

People use the phrases "urban forestry", "urban natural resources", and "urban agriculture", as if deliberately to break — by the pairing of words alone — the historic, but largely 20th Century, severance of city doings from watershed doings. There has always been urban agriculture of some form, although it may not always have been labeled as such. Today it is being promoted as an adaptive response to climate change (Dixon *et al*, 2009). Indeed, it is taking advantage of the modern shapes, forms, and abandoned industrial sites of the contemporary built environments of cities to open up creative niches for its implementation and success. Will Allen, for example, has been described as an urban farmer (Milwaukee Journal Sentinel, 29 April, 2010; www.jsonline.com; accessed 15 May, 2010). He received a 2008 MacArthur Foundation grant (a "genius award") for pioneering vertical farming in a five-storey Milwaukee building.

We are guilty now of having emphasized metabolism of the city's daily bread at the expense of taking care of its daily water. It is time to re-focus back in upon the water sector, to ponder whether all this systems thinking of *Step (2)* and the case history of Paris has expanded the portfolio of options for re-engineering the city's wastewater infrastructure.

Amidst the explosion of opportunities for change and innovation arising from taking *Step (2)* — in pursuit of the inter-generational vision of PeFe; in striving to justify the choice of Separation at Source (S@S); or in following the decentralizing zeal of Small is Beautiful (SiB; Box 1), to recombine it with the companion "miniaturizing" sentiment of local urban agriculture — certain things, grounded fundamentally in the water sector, are neither to be forgotten nor sacrificed. We know this. It was the *Water* Closet that cut the riskiest and shortest of all water-borne disease-vector paths, within the small and personal spaces of households, hence its supreme achievement in securing public health for urban dwellers.

When earlier we took *Step (1)*, we assumed there would be conveyance by road of the urine separated at its household point of origin. We could have made the same substitution — of truck for water (as the means of conveyance) — for the combined residuals of urine and feces (but instead we worked with the assumption of a vacuum system of conveyance). Truck transport of these household fluxes of nightsoil is known to have "dramatically contributed to improved sanitary conditions in Japan", especially in peri-urban areas (Matsui *et al*, 2006). A retreat from the water-based paradigm — from the structural arrangement of Figure

[37] Although economist Pearce seems somewhat pessimistic about the prospects for success in practice with market-based instruments of environmental policy (Pearce, 2004).

1(a) to that of Figure 1(c) — does *not* need therefore to be a turning of our back on all that has been achieved for public health in cities.

If we were to be so aggressively eco-efficient as to lower the water metabolism of the city yet further, to nigh on zero — the highest of egalitarian salutations to water frugality in the profligate Global North — what then would be the challenge? If we were to tighten our collective belts to the very limit of excising altogether the "Water" flux emanating from the downside of the city, to progress conceptually beyond Figure 1(c) to the driest of sanitation arrangements implied in Figure 1(d) (and the target vision of Dry-as-Dust in Figure 2), how then should *water* utilities, *water* associations, and *water* professionals gainfully employ themselves? Looking back to the Paris of the 19th Century, what, we might well ask, should any of us be doing, had the Reverend Moule — with his (dry) Earth Closet (EC) — beaten out Mr Crapper's WC in the technological sweep-stakes of Victorian Britain?[38]

In spite of the several further building blocks added now to the platform of our response to the challenge of re-engineering the city, so that it may act as a force for good (in the environment), this calculus of metabolism also has its limits. Our numerical results are restricted to statements essentially about the flows of substances and material transformation. They are silent in respect of the maintenance, if not enhancement, of ecosystem services. They are silent too on the question of gauging the *distortions* in the global cycling of materials wrought by the arrival of the city over geological time, and by the subsequent installation of its water and wastewater infrastructure. Taking the long view, across future generations, we might ask: what constitutes harmony, as opposed to "cacophony", in the way in which the city and its infrastructure are suspended in the global web of material cycles? How could one measure the topology of the network of flows in a distorted web relative to a restored web; and could the difference meaningfully inform policy, *ergo* direct specific actions towards urban infrastructure re-engineering?

[38] For one thing, Moule's EC is celebrated as the title for one of the styles of engineering sustainability in Box 1. For another, reflecting on the word many believe (incorrectly, speaking etymologically) Mr Crapper has given to the English language, the ungracious might accuse me here of writing a "load of old Moule" in this *Concepts Paper.*

Taking stock again, something is still not complete in our big picture. Appetite (footprint) conveys a sense of the sheer volume of stuff required to support the city — spatial thinking. These biogeochemical cycles give us a sense of flux, circulation, chemical transformation, and the connectivity of the city suspended in a web of interactions with the rest of the biosphere. The bulk of the bull is standing there in our mind's eye, its footprint static and obvious. Latent is the fact of the bull's metabolism quickening to a pace more akin to that of the shrew. Something, some sense of metaphorical movement, is missing yet. Some thought must be given to what happens in time, as opposed to space and biogeochemistry.[39]

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, changing all the time.

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. We know this already from Figure 7(a). Construction and installation of the treatment system 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, 2005; Beck and Cummings, 1996). Over (geological) time, the spectrum of material load disturbances has migrated through the three stills sketched in Figure 7(a) (Beck, 2005). Power in the spectrum has been shifted from the lower-frequency to the high-frequency components.

At the very least, 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. All of the technological options — any of the red rectangles of Figure 2 or the styles of engineering sustainability of Box 1 — have an Achilles heel. Studies of the interdependence of

[39] The three — space, biochemistry, and time — define the logic of how we monitor the behavior of things, hence assess them too (Beck *et al,* 2009).

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; Zimmerman and Restrepo, 2006). Vulnerability of the wastewater infrastructure may be further exacerbated, if climate change is likewise transferring power in the frequency spectrum of hydrological/precipitation regimes to the higher-frequency, possibly extreme (high-amplitude), components (Beck *et al*, 2010a).

To reiterate, 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 (CSO) — or some other acute fault — to wipe the fish away, in just a heartbeat. As the city of Atlanta well knows, so too does the city of London: suppressing transient pollution events from CSOs, with their predominantly high-frequency components in the spectra of Figure 7(a), can be expensive — very expensive in the case of London (estimated as $3.3 Billion in 2006; McCann, 2010).

As geological time passes, the pulse-rate of our athlete of a city has been quickening. It is as though the bass tones are progressively being removed from his voice, pushing him to an ever more dominant falsetto, frenetic pitch — another metaphor for conceiving of the changes recorded in Figure 7(a). 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, imprinting then his entire body therein.

In cities of the Global North, it is the wastewater infrastructure that prevents polluting activities becoming pollution actualities. These arise largely from the need to juggle with the inextricably intertwined tasks of *jointly* returning the residuals of the city's daily bread and daily water to the city's environment (Figure 1(a)). If successful for long enough, that water-based paradigm of infrastructure 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). Inadvertently, the inadequate infrastructure supported a set of ecosystem service providers we might still want today, albeit for somewhat different services.

It matters too against what background *level* of ambient "good health" of the river a transient pollution event occurs. Sustainability will be measured in ways other than that there is an appropriate balance amongst 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). Yet 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, but 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. But as in a public health system, the aquatic ecology of the 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). This, however, may strike some as not merely provocative, but offensive to their valuing of ecological health and integrity.

Uncoupling the city's water- and nutrient-return infrastructures (Figure 1(c)) ought, by reflection, to have obvious and welcomed benefits, because it is

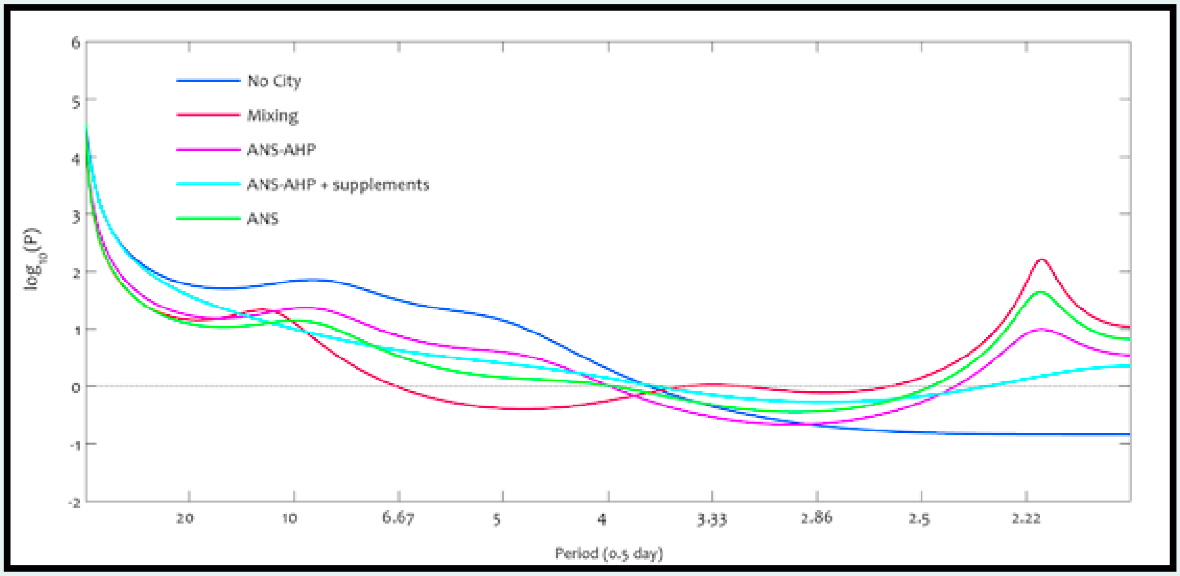


Figure 9
Specific computational realizations of the concept of spectrum sketched out in Figure 7. Frequency spectra (or city-watershed pulses) computed from time-series, such as those of Figure 10, generated from a simulation model (***M***) of the city of Atlanta within the Upper Chattahoochee watershed in the South Eastern USA. Hydrological conditions relate to the year 1986, in the Chattahoochee River immediately downstream of the discharge of the R M Clayton wastewater treatment plant of the city of Atlanta (yellow dot in Figure 8(b)). A variety of conditions are reflected: current conditions, i.e., with the conventional water-based paradigm of wastewater infrastructure ("Mixing"; the situation, in effect, of Figure 1(a)); source separation, for example, using a device similar to the urine-separating toilet, in which urine ("anthropogenic nutrient solution"; ANS) is separated from all other household fluxes of sewage ("ANS"; the situation, in effect, of Figure 1(c)); an alternative form of source separation, in which urine and feces ("anthropogenic humus precursor"; AHP) are separated from all other household fluxes of sewage ("ANS-AHP"); source separation with the issue of nutrient supplements to the river ("ANS-AHP + supplements"); and conditions without the city ("No city"; perhaps even the "city with dry sanitation").

essentially the coupling of the two that makes a bull of the city in the china shop of its restored watershed. To the case being assembled in response to the challenge of Chapter 2.4, therefore, can yet another building block be added.

Step (3)

Our favored technological path for uncoupling these water-nutrient infrastructures through source separation (S@S; Box 1) should make the river and watershed less vulnerable to accidents, faults, and failures. For it is not the water released in an uncontrolled manner from the city's currently coupled wastewater infrastructure (Figure 1(a)) that is the greater threat to the watershed, but the nutrients and contaminants borne in the sewage *and* the biomasses employed to remove them from the water flux, at the heart of the engine of biological wastewater treatment. The sudden, intense release of both, beyond a certain level, constitutes impairment of the receiving water body.[40]

Synoptic representations of the pulse of the city-watershed system, computed from simulation experiments (Figure 9; Beck *et al*, 20011a), substantiate earlier conjectures on how arrival of the city has "quickened" the pulse of the city-watershed system (Figure 7(a); Beck, 2005). These numerical results refer again to the city of Atlanta (Beck *et al*, 2010a, 2011a). Roughly speaking, the presence of the city transfers some of the power in the signal of the pre-city watershed from the lower-frequency (bass tones) to the higher-frequency (treble-falsetto) components of the spectrum, especially those at the weekly and diurnal frequencies. These appear (in Figure 9) as peaks in the spectrum of the in-

[40] And once that biomass engine is lost or compromised during an event, its fully-functioning state takes a significant amount of time to be restored after the event.

stream total P concentration variations, even under a current regime of fairly comprehensive biological wastewater treatment of the conventionally mixed flux of influent crude sewage to the plant.

When the various sewage fluxes are separated at source and the treatment plant re-arranged for the express recovery of perfect fertilizer (in the distant future), it is apparent how the pulse of the system — in terms of in-stream total P behavior — can be lowered, but only up to a point. Expressed technically, when the structural change by separation at source is effected from Figure 1(a) to Figure 1(c), some of the "power" (predominance) of the diurnal-frequency component is attenuated and some of the originally present, "primordial" (or "No City"), somewhat lower-frequency components (with periods of some 2 to 6 days) are recovered. The difference is as that between the red line indicated as "Mixing" in Figure 9 and either of the green and magenta lines in Figure 9, indicated respectively as ANS and ANS-AHP.[41]

Cast in symphonic terms, some of the over-abundant flutes and violins have been removed from the orchestra and replaced with clarinets and violas, if not cellos. Put otherwise, yet again, the entire picture of Figure 9 — whichever structural arrangement or re-arrangement is being thought of — has to do with keeping in mind the "long [wave] and short [wave] of it all [spectrum]".

This, however, is to be thinking of merely restoring the watershed to something approximating a former condition, by compensating for the ills of the city. The challenge of re-engineering the wastewater infrastructure of the city, so that the city-infrastructure couple can act *par excellence* as a force for good in the watershed, calls for yet something more — one further, culminating step.

[41] ANS stands for Anthropogenic Nutrient Solution, a sanitized term coined by Larsen and Gujer (1996) for urine; AHP stands for Anthropogenic Humus Precursor, a like term for feces. Separation of ANS from the other household fluxes is re-engineering strategy S@S(1) of *Step (1)*; separation of ANS-AHP from the other household fluxes is re-engineering strategy S@S(2) of *Step (1)*.

3.4 An Expansive Prospect: The City and Its Infrastructure as an Intelligent Bull Gifted with Deft Movement

Think on this. There was a pre-city hydrological regime, or frequency spectrum, a similar sediment spectrum, *and* a similar spectrum of nutrient perturbations, all collectively giving rise to the pre-city natural capital, ecosystem services, and service providers in the watershed. Man's structural interventions in the watershed to meet the demands of agricultural and energy production have in part distorted that frequency complex (Figure 7(b)), as have, in other ways, the interventions geared to the rise of the city (Figure 7(a)). If then the uncoupling of the city's water- and nutrient-return infrastructures were to be realized through the wholesale introduction of urine-separating toilets, with subsequent conveyance of the separated urine to a riverside treatment facility, for recovery and preparation there of a nutrient product, to what further purpose should this conceptual PeFe be put? Most obviously, it should be returned to the agricultural sector, subject to considerations of transport costs, which themselves might be diminishing where intensive agricultural production is itself pressing in upon the city (Ermolieva *et al*, 2009). Less obviously, after decades of removing nutrients as the causes of polluting eutrophication, this PeFe might instead be turned to the intensive cultivation of algae, hence the beneficial production (on-site) of a diesel-like fuel (Lardon *et al*, 2009).

Less obviously yet, we can imagine the following. From time to time, perhaps contingent upon the competing demands for directing this product into agricultural and/or energy services, it might instead be dosed to the river. The deliberate intention would be to go beyond merely restoring the distortions wrought in the nutrient spectrum by the city, to achieve — no less — the *good* of compensating for the distortions arising from the needs of agriculture elsewhere in the watershed. From computational assessment of this conjecture, we can set one last plank into place in our preliminary platform, on which to build a response to the challenge of Section 2.4.

Step (4)

It is indeed possible to simulate the occasional injection of nutrient supplements into the Upper Chattahoochee River from the re-arranged treatment facilities of the city of Atlanta, attuned at some point in the imagined future to a comprehensive uncoupling of that city's water- and nutrient-return infrastructures (Figure 10; Beck *et al*, 2011a). The spectrum of in-stream total P concentration variations can thereby be manipulated, deliberately to shift power out of the higher-frequency and back into the lower-frequency components (Figure 9). There is the capacity to wield power in this way, in principle. What is more, the simulated prescription for these nutrient supplements (Beck *et al*, 2011a) looks remarkably similar to those designed to deliver environmental flows for sustaining river ecosystems (Figure 11; Richter *et al*, 2006). The strategy is also (provisionally) robust in the presence of a relatively simply prescribed changing climate for the Atlanta-Chattahoochee system (Beck *et al*, 2010a).

Technically speaking, the nutrient supplements re-shape the spectrum by attenuating still further the prominence of the diurnal (24-hour) and weekly (7-day) frequencies. The turquoise spectrum of the ANS-AHP + Supplements in Figure 9 is markedly lower than its ANS-AHP counterpart (magenta line) at the 24h frequency. The progressively fading peak at the weekly frequency has disappeared altogether. This is especially apparent in Figure 9, if one tracks the changes in the spectral curves around this frequency across the sequence from red (current situation) to green to magenta and finally turquoise (separation with PeFe supplements). The S@S strategy with these supplements ameliorates the consequences for the aquatic environment of the way in which we have tuned the intensity of socio-economic life in the city to the focus of the 24-7 routine.

In the metaphor of the symphony, more of the previously still over-abundant flutes and violins have been taken out of the orchestra; some of the original complement of bassoons, cellos and double basses has been re-introduced.

What we have yet to discover is how to wield such power wisely, if at all, eventually in practice, and with {social legitimacy}.

Eco-efficiency and Eco-effectiveness

This culmination of a response to the challenge of re-engineering the city so that it can act as a force for

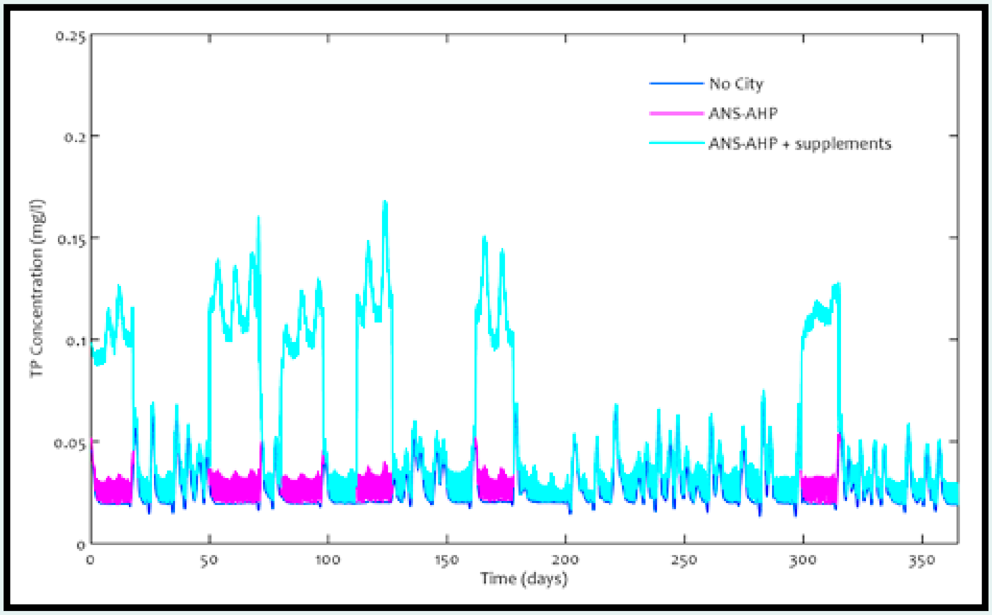


Figure 10

Model (***M***) simulated variations in total-phosphorus concentrations for 1986 in the Chattahoochee River immediately downstream of the discharge of the R M Clayton wastewater treatment plant of the city of Atlanta (yellow dot in Figure 8(b)), for conditions without the city ("No City"), for the ANS-AHP source-separation strategy, and for the ANS-AHP strategy with occasional nutrient supplements.

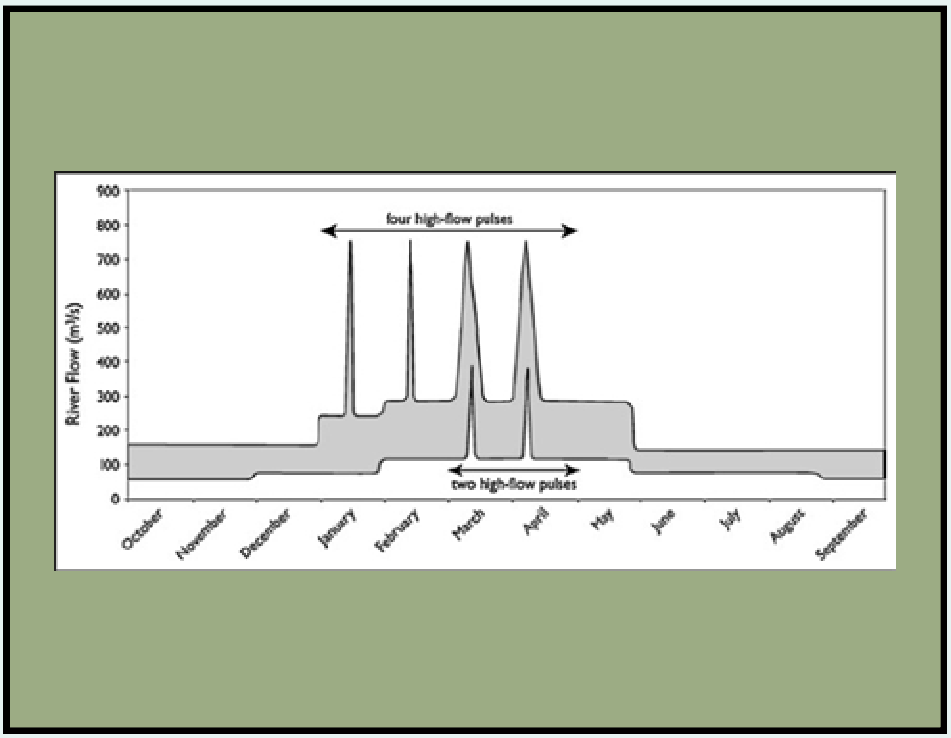


Figure 11

Specification, i.e., prescription, of the temporal pattern of environmental flows intended to restore and preserve the well-being of fish assemblages in the aquatic ecosystem of rivers, such as the Savannah River in Georgia and South Carolina, South Eastern USA (reproduced with permission from Richter *et al*, 2006).

good, however, has been expressed in terms of the subtle, if not obscure, image of the pulse (spectrum) of a system. That image may lack the intuitively understandable quality of the city's ecological footprint. Reducing the footprint of the city, as well as reducing its water and nutrient metabolisms (using yet another biological analog), conveys simply and succinctly the intent of a collective tightening of our belts — of our becoming "less bad". Yet being less bad, some have argued, is not the same as being "good". Associating frugality with the phrase eco-efficiency, they claim this will not in fact guarantee sustainability (Huesemann, 2004). The same has been expressed before (Dyllick and Hockerts, 2002) and since (Rees, 2009) — in more measured tones.

Terms such as eco-efficiency and, especially so, ecological footprint, can be aligned with the sentiment of "bounded by zero" and the invocation to head towards "zero" — as in cutting out altogether the "Water" efflux from the city in Figure 1(d). These terms too might be understood by some as redolent of an accompanying moral rule of "shouldn't do".

"Eco-effectiveness", on the other hand, has been introduced as cleaving to a principle whereby human systems are designed to nurture and feed natural, ecological systems, rather than depleting and contaminating them (McDonough and Braungart, 2002; Villarroel Walker, 2010). If "more good" is to eco-effectiveness what "less bad" is to eco-efficiency, then the understanding of eco-effectiveness that has guided our discussion towards its present culmination has more to do with the sentiment of things being "unbounded" (and a moral compass of "can do").

This is what the criterion of pulse, opaque and unfamiliar though it may be for the time being, has enabled us now finally to conceive of and explore. It evokes a sense of expansiveness of outlook, of being a liberating thought: the sheer *joie de vivre* of up-ending a "bad" and opening it out into an ever-expanding "good". If the expected outcomes, such as those adumbrated in the principle of nutrient supplements, could be cast in the much more familiar calculus of the Ecological Footprint, the city might almost be judged capable of "walking on air".

Taking Stock

In retrospect, we opened our computational-model ($\boldsymbol{M}$) course through the Atlanta-Chattahoochee case study with an assessment of the {environmental benignity} of policies of re-engineering according to the criterion of ecological footprint, rooted in the dimension of space (relative to that of the globe's surface). Self-evidently, this begins with the city, yet the numbers it generates are all about the input resources ($\boldsymbol{u}$) and output residuals-wastes ($\boldsymbol{y}$), with a loss of how the one is connected to the other. Symbolically, judgements are made on the basis of [$\boldsymbol{u} \parallel \boldsymbol{y}$], where $\parallel$ symbolizes indeed a gap — the absence of an account of how $\boldsymbol{u}$ is transcribed (→) by the city into $\boldsymbol{y}$.

That, of course, is precisely what is achieved through the assessment of the metabolism of the city, suspended (as it is) in the web of biogeochemical transformations taking place around the globe. With it, judgements can be made about [$\boldsymbol{u} \rightarrow \boldsymbol{y}$]. According to the way in which we have herein employed the notion of metabolism, moreover, the city is inextricably interwoven with the watershed, so that strictly speaking [$\boldsymbol{u} \rightarrow \boldsymbol{y}$] refers to the city-watershed couple. Notwithstanding the *water* in the *water*shed, furthermore, our account of [$\boldsymbol{u} \rightarrow \boldsymbol{y}$] has been multi-sectoral and — for the sake of argument — decidedly non-water-centric at times.

These assessments of the appetite (footprint) of the city and the metabolism of the city-watershed couple are both static. The notion of the pulse of the city-watershed system provides the element of "dynamics", of things varying throughout the dimension of time (t), encapsulated succinctly in the plots of spectrum. In particular, Figure 9 charts the changes wrought by different ways of configuring — *and* operating — the technological complex ($\boldsymbol{\alpha}$) of the infrastructure that mediates some of the ways in which $\boldsymbol{u}(t)$ is transcribed by the city into $\boldsymbol{y}$(t): [$\boldsymbol{u}(t) \rightarrow \{\boldsymbol{\alpha}(t)\} \rightarrow \boldsymbol{y}(t)$]. All — appetite, metabolism, pulse — contribute to a more rounded sense of what might constitute an environmentally benign policy intervention.

We have pushed our biological-ecological metaphor towards an engineering turn of mind: of the city and its water-nutrient infrastructures ($\boldsymbol{\alpha}$) as the bull invested now with enhanced intelligence enabling purposeful and deft (metaphorical) movement about the china shop of a restored yet vulnerable watershed. What the rural-agricultural parts of the watershed cannot do for themselves, lacking this technological intelligence and deftness of action, the city-infrastructure couple might do on their behalf, in the interests of contributing to enhanced ecosystem services across the entire watershed.

Such smartness, intelligence, and deftness are, of course, the very essence of the vision of "Control Freak's Delight" in Figure 2. They are also core features of the Dynamics and Control (D&C) school of thought in Box 1, as one means of engineering our way out of the currently unsustainable "Business-as-Usual" (BaU), in concert with S@S (Separation at Source) or some alternative strategy, towards the favored vision of PeFe so convincing to our hypothetical community in the foregoing case study of Atlanta. It is through contemplating D&C in rather more detail, however, that we can gain a better sense of the true scope of how to infuse ecological resilience (Holling, 1996) into the behavior of the city's web of infrastructure. Given that, there is then Holling's ecological definition of sustainable development to be considered, and its relationship with biodiversity, not to mention the biomedical notions of self-healing and the auto-immune response of systems. But all that is the subject of Box 3 (see also Beck *et al*, 2009).

While Stepping Out in a Different Direction

Other conceptual and logical circuits could be circumnavigated around the city and its strands of infrastructure: always on the lookout (again) for the positive expansiveness of cities as forces for good, but this time in respect of restoring and enhancing terrestrial ecosystem services rather than their aquatic complements.

Following *Step (2)* in our case study of Atlanta (above in Chapter 3.3), we have seen how urban agriculture may benefit from occupying the urban land forms and space vacated by fallen industries. Urban biodiversity may likewise thrive. The titles of presentations from an October, 2010, conference on Urban Biodoversity signal how: "Brownfields: Oases of Urban Biodiversity" (Craig MacAdam); "Biodiversity on Bings [spoil heaps from past mining of coal]" (Barbra Harvie; see also Harvie, 2007). The conference was organized by the Glasgow Natural History Society (www.glasgownaturalhistory.org.uk; accessed 11 March, 2011). That conference would also have heard how prosperity of the urban flora and fauna should lead to well-being in the community of urban dwellers (from a presentation by Malcolm Muir).

In its turn, wildlife conservation tends to anticipate the forward process of urbanization, i.e., the conversion of natural habitat into urban forms with but fragments of the pre-existing landscapes, and "to the detriment of wildlife" (Marzluff and Ewing, 2001). Our interest would be in the reverse: in marshaling these fragments so that they may become a force for enhanced urban biodiversity, which might then reverberate outwards into enhanced terrestrial ecosystem services (in the surrounding watershed).

For his part, Lefèvre (2009) pleads for planning of the city to be based on a joined-up understanding of the way land-use and transport co-evolve. He asserts this has hitherto rarely been the case. He fears that cities of the Global South might otherwise grow rapidly in ways contrary to the needs of conserving energy under the threat of climate change. For those cities he sees a stark choice, between the extremes of Atlanta and Barcelona, Spain, as contrasting exemplars of cities of the Global North. The two have about the same population (somewhat above 5M), but Atlanta occupies over 25 times as much land as Barcelona and its associated system of transport emits over ten times more CO_2 (at about 7.5t/hectare/annum).

Amidst this complex of climate, energy, transport, urban form, land-use, and biodiversity, Grimm *et al* (2008) have observed that "[i]ntroduction of nonnative species combined with the UHI [urban heat island] may in some cities actually *enhance* ecosystem services, such as soil mineralization" (emphasis added).

Sparking the Transition

Altogether, given the ambition of PeFe, and S@S as a means of attaining it, we judge we have the promise of a policy that is variously:

climate robust (Beck *et al*, 2010a);

capable of uncoupling human and economic development from industrial N fixation (the Haber-Bosch process);

capable of being "calming" in respect of lowering the city's nutrient and water metabolisms;

a potential contributor to ecosystem services;

but not disposed towards jeopardizing the security of public health in the city.

Yet we risk all this being quite a bit too good to be true. For it mirrors exactly the challenging juxtaposition of "lofty principle" with the "little things in life", which we placed at the close of Chapter 3.2 on {economic feasibility}. Surveys show that attaining the heights of PeFe through S@S will be contingent upon just the right kind of intensely local, intimate, and strictly personal behavior (Lienert and Larsen, 2009).

The entirety of our reporting on the Atlanta-Chattahoochee case study has been a "quantum leap": from start (BaU) to any other kind of "finish", i.e., any one of the plural visions, drawn as the green ovals in the upper right corner of Figure 2.[42] Our numerical results relate to just two instants in time: present and distant-future annual performances. No account is taken of any transient increases in ecological footprint, or temporary increases in the water, energy, or nutrient metabolisms, or yet further emphasis on the 24-7 character of life in the city, in implementing the transformation over time — stepwise from the current initial conditions to the completed target "end point" generations hence. Things may have to get worse before they can get better. This was the dilemma put to us by Solow in respect of what constitutes {economic feasibility}. Indeed, choosing the technological trajectory of source separation (S@S) may itself have great appeal, both at its outset and in the sunlit uplands of its end point. Yet it may also require the city-watershed system to pass through an especially risk-prone intermediate phase (Beck *et al*, 2010a; Box 1). Beware of not "optimizing the part while pessimizing the whole", caution Hawken *et al* (1999). Optimizing for the "short-term" and for the "long term" might somehow add up to pessimizing for "all" of the technological path over time from BaU to PeFe (or whatever).

Thus has our discussion threaded its convoluted way through the triple bottom lines of the present chapter, in order to generate a set of technological alternatives (the red rectangles in Figure 2) enabling paths of progress towards but *one* of the several, alternative green ovals in Figure 2, of distant aspirations for greater sustainability in IUWM within IWRM. What, we must now ask, might spark the transition; and how might we gauge progress in such change?

Prevailing water policy seems an unlikely instrument of change. In the years it has taken to produce this *Concepts Paper*, the City of Atlanta has been obliged under such policy to commit its wastewater treatment facilities (specifically the R M Clayton plant) to further aggressive and expensive extensions for eliminating "phosphorus the pollutant". According to our analyses (Jiang *et al*, 2005), ridding the system of a further 50 tonnes of phosphorus the pollutant (beyond typical current rates) might easily cost at least $2-4M for a large-scale plant (as a Total Annualized Economic Cost). Costs could be perhaps as much as three times more if these 50 tonnes had to be eliminated from a collection of small-scale treatment plants, possibly amounting to $6-10M per annum. Recovering instead 50 tonnes of "phosphorus the resource" could return each year the benefit of $130k worth of fertilizer (Villarroel Walker and Beck, 2011b). Is this sufficiently visceral to spark the transition? Might not "small" — and incrementally "decentralized" — not only be "beautiful", but also "economically compelling", if not socially legitimate?[43]

Addressing these questions is the purpose of Chapter 4, and then Chapter 5.

[42] "Finish" or "end point" fully deserve their wrapping in quotation marks. Attainment of the attaching targets will not imply cessation of the search. Any "end points", labeled as such for convenience in our discussion, will merely punctuate the process of continual adaptation and evolution in the form and function of the city's infrastructure.

[43] The authors of the "Peak Phosphorus" scenario would probably tell us $130k will look cheap at the price before not too long (Elser and White, 2010). However, the benefit stream has been expressed *without* the costs of plant adaptations required to bring it into being, such as those, for example, of Britton *et al* (2007). Nevertheless, in principle, an incoming benefit stream still appears more attractive than none whatsoever.

BOX 3

Engineering Resilience into the System: At the Interfaces Amongst Ecology, Engineering, and Biology

There is a style of engineering sustainability, or school of thought, with vision extending but very little beyond birth and infancy in the life-cycle of an urban infrastructure. We know this from Crandall Hollick's sorry account of the wastewater system in the city of Kanpur, India (Crandall Hollick, 2007). There are many who will now rail against this kind of technocracy, myopic or otherwise, and not least against the engineering technocracy in that country (India). There are other schools of thought, or technocratic styles, which adopt the long view essential to sustainability. They look beyond planning, design, and construction, almost from before project conception; and they have been described herein as fixated, no less, on the adulthood of operations and beyond (Beck, 1981). We recognize this as the Dynamics and Control (D&C) school of thought in Box 1.

Thirty years on, after the passing of more than a generation, the inability of this school of thought to have gained any real purchase in the water sector, can still (regrettably) be argued with conviction (Beck, 2005). There are still institutions not ready to release any funds to study/enact operations in the life-cycle of water-sector infrastructure and governance, not even ready to release funds for planning, but prepared only — in effect — to allocate funds for planning to plan. Myopia, and the absence of a long view expressly peering into the details of the more mature stages of the infrastructure life-cycle, can still prosper, if not prevail.

Pulse, Spectrum, Dynamics and the Engineering of Control

All these phrases — pulse, frequency spectrum, dynamics — have quintessentially to do with the way things vary with time.

Sir Alan Harris, an eminent engineer who regretted the intellectual and professional separation of mechanical engineering from civil engineering, put it this way: if an object is meant to move, that is mechanical engineering; if it is meant to stay put, that is civil engineering. Control engineering, taught in the disciplines of mechanical engineering, electrical engineering, aerospace engineering, and chemical engineering, is about engineering the dynamics of change and variability in the behavior of an entity — "movement" in an object — *after* its conception, design and construction. Civil engineering, which embraces engineering hydrology and environmental engineering, has generally had little pressing need to devote attention to the operational stage in the life cycle of its products, even over the past three to four decades.

Control engineering concerns itself, then, with manipulating the system so that such changes are more to "our liking", as in achieving for us a smooth, as opposed to a bumpy, flight in an aircraft, for example. In this sense, control is primarily about manipulating the function (performance) of the system, not its structure. It is not about manipulating the manner in which the parts of the system have been put together, or come together naturally (through evolution).

In terms of our metaphor of the bull in the china shop, control amounts essentially to what we have described as the attributes of "smartness", "intelligence", and "deftness of movement" in the re-engineered city-infrastructure couple (in Chapter 3.4).

BOX 3

Engineering Resilience and Ecological Resilience

Holling, an eminent ecologist and author of the Myths of Nature caricatured in Figure 3, has argued persuasively that we have engineered most of our infrastructure, technologies, and industrial production systems so as to enslave their functioning to achievement of what he calls "engineering resilience" (Holling, 1996). To this has control engineering historically been dedicated. For as long as the system is not subject to significant disturbance, the exercise of control can maintain function at some desired level, usually constant or narrowly circumscribed, because that so often seems to be much more to our liking. This is life, in effect, on the potential surface in the lower-left quadrant of Figure 3. In the face of substantial disturbance, however, such achievement of engineering resilience can be revealed as brittle in quality (Holling would argue). The performance of the system may be knocked out of its comfortable equilibrium and descend into an altogether quite different pattern of function, not at all to our liking — a consequence of the vulnerability of contemporary wastewater infrastructure depicted in the frequency domain of Figure 7.

"Ecological resilience", on the contrary, would enable the maintenance of essential (and desired) functions under even such circumstances. In other words, dynamic behavior would be experienced according to the stability surface in the upper-right quadrant of Figure 3. Its manifestation in the "self-organized" behavior of a system, especially the Environment, is considered to be the result of natural evolution — anything but induced by the hand of Man. It undergirds Niemcynowicz's urging retreat upon us, from the modern technocracy of environmental engineering (20CTP), towards a renaissance of *manipulating* the more natural systems of ecology of earlier times (Niemcynowicz, 1993; as SOS in Box 1). Having the attribute of ecological resilience in the behavior of what we cherish would seem only but to add to what we should just as much understand as sustainability. It might also have a vital role to play in responding to the search for robustness in the face of climate change (Beck *et al*, 2010a).

Ought we not, then, to consider engineering ecological resilience deliberately into IUWM, if not IWRM? For as (dynamic) pulse is to (static) metabolism in Chapter 3.3, so these notions of resilience complement those of industrial ecology. If successful in such a re-engineering, would this not be an apt riposte from the (humbled) Engineer to the Ecological thrust ascendant in that great "sustainability debate" of the 1990s?

Changing Function and Changing Structure

As caricatured in Box 1, 20CTP and D&C stand respectively at the two boundaries — 100% and 0% — of a scale of reconstruction. At the one extreme (0%), not a metaphorical brick of the urban water infrastructure is removed, except for inserting the small boxes housing instrumentation and real-time control devices, the essence of intelligence and deftness of movement — a change of function, in other words. At the other (100%) everything is demolished, including the vast hull of the sunk historical investment in plumbing, pipe networks, channels, tanks, and so forth, as the prelude to building completely anew — a change of structure. Without thoughtful management, the "hard path" of a 100% reconstruction strategy (changing structure) should suffer from a large ecological/carbon footprint arising from the movement, if not the recycling, of so much material. In like terms, the 0% strategy (changing function, i.e., D&C on a grand scale), would in principle retain the hull of the city's sunk investment of past decades and centuries in its unreconstructed, centralized forms of sewerage and wastewater treatment (rather now, nutrient-resource recovery).

BOX 3

Pragmatically, in between the extremes, simulation results for a large wastewater treatment plant indicate that upgrading plant performance from an effluent total P requirement of 2 gm^{-3} to that of 1 gm^{-3} could be achieved at a cost of about $2M, as a Total Annualized Economic Cost (TAEC), assuming a facility life-span of 20 years under a (nearly) 0% reconstruction strategy, as opposed to $5M for a strategy more akin to substantial, if not 100%, (re)construction (Jiang *et al*, 2005; Jiang, 2008).[1]

Engaging in a wider, constructive disputation amongst the differing schools of thought of Box 1 (the portfolio of red rectangles of Figure 2) might be initiated by charging 20CTP and D&C with the task of coming up with strictly comparable triple-bottom-line accounts of their respective paths: of soft (→0% reconstruction) versus hard (→100% reconstruction). The alternative (technological) paths would be required to proceed from the initial conditions of today's hull of conventional centralized wastewater infrastructure (BaU) and to arrive generations hence at the target end-point of, say, the PeFe aspiration. For D&C, the additional challenge would be to engage in occupying the quite unknown territory of requiring the operational water-centric goal of BaU to be re-oriented to maximizing resource recovery (nutrients, energy), without abandoning the constraint of producing very clean water. This is no small challenge, given the historic operational straitjacket of BaU, at least on the downside of the city in Figure 1(a) or 1(b) (Beck, 1981, 2005).

Introducing More Cellular Function

In its pure form, the "0% school of thought" would seek to suffuse the system of infrastructure with ecological resilience by applying control "externally". Barely a brick would be moved. But as observed in Chapter 3.3, it might make the system increasingly vulnerable to cascading failures arising from a growing reliance on information technology for effecting communication and operations (Zimmerman, 2001; Rinaldi *et al*, 2001; Little, 2002; Zimmerman and Restrepo, 2006). Such vulnerability would be heightened in the face of high-frequency (fast-acting), high-amplitude threats. The pure strategy could thus yet run the risk of coming to epitomize (again) the brittleness of Holling's engineering resilience. This we can recognize quantitatively in our own simulation studies of the concept of pulse and frequency-spectrum of the city-infrastructure couple (Figures 9 and 10; see also Beck *et al*, 2011a).

Relaxing strict adherence to a pure strategy, there could be significant merit in designing ecological resilience into the system, as opposed to enacting it through operations from "without". Seeing how this might be achieved requires us to shift disciplinary gears, from ecology to the features of dynamic behavior found in cellular biology — a kind of "biologizing of control" that theorists have argued should be the next strategic step in the development of control engineering itself (Casti, 2002; Beck *et al*, 2009). This is to ask, in effect, whether technological parts of unit processes capable of mimicking the cellular, biological properties of subliminal immune response, damage limitation, self-repair, and self-replication could successively be incorporated into the body of the infrastructure as a whole (an intent already embodied, in fact, in the idea of a "self-healing energy infrastructure"; Amin, 2001).

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[1] These results derive from a study of cost estimation for pollutant trading schemes assuming only a conventional mixed crude sewage influent to the plant.

BOX 3

Ecological resilience in behavior over time is a function of the interplay amongst relatively slowly changing (low-frequency) and relatively swiftly changing (high-frequency) components of behavior, i.e., the cross-spectrum interactions introduced at the beginning of Chapter 3.3. These inescapable interactions — the fact that the proper study of high-frequency, transient pollution events could not be isolated from all the other frequencies of variation in the behavior of the system — were indeed the motivation for reaching out to the concept of spectrum-pulse in the first place (Beck, 1996).

Ecological resilience has companion interpretations in respect of cross-scale interactions (Peterson *et al*, 1998):

> [E]cological resilience is generated by diverse, but overlapping, function within a scale and by apparently redundant species that operate at different scales, thereby reinforcing function across scales.
>
> The combination of a diversity of ecological function at specific scales and the replication of function across a diversity of scales produces resilient ecological function.

What principles for re-designing the dynamic performance of a city's water infrastructure could we derive from these, through merely substituting the word "species" by "unit process technology" (and eliding thus the disciplinary and conceptual distinctions amongst Engineering, Ecology, and Cellular Biology)?

For Holling, sustainable development itself is founded upon such insights about redundancy and (in)efficiency of function, specifically in endotherms (warm-blooded animals), whose "average temperature is perilously close to lethal" (Holling, 1996):

> Five different mechanisms, from evaporative cooling to metabolic heat generation, control the temperature of endotherms. Each mechanism is not notably efficient by itself. Each operates over a somewhat different but overlapping range of conditions and with different efficiencies of response. It is this overlapping "soft" redundancy that seems to characterize biological regulation of all kinds. It is not notably efficient in the engineering sense.
>
> At least some aspects of ecologically resilient control are equally familiar to the control engineer, for operation at the edge of instability is characteristic of designs for high-performance aircraft. Oddly, the result is opportunity. Effective control of internal dynamics at the edge of instability generates external options. Operating at the edge of instability generates immediate signals of changing opportunity.
>
> That surely is at the heart of sustainable development — the release of human opportunity.

Pulse-Spectrum and the Volume/Quality of Ecosystem Services

The idea of pulse-spectrum has been drawn herein from the perspective of Engineering. We have projected it outwards therefrom, i.e., from the infrastructure of IUWM, into the domain of gauging the volume and quality of the services provided by the aquatic ecosystems of watersheds (within the setting, therefore, of IWRM). And we have explored the capacity of the city-infrastructure couple to work to the betterment of those services. What, we must ask now, are the theoretical and empirical justifications for asserting that the spectrum of variations to which ecosystems are subject is related to the volume and quality of ecosystem services?

BOX 3

On theoretical grounds, we find that (Arthington *et al*, 2006):

> ... [T]he literature does strongly support the generalization that different types of flow variability support different ecological communities and life history strategies ...
>
> There is now general agreement among scientists and many managers that to protect freshwater biodiversity and maintain the essential goods and services provided by rivers, we need to mimic components of natural flow variability, taking into consideration the magnitude, frequency, timing, duration, rate of change and predictability of flow events (e.g., floods and droughts), and the sequencing of such conditions.

The "mimicking" advocated by stream ecologists would be strongly akin to the enduring motivation of control engineering, no matter how shocking such might be to them.

On empirical grounds — if we are permitted to equate these with practical prescriptions for maintaining environmental flows and to accept as fact that "environmental flows" are intimately related to "vibrant ecosystem services" — we find in Richter *et al* (2006) a sampled approximation of spectrum (variability) comprising the following elements: (i) "floods", or higher-amplitude, high-frequency[2] events; (ii) "high flow pulses", or lower-amplitude, high-frequency events; (iii) "low (base) flows — normal", or low-amplitude, low-frequency events; and (iv) "low (base) flows — drought", lower-amplitude, lower-frequency events.

Elsewhere, in a quite different setting, there is further empirical evidence touching upon the same generic principle. Studying the scope for discharging toxicants in a manner less unsympathetic to the recipient (marine) environment — the obverse of nutrient supplements, yet not quite the notion of environmental vaccination — Johnston and Keough (2005) assert that:

> Managers will benefit from experimental work that identifies ways of reducing environmental impacts by varying the frequency and intensity of toxicant releases.

We may conclude that vibrant ecosystem services are sensitive to disturbance spectra, in general, and derive specifically from a given spectrum of stream flow variations, but — as yet — not necessarily that they derive from a given spectrum of nutrient concentrations (or fluxes).

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[2] "Frequency" refers again here strictly to the components of variability with time, not to the statistical property of how often a flood, or a pulse, or a drought occurs.