Chapter 2: Engineering, Water, and Sustainability

> In proposing a new model of watershed management for the 21st Century, ecologists have rejected the "quick engineering fix" of the 20th Century (Poff *et al,* 2003).

Looking back over twenty years of the Ganga Action Plan, Crandall Hollick relates the sad tale of a technocracy bent on cleaning up that river through centralized wastewater treatment systems, as in the city of Kanpur (in *Ganga: A Journey Down the Ganges River*; Crandall Hollick, 2007). Funds were available for planning, design, and construction, in rapid succession, but *not* beyond: *not* for the lengthy, drawn-out operational stage in an infrastructure's life cycle.

That there might at project conception be such short-sightedness in the "quick engineering fix" has long been well known. The case of Kanpur would seem to have played out on a grand scale what had become recognized by the late 1970s as the stunted conceptual life-cycle of most of the then civil and environmental engineering projects (Beck, 1981; compare with Beck, 2005). If the fixation on operations of Beck (1981) could be deemed prescient with hindsight — or simply an alternative, minority school of thought (as eventually set out in Box 1 and, in more detail, in Box 3) — we should derive no joy whatsoever from what has unfolded since in the Ganga Action Plan.

One of the defining features of sustainability has become that of providing the dogged, determined, compensatory focus on the distant future — on the long view. At times it will be discomforting, and should be.

2.1 Integrated Water Resources Management and Integrated Urban Water Management

Much has been said of Integrated Water Resources Management (IWRM), since the concept was brought back to the center-stage of our thinking and further elaborated by the Technical Advisory Committee of the Global Water Partnership (GWP) in 2000 (GWP, 2000; Giupponi *et al*, 2006; UCOWR, 2006; Jeffrey and Geary, 2006). Some of what has been said of it, moreover, has been to this effect: that IWRM has been practised in various successively less rudimentary forms for more than a century in the modern era (Beck, 2005), most notably in the industrial watersheds of northern Germany (see, for example, the Emschergenossenschaft; Raasch and Schüler, 2007).

Not for the first time, IWRM has become the well-spring for conceiving of how to steward water, infrastructure, and land use within a watershed — now in "sustainable ways", in contemporary parlance. Integration here has several dimensions to it, along each of which the purview of our thinking is being enlarged, to embrace a more balanced spectrum of disciplines and to erase unhelpful and entrenched divides amongst the parts[4] (Beck, 2005): over time, as in thinking across the various stages in a project's life cycle; in space; in respect of surface and sub-surface waters, and likewise aquatic and terrestrial environments; in what is to be counted (literally) in the economics of providing water and sanitation services; amongst fragmented institutional units for managing each component of the infrastructure; amongst the perspectives of individuals, communities, and local, regional, and central governments; and between the lay member of society, on the one hand, and professionals and experts on the other.

Falkenmark (2005) has summed up the gathering social orientation of IWRM in her phrase "hydro-solidarity". She has since extended this to embrace "ecohydrosolidarity" (Falkenmark, 2009).

With the "I" of IWRM (and IUWM) comes the recipe for ever greater complexity in assessing the sustainability of an engineering intervention or a policy. Intuitively, we appreciate the spreading scope of sustainability: the shared exhortation, both to attain the whole perspective of Earth Systems Analysis, and to reflect on the most intimate of personal choices and ethics. In short, as in the deceptively trite aphorism, we are to:

> "Think (ever more) globally, while continuing to act (very) locally".

[4] And the number of those constituent parts can only but increase the broader the purview becomes.

From the Global Appropriation of Water for Agriculture ...

We know the enormity of the impact of agriculture on water resources and water quality in the watershed. With book titles such as *When The Rivers Run Dry*, we can be left in little doubt as to the dominant role of agriculture in the way in which regions and countries "burn up" their natural, geographical endowments of water in producing food (Pearce, 2006). An article in the *New Yorker* of the same year seeks similarly to grab the general public's attention with its title *The Last Drop* (Specter, 2006).

Cities and urban communities, in contrast, are the focus of the most intense social and economic activities within a watershed. Witness, for example, the recent accounts of a comprehensive study of the interplay over the centuries between the city of Paris and the Seine watershed (Billen *et al*, 2007a,b). People across the world continue to migrate from rural to urban areas, today in ever larger numbers. There, in the city, they may move along the poverty-affluence continuum, with accompanying changing choices over diet (Tilman *et al,* 2002). Thus will derive changing market signals sent out from consumers in cities in respect of the preferred foodstuffs to be produced in the rural hinterlands (SIWI-IWMI, 2004).

While no-one could doubt the magnitude of the impact of cities on their environments, there *is* nevertheless a tenable proposition: that when viewed globally within the context of water resources, savings on water consumption in cities may be of but marginal significance, relative to "doing something about agriculture". Yet very personal and local choices within the city, and very many of them, all regarding food, *not* water, can have significant consequences for agriculture.

Agriculture, as if we needed reminding, is primarily about putting nutrients in our mouths — *More Nutrition Per Drop* (SIWI-IWMI, 2004)[5] — albeit with massive, secondary implications for water. With food in our mouths, with the flux of nutrients into the city, what then is the fate of these nutrients thereafter, other than sequestration in the standing stock of city dwellers? What, even though this is a paper about sustainability in the water sector, is the impact of the city not merely on water resources (and allied energy resources), but also on the nutrient-resources sector, and its allied part of the energy sector?

Huge quantities of water and nutrients may be pushed through the rural systems of agriculture and livestock production. Increasingly, however, personal preferences and market signals as to what should be produced in those systems, if not how this "daily bread"[6] is produced, will emanate from urban communities, as the motor of that "pushing" (SIWI-IWMI, 2004). Modernity, industrialization, and technocracy, focused on urbanization and cities (often creatively so; van Noorden, 2010; Glaeser, 2011), are collectively the driving forces today. They are the unseen, but far from insignificant, forces driving what become manifest as "water crises" in the rural landscape. In that sense, the social and economic activities of cities are primary drivers of the movement of materials around the globe. The history of Paris within the Seine watershed, and the city's symbiotic relationship with its rural surroundings in respect of their common "nutrient metabolism", especially during the 1800s, is exceptionally well recounted in Barles (2007a,b), Billen *et al* (2007a,b), and their accompanying papers (in a special issue of *Science of the Total Environment*).

... To the Local and Personal Appropriation of Water for Urban Sanitation

Those same social and economic activities of cities, driving (in part) Man's appropriation of water across the agricultural landscape, are themselves enabled, if not powered, by Man's appropriation of water in systems of sanitation for maintaining public health in cities. McGreevey *et al* (2009) observe this:

> Until there could be a solution of child death from water-borne infections, the [industrial] revolution that began with science and invention decades even centuries earlier would remain incomplete.
>
> Ill health in cities before 1870 created a barrier and a bottleneck inhibiting the growth possibilities deriving from propinquity. The barrier, once broken, allowed urban agglomeration to flourish, producing conditions that accelerated information exchange, invention, innovation, and economic growth.

[5] As an advance on the preceding slogan of "more crop per drop".

[6] Or whatever is the culturally appropriate staple of one's diet.

The same relationship, between public health and the economic success of cities, has contributed to economist Glaeser (2011) nominating cities as mankind's greatest invention.

What happens in cities is profoundly affected by Man's *local* appropriation of water from its natural cycle (for sanitation) and profoundly important for his *global* appropriation of water (for the production of food and fiber) — and every bit as important for the local removal of nutrients from cities and their return into the global cycling of nutrients.

The concept of Integrated Urban Water Management (IUWM) seeks much the same benefits as does the concept of IWRM. These are benefits to flow from integrating considerations over all of the physical and engineered features of the urban water infrastructure: abstraction of water from the environment; its treatment; distribution through the potable supply network; the sewer network; the wastewater treatment plant; urban surface water; urban groundwater; and so on. When nested within the wider perspective of IWRM, however, such features may often pale into insignificance. Worse still, yet other features of vital importance can appear to have been overlooked altogether, even in the very best of contemporary studies (see Beck *et al*, 2009).

Consider what for many epitomizes the role of Engineering as a provider of solutions: the computational, or mathematical, model (***M***). Its assembly and deployment in the service of IUWM (within IWRM) are especially revealing, of what is to be counted (and what not) in the associated thinking and analysis. For all their other successes, the Paris-Seine studies convey this impression (Billen *et al*, 2007a). The vast and intense social and economic activities of 10,000,000 agents — people, that is, behaving as consumers, citizens, enfranchised stakeholders, adopters of technologies, holding a plurality of cultural perspectives on sustainability, having a growing interest in Man's relationship with the Environment, perhaps even contemplating Gibbons' (1999) suggestion of Science being in need of a new contract with Society — are compressed into but a single, inanimate vector of time-invariant boundary conditions of the watershed model (***M***). All this is compressed down to a point, as in a point-source discharge of treated wastewater.

People, of course, should be highly prominent in the account of the city. Without such, IUWM does not deserve to be credited with the quality of being "Integrated". It is thus the citizens, their diets, their tele-connections to the wider global system of food production, and their local connection to a system of sanitation, that should appear in the picture — and be counted. People as farmers, after all, are in sharp contrast frequently acknowledged and accounted for expressly as simulated agents in the simulated landscapes of watershed analyses (Janssen and Carpenter, 1999), in support of IWRM. The difference is as stark as the prominence given to the agency of the lone farmer in the landscape and the insignificance accorded to the *individual* agencies of 10,000,000 inanimate, urban, pollution generators.

If one conceives of what passes through the individual, the individual household, garden, back yard, street, office complex, industry, or any other water- and nutrient-processing entity in the city, and then thinks through the literally global ramifications of the engineering and management of the infrastructure required to secure the health and prosperity of those entities, within the city, within its watershed — then that is Integrated Urban Water Management (IUWM), embedded within IWRM.

2.2 Cities of the Global North: Infrastructure and Technological Lock-in

> "Wastewater treatment plants would work fine, if only people would eat just salads in winter and just goulash in the summer" (Watts, 1993)

Most discussions of IUWM equate the generic "Urban" with what happens specifically in cities of the Global North, with their paradigm of using water to convey the residuals of the metabolisms of the city and its citizens, from within the core of the city's confined spaces, back into its surrounding environment. Some mischievous reader of Barles' (2007a) historical analysis of Paris in respect of "feeding the city"— taking advantage of well-known cultural diversities — might ruefully argue that introduction from the late 1800s onwards of the British invention of the water closet (WC) caused Paris to become an unappealing "bull" in the "china shop" of the Seine watershed.

From the invention of the WC, historically pivotal in the genesis of the infrastructure required to secure public health in the city, hence debatably economic growth (McGreevey *et al*, 2009), can now be seen to have flowed — with the benefit of substantial hindsight — three less-than-positive consequences:

(i) The symbiosis of the urban-rural *nutrient* metabolisms, so prominent in the case of Paris, was severed, as meticulously revealed in Barles (2007b) and echoed likewise in Neset *et al* (2008);[7]

(ii) Nutrients, and subsequently other (polluting) substances, were diverted into the aquatic environment, where they would not "normally" have been headed; and

(iii) The inexorable migration was set in motion, towards the rigid technological lock-in of the current paradigm of comprehensively muddled water and nutrient metabolisms of the city.

Thus we have the lock-in of Figure 1(a), but not everywhere. Cities of the Global North are not *all* of the cities in the world.

The infrastructure of the city of the Global North has been arranged such that the city (in Figure 1) can receive its daily water and daily bread as a matter of stable routine, largely free of the risks and threats arising previously from the vagaries of the weather, principally precipitation. Drought is a continuing clear and present threat to our daily water, of course. To our daily bread, however, it is these days but a remote, if nevertheless economic, threat (for many of us in the Global North, that is). It has become one of those tele-connections we can take for granted, as the sources of foodstuffs are switched amongst the variety of globally distributed food-producing regions, any one of which (though not all at once) may be suffering from some form of precipitation-related damage or elimination. Flooding of the urban environment remains just as much a risk to public health as always, through either the presence of combined sewerage, or the literal overwhelming and debilitation of the normal services of low-lying water and wastewater treatment facilities by extreme events, such as hurricanes in the south-eastern USA (Burkholder *et al*, 2004). The threat of flooding — from precipitation (as opposed to sea-level rise) — may itself be heightened by the processes of urbanization themselves (Shepherd *et al*, 2010, 2011).

[7] Barles' analysis was of the N metabolism of Paris (1790-1970); that of Neset and colleagues was of the P metabolism of the city of Linköping in Sweden (1870-2000).

Unsurprisingly, city infrastructure in the Global North has altogether been arranged to our liking (our social lock-in): to concentrate on conducting our lives according to the daily routines and weekly rhythms we favor; and largely to ignore the mere inconveniences of fluctuations in the natural order of things — droughts over months and years, storms lasting hours and minutes.

The archetypal city of the Global North is intimately connected to the "big picture" of Earth Systems Analysis (Hall and O'Connell, 2007), of "thinking globally": of the global trading, *ergo* movement, of the "virtual water" embodied in producing foodstuffs (Allan, 2003; SIWI-IWMI, 2004), as much as of the global movement of the nutrients embodied in those foods (Grote *et al*, 2005). For every kg of beef eaten, 15 metric tonnes of water have been "burned up" in its production, 2 metric tonnes for each kg of cereal (wheat) consumed (Mekkonen and Hoekstra, 2010). Of all the nitrogen (N) applied to the land in fertilizers, roughly 35% of it will reach our mouths in those cereals (Ladha *et al*, 2005), but only 1.5% in any meat eaten (van den Hoek, 1998). Choices over diet have a significant impact on the big picture (Tilman *et al*, 2002; Kytzia *et al*, 2004; Duchin, 2005; Neset *et al*, 2008). Each of us is thereby connected as an individual into the grand scheme of things and, just as much, into the personal and intimate ways of "acting very locally". Would I, we, or you, dear reader, choose a diet in the interests of generating a "designer sewage" (Henze, 1997) — as Watts (1993), quoted above, so amusingly entreats us?[8]

Whereas the city of Figure 1(b) pulls in from afar the virtual water and actual nutrients of its upstream daily bread, so it has its tele-connections with the distant downstream environment. The rise and fall over the centuries of Paris's discharge of nutrients to the Seine River are mirrored in the (inferred) historic changes in what has been the limiting nutrient of algal growth in the distant coastal Seine Bight (nitrogen, phosphorus, or silicon) and in the occurrence or otherwise of harmful marine algal blooms (Billen *et al*, 2007b). More generally, nutrients are depleted in the soils

[8] Lord Stern, author of the "The Stern Review Report: the Economics of Climate Change" (2006), created something of stir in October, 2009, when he suggested — and very publicly so — that we should stop eating meat. It is unlikely he had a designer sewage in mind, however.

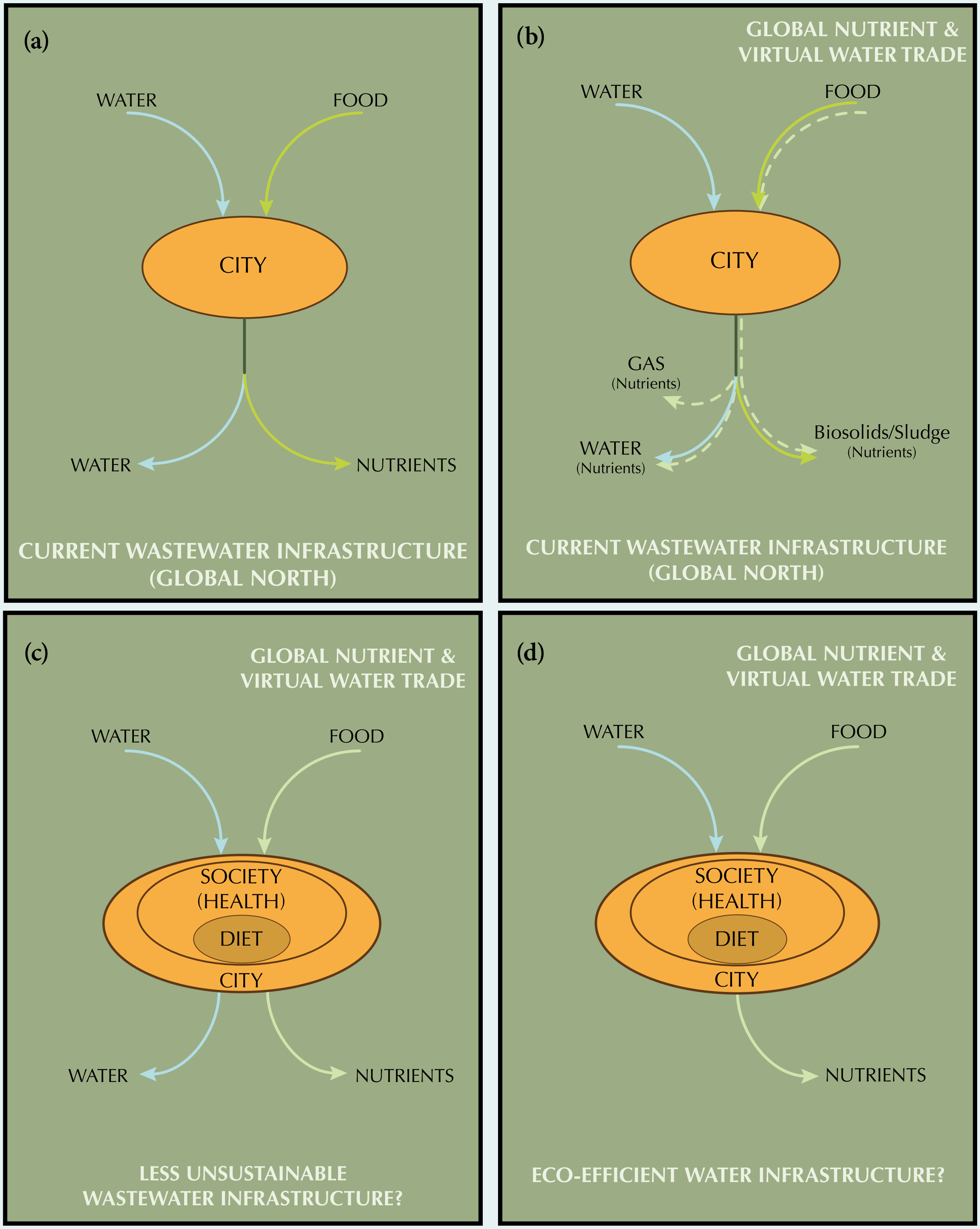

Figure 1

Schematic of the city, its daily water and daily bread, its metabolism, and its water and nutrient return infrastructures: (a) current water-based wastewater infrastructure of cities of the Global North (comprehensively coupled return infrastructures); (b) the current paradigm of (a) bent to some other purpose, e.g., the recovery of resources from the solids (sludge) stream, with yet resource losses to the water and atmospheric media; (c) future vision of uncoupled water and nutrient return infrastructures, with people, their health and their dietary choices in the picture; (d) the logical limit of a maximally eco-efficient city water metabolism, i.e., a dry sanitation system.

of food-exporting countries only to end up fueling eutrophication along the coasts of food-importing countries, through their excess in the residuals of the metabolisms of the cities located by those coasts (Grote *et al*, 2005). Erisman *et al* (2008), for instance, suggest that the transfer of reactive nitrogen from terrestrial to coastal systems has doubled since pre-industrial times.

Thus is the following well worth contemplating. In the desperate and urgent struggle to provide citizens with their daily water, desalination can today be fairly described as a "hot technology" (Frenkel and Lee, 2011). Perhaps this very innovation will be capable of accelerating the migration of people to coastal cities. However, given then that installing infrastructure for dealing with the metabolic residuals of the city's daily bread — through wastewater treatment, that is — always lags behind the provision of infrastructure for supplying the city's daily water, one could mount the argument that broad-scale innovation of desalination will lead to wholesale coastal eutrophication and consequent distortions of marine foodwebs and ecosystems beyond (Jackson *et al*, 2001).[9] And such a downside is conceivable, without even considering the carbon emissions of desalination and the larger number of citizens exposed, ultimately through this technological innovation, to threats of flooding from sea-level rise, possibly exacerbated by the changing intensities of extreme meteorological events.

Context, place, the onlooker's perspective, and how this changes with time, all matter with respect to what is a sustainable technology and its sustainable application in cities.

What might have been, we can but speculate, had an Air (Vacuum) Closet (VC) or Earth Closet (EC) achieved popular adoption ahead of the Water Closet. Would we today be instead concerned about the airborne propagation of disease (from the VC) and the wholesale pollution of urban groundwater systems (from the EC) — "come wind or come rain", respectively — had cities of the Global North spent a century and more locking onto an infrastructure of dry sanitation?

[9] McGreevey *et al* (2009) observe in passing that the lag referred to here is about 20 years. Other evidence generally supporting some of the threads of the overall conjecture regarding the innovation of desalination can be found in Grimm *et al* (2008).

2.3 Breaking the Paradigm: the Approach of the Millennium

Everywhere is the biological metaphor appropriated. That projects and products have life-cycles is a commonplace. We pointed to the stunted conception of the life-cycle of centralized sewerage and wastewater treatment for the city of Kanpur, under the Ganga Action Plan. For there, in the conceptual scheme of things, i.e.,

planning — design — construction [— operation — disassembly & recycle — {reincarnation}]

adequate forethought had not been given to any of those stages in the life-cycle beyond construction, hence the fixation of Beck (1981). An inter-generational long view, in effect, was absent. All life bracketed within [...] above should somehow take care of itself.

Having emerged in the late 1960s, life-cycle assessment (Frankl and Rubik, 2000) sees itself as addressing a form of cradle-to-grave analysis, which in turn can be extended to the concept of "cradle-to-cradle" analysis (Stahel, 1997; McDonough and Braungart, 2002; WWAP, 2006), wherein the metaphor of {reincarnation} might be brought to mind. Much vaunted too is the notion of biomimicry, with its proposed access to the vast store of intellectual seed-corn for the technological innovations of the Second Industrial Revolution (Benyus, 1997). Industrial Ecology has been formally in place as an academic subject for two decades (Ayres and Ayres, 2002). The *Journal of Industrial Ecology* was first published in 1996. In 2007, noting that "[c]ities have not been major units of analysis in industrial ecology", it produced a special issue on *Industrial Ecology and the Global Impacts of Cities* (Bai, 2007a). The city can be conceived of as having an ecological footprint, an appetite, a metabolism, a pulse, and so on (Wolman, 1965; Beck, 2005; Barles, 2007a,b).

In 1996, as the new millennium approached, Rees and Wackernagel invited us to imagine the city as a large animal grazing in its pasture, as a means of engaging us in conceiving of the rather successful innovation of the urban ecological footprint — massive, of course, for cities such as Paris, New York, and the like (Rees and Wackernagel, 1996). Viewed thus as an organism, the city takes in its daily bread and daily water (as Figure 1 shows), together with life-sustaining "breath". And we have engineered the return of the residuals of this metabolism to the air, water, and land environments surrounding the city. In the Global North, a good deal of the city's daily water is used to convey the residuals of its daily bread — as wastewater — away from the confines of the urban space, so that citizens can lead healthy and productive lives. Much technological effort has been invested in treating that wastewater, not always to the good of the air, missing an opportunity to benefit the land, while not being a wholly unmitigated good for the water environment.

Consider the global N cycle (Galloway *et al*, 2003; Boyer *et al*, 2006) and place conceptually within it the metabolism of the city, connected to its surrounding watershed. To deal, on the one hand, with the deleterious consequences for the aquatic environment of employing water-based conveyance in removing from the city the metabolic residuals of its daily bread, great effort and cost are invested in accelerated biological nitrification and denitrification of sewage during wastewater treatment. On the downside of the city, therefore, N is deliberately shunted into the atmosphere (as now in Figure 1(b)) — in order to avoid historic problems of water pollution — whence it must then, also with great effort and cost, be fixed through the Haber-Bosch process for incorporation back into the production of artificial fertilizer, for application to the land, on the upside of the city. Roughly two-thirds of the N "removed" in this manner from urban wastewater during treatment, across the whole of Finland, is vented as gaseous emissions to the atmosphere (Sokka *et al*, 2004).

To a degree, the paradigm of urban wastewater infrastructure into which cities of the Global North have become locked can be bent towards other purposes (as in Figure 1(b)), most obviously the recovery of water, nutrient, and energy resources (Guest *et al*, 2009). But this does not seem a sympathetic way of organizing the metabolism of the city and its compensatory wastewater infrastructure; of enabling the city to sit more comfortably within its surrounding environment and the web of global material cycles in which its metabolism participates (Beck, 2005).

What was novel about the approach of the new millennium was not so much the unprecedented pace of change in technology, the economy, and society, but the unprecedented willingness to ask, at a fundamental level, and without fear of overturning long held and much cherished habits of mind: has Man got his relationship with the Environment about right? And in the ensuing reflection it was claimed that the water-based paradigm of wastewater infrastructure in the archetypal city of the Global North was not only "broken" but sore in need of "fixing". In particular, a retreat was to be beaten from the modern technocracy of environmental engineering to a renaissance of manipulating the more natural systems (of ecology) of earlier times (Niemcynowicz, 1993).

This, in fact, was to be a retreat from the modern technocracy itself (Barraqué *et al*, 2006). Experts and professionals — engineers included (presumably) — have been put on probation (Massarutto, 2006):

> Increased corporatization (if not privatization) of water service operation implies a loss of control and a strong delegation of power to professionals and 'water experts', whose faithfulness to the general interest of the community has to be proven.

2.4 Challenge and Vision

> Once the public health of city-dwellers has been secured, the purpose of the urban wastewater infrastructure is to keep the soil fertile (Otterpohl *et al*, 1999).

About 50% of the world's population is now (2011) classified as urban. Much of the built environment can be equated with infrastructure for sustaining the city's metabolism. The intellectual argument may well be:

> that "footprints depict negative impacts of cities without accounting for the probable efficiency of dense urban living" (Kaye *et al*, 2006);
>
> that we should hope for cities to become "hot spots for solutions as well as problems" (Grimm *et al*, 2008; likewise, Sassen (2009), van Noorden (2010), Rosenzweig *et al* (2010), Glaeser, 2011); or even
>
> that at the risk of lionizing slums, they "Can Save the Planet" (Brand, 2010), since the squatter cities resulting from the mass rural-urban migration in developing countries "can teach us much about future urban living" (Brand, 2010).

The visceral reaction might be quite otherwise: cities and the built environment are most likely viewed (in the popular mind-set) as inherent environmental "bads", with no extenuating circumstances. And that view has in turn its intellectual argument: "parasitic" ecosystems is how systems ecologist Eugene Odum (1989) perceived them, living at the expense of other systems.

Things do not have to be this way, no matter how hard it may today be to conceive of cities as forces for good in the environment. Far from the burden of infrastructures having to compensate for the ills of cities, the two should "act" deliberately to contribute positively to enhancement of the environment about them.

Let us take the metaphor of Rees and Wackernagel (1996), therefore, with its obvious basis in ecology, and see just how far it can be pushed to serve the purposes of an engineering turn of mind. Imagine their animal as a bull, as already suggested in the case of Paris. The "bull" of intense social and economic activity in the city might be shod in the future with the "padded athletic trainers" of re-engineered infrastructures and imbued with a technological deftness and intelligence sufficient for restoring the business of running the environmental "china shop" in which it charges about. Pushing the metaphor yet further, the city might even profitably expand the shop's operations, by becoming a net contributor to some of the watershed's ecosystem services. Projections show that, by the compliance date (2015) of the EU Water Framework Directive, Paris might well look like the bull in the restored but vulnerable china-shop of the Seine watershed (Billen *et al*, 2007a,b; Even *et al*, 2007), yet not at all self-evidently shod with padded trainers, nor necessarily in possession of the technological deftness required for expanding the shop's operations.

Thinking in terms of the attributes of an organism and of the manner in which that organism lives and prospers harmoniously within its environment is, we now appreciate, a powerful metaphor for engineering and industrial design. It augments the image of the clockwork mechanism as the earlier epitome of the same, manifest itself indeed in the caricature of a mathematical program to be set out shortly below. Courtesy of the biological metaphor, therefore, we can compose the following set of challenges, all geared to realizing the vision of "Cities as Forces for Good" (CFG, for short) in the watershed and the wider environment (Crutzen *et al*, 2007; Beck *et al*, 2010a,b).

Broadly, we ask:

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

More specifically, rising stepwise up from the scale of the intensely local aspects of household plumbing to matters global, we ask herein:

What trajectories of technological innovations towards alternative, future metropolitan water infrastructures might:

(a) Secure public health and enhance well-being in the city [local and community scales];

(b) Uncouple the water and nutrient metabolisms of the city [city scale];

(c) Enable the city-infrastructure couple to be a net contributor to ecosystem services [watershed scale];

(d) Lower the global nutrient and virtual water metabolisms, i.e., uncouple human/economic development from industrial N fixation [global]; and

(e) Be robust and resilient — in particular, in an ecological sense (Holling, 1986) — under climate change (Beck *et al*, 2010a)?

The key is implied in the transitions from the arrangements *and* perceptions of Figures 1(a) and (b) to those of Figure 1(c), where the "nutrients" are somehow to be separated from the "water" on the downside of the city. The goal would eventually be to prize apart the water and food-nutrient cycles in which the city and its dwellers participate. The future strategic aspiration — one among several possibilities — might be to achieve thereby an urban wastewater infrastructure that generates a perfect fertilizer product and, incidentally, a very clean by-product, i.e., water (Beck and Chen, 1999; Jiang and Beck, 2007; Beck *et al*, 2011a).

The essential thrust of all of this, of course, is towards accounting predominantly for the bottom line of our achieving {environmental benignity}, through becoming less unsustainable. We make no apology for this. In the approach to the new millennium dawned the realization of our collectively bumping up against the boundaries of the biosphere. Whatever form of less unsustainable styles of IUWM nested within IWRM are chosen, their genesis should be inspired, first and foremost, by their perceived contributions to sustaining the biosphere, neither the economy, nor society.

Significantly, throughout those most healthy and liberating debates of the 1990s — over the worthiness of the goals and styles of environmental engineering — no radically different alternative emerged for the kind of infrastructure that would supply the city with its daily water. On the upside of the city in any of the panels of Figure 1, nothing structurally is changing. Infrastructure for getting water to our mouths may indeed be as "old as the hills", as some have bluntly put it. It continues to co-evolve incrementally, of course, in tandem with suppressing the propagation of an ever-evolving array of contaminants. The water-based paradigm of nineteenth-century sanitation cut the short feedback loop of pathogens returning to the mouth; on the downside of the city, it conveyed them well away from our personal living spaces. As our individual status moves back and forth along the continuum of health and well-being, we shed not only pathogens, but metabolites of the medications (pharmaceuticals) we take to recover from and avoid ill-health, as well as residuals from the personal-care products that enhance our sense of well-being. These too will be unwelcome constituents in the daily water of those downstream of us (and the nature in between), no matter the distance of their city from ours — and irrespective of the fact of our sharing the planet ever more intimately with more than 6 billion others. But still our daily water reaches the city as it always has done (Figure 1).

Wherever there was radicalism in those sustainability debates of some twenty years ago, it was focused on casting off the straitjacket of the wastewater infrastructure on the downside of the city of Figures 1(a) or 1(b). Thus was revealed the notion of what we shall now call the city's *nutrient infrastructure* — its means to deal primarily with the residuals from the metabolism of the city's daily bread.

2.5 Engineering for Sustainable Development: Triple Bottom Line — Just Another Mathematical Program?

We — members of the predominant school of thought in environmental engineering of the second half of the twentieth century — have had a couple of decades to become accustomed to realizing we are not self-evidently doing good by the biosphere, precisely because of the apparent radicalism of Niemcynowicz (1993) and others.

A paper such as this, focusing essentially on concepts (of sustainability) and setting out the elements of constructing a vision of a more distant future for IUWM within IWRM, should provoke the possibility of our putting aside some of the old, much cherished, habits of thinking. And we can all recognize these traits in ourselves. Those of us interested in the "hi-tech" of control and dynamic systems theory, which gave us the fixation on the operational stage of an infrastructure life-cycle (as in Beck (1981), for example), may be persuaded to mount an argument against decentralized, local, self-organized, ecological, non-technocratic forms of IUWM, because they do not appear to call for much of our favored theory. This is not necessarily unhealthy, for we shall in due course advocate a plurality of schools and styles of engineering thought (below in Box 1 of Chapter 3). It might indeed be quite creative (as in due course we shall see in Box 3); but it is as well to admit its occurrence.

Others amongst us, acknowledging the systematic and quantitative style of analysis that is defining of the Engineering tradition, might welcome with keen anticipation the evolution in thinking over these past fifteen years, towards the Triple Bottom Line (Elkington, 1998). The unabashed allusion of the Triple Bottom Line to a quantitative accounting procedure of business — albeit cast within the context of its moral imperative — might present too attractive an opportunity not to draw ever more of the human dimension into our tradition of engineering analysis. After all, subjecting our paraphrasing of the original exhortation of sustainability to the strictures of the three components of the Triple Bottom Line, yields something of a caricature of the classical optimization problem of mathematical programming (which underpins, formally or informally, so much of "objective" engineering design and decision-making). Thus we have:

{Doing well now by the biosphere and the stock of natural capital and flow of services therefrom entails doing at least as well generations hence}

Subject to attainment of this objective of "doing well" being witnessed by all the stakeholders to satisfy the properties of

{environmental benignity}
{economic feasibility}
&
{social legitimacy}

There will indeed be those kinds of community water problems that are amenable to being addressed and resolved using quantitative methods from the traditional engineering toolkit, in which case the fine line separating this form of technical analysis from public debate and democracy might well be able to penetrate deep into the property of {social legitimacy}.

In others, it will be decidedly inappropriate, with that line barely able to penetrate the property of {environmental benignity}. There may even be no common ground for formal agreement amongst the various groupings of stakeholders on the science underpinning projections of what constitutes "doing well" by the biosphere, let alone on the form of democracy, debate, and governance through which the "doing well" can be witnessed by most, if not "all", as about to be done.

As engineers, we have been drawn on by the appeal of being "objective". Yet as the following reveals with some obvious discomfort, we know that attainment of complete objectivity in assessing sustainability is beyond our grasp. This is taken from the work of another awardee of the inaugural (2008) IWA Prize for Sustainability in the Water Sector (Sharma *et al*, 2009):

> Which is the 'best' water servicing scenario? This is a complex, multi-dimensional question. No matter how much modelling is undertaken, some degree of subjective value judgement is required by the decision maker(s). Morse *et al* (2001) also indicated that an element of qualitative integration incorporating value judgement and subjectivity is inevitable with a concept like sustainability. The sustainability assessment framework presented in this paper reduces the subjectivity and increases the objectivity in the decision making process, but none the less, a subjective value judgement is still required.

As goes Science (Nowotny *et al*, 2001), so may need to go Engineering for the purposes of achieving IUWM within IWRM: towards a style we might call "socially robust engineering", similar in spirit, but not content, to the original engineering of water infrastructures a century and more ago.

With this shifting line in mind — with its accompanying implication of tailoring appropriate, but different, styles of water engineering to different problems — we now embark on setting out the elements of the framework of the Triple Bottom Line, placing that of {social legitimacy} firmly in the first rank, as "first amongst equals" (*primus inter pares*). We may have come upon the Triple Bottom Line through confronting the problems of sustaining the biosphere. Any approaches to overcoming the problem, however, will surely have to be socially and politically legitimate, as a priority. Chapter 3.1 must therefore address the labyrinthine complexity of the interaction between Society and our notion of IUWM within IWRM.

The second of the bottom lines, that of {economic feasibility}, is treated in Chapter 3.2, there to reveal, if anything, the size of the intellectual gap between some high-minded principles of economics and ecosystems theory and the practical needs of engineering urban water infrastructure.

The struggle to achieve {environmental benignity} in that engineering will be examined in Chapters 3.3 and 3.4, starting from the global perspective of Earth Systems Analysis and in response to the challenge and vision just set out above in Chapter 2.4.

All these elements of the framework for a less unsustainable IUWM within IWRM, emerging from Chapter 3 (and then Chapter 4), will eventually be gathered together and tabulated in cryptic form (in Chapters 5 and 6).