Applying Systems Thinking: An Outreach Paper

Understanding the Science of Ecosystem Services: Engineering Infrastructure for Urban Water Services

Applying Systems Thinking: An Outreach Paper

Prepared for the International Water Association (IWA)

UNDERSTANDING THE SCIENCE OF ECOSYSTEM SERVICES: ENGINEERING INFRASTRUCTURE FOR URBAN WATER SERVICES

An Introduction to the Science and Technology of Contemporary Practice

M B Beck

Department of Civil and Environmental Engineering
Imperial College London
London SW7 2BU
UK

ABOUT THIS PAPER

Last year's seventh World Water Forum in Korea (April 2015) included a theme on Science and Technology – for the first time (since the inaugural Forum held in 1995). The Forum is the largest international event in the field of water. The new Science and Technology theme sought to share expertise and experience, and to showcase new technologies.

That science and technology are perceived thus by the World Water Council (the host of the Forum) as having such "newness" speaks to the need for a better articulation of their relevance on the global water scene. For two decades and more, as water has progressively been propelled up national and international political agendas, so often was this sentiment expressed: "If the world's water problems were a matter of science and technology, they would have been fixed long ago". Indeed, often was this quite rightly expressed, to highlight the crucial role of governance: *good* governance, that is. Social and political processes have been the focus of World Water Forums hitherto. Each has produced a Ministerial Declaration. Now, for the first time, science and technology for water are to be communicated and understood in terms appropriate for inclusion in such Declarations.

This Paper has accordingly been prepared for a general readership both of technical experts and of members of the general public – lay persons, in fact, with an interest in what is happening to their water and their water environment. Accordingly, the Paper takes a longer-than-usual view over the history of water pollution control: to provide the general reader with a context in which to appreciate the impacts on the environment of things we have customarily regarded as pollutants, yet which are not necessarily so.

Thinking about ecological systems, namely ecosystems, entails grasping the "big picture", or being "holistic" in one's thinking. Or, better put, it just requires some *Systems Thinking*, to which, quite without any doubt, the subject of ecology (among many others) has contributed massively. For systems thinking is quintessentially inter-, multi-, and trans-disciplinary in nature. It is, for example, the process of thinking about the city as if it were like the human body; or the process, in another instance, of thinking about technological innovation as something to be orchestrated in a way that mimics the behaviour of an ecosystem. The systems approach, cast at a level consistent with everyday experience, is defining for this Paper.

But so too is what is happening in practice. The Paper's narrative is motivated by six case studies. Sufficient science is recounted for understanding, first, what ecosystem services amount to and, second, how that science is being put to work in shaping the technologies of city infrastructure for managing those services. The subjects of the case studies range from restoring declining salmon populations along the Pacific northwest coast of North America (by "dumping" what we have come to know as "pollutants" into "natural" streams), to costing out the economics of an urban climate adaptation park in metropolitan London, where the so-called cultural services offered by the park are by far the most highly valued of its ecosystem services.

PREPARATION OF THIS PAPER

While drafting this Paper has been my (MBB) sole responsibility, I have been ably assisted by a formally appointed team of reviewers: Cheryl Davis, Peter Goethals, Kuei-Hsien Liao, Betsy Otto, Francis Pamminger, Jamie Pittock, and David Smith. Their assistance in providing feedback and literature for review and incorporation into the Paper is gratefully acknowledged. The Paper has undergone three rounds of review, one by two anonymous external reviewers, who are likewise thanked for their comments. Katharine Cross has provided a further, fourth review. Her incisive comments are greatly appreciated. Last, but surely not least, Hong Li, Manager of Science, Technology and Specialist Groups at IWA, has worked from start to finish with me over some 20 months to have this Paper produced. I am indebted to Hong for her ever-attentive assistance.

THE NARRATIVE – WHAT THIS PAPER SAYS – IN SHORT

What exactly are ecosystem services? For they are not easily understood, and indeed often not readily appreciated until they have been "lost". There is little surprise, then, that puzzlement may surround the manner in which any such understanding might be channelled into the design of clean technology and green infrastructure for restoring them. And to conceive of ecosystem services being accorded their very own free-standing economic sector – like the banking and financial services sector, for example – may be greeted with disbelief, if not dismay.

THE CITY'S CONCISE ENVIRONMENTAL HISTORY

To begin, the "long view" of some history is needed. The city's environmental history is first separated into three stages and then retold, slightly differently, as comprising several eras in over a century of policies for water pollution control. What constitutes "environment" needs to be refined as well, so that we may think in terms of the natural environment, the human environment of the city, and the built environment, in particular the city's infrastructure, which – in the context of the city (as opposed to the village) – mediates the relationship between "Man and Nature".[1] These three systems (natural, built, and human environments) interact with each other. There is, in fact, a symbiosis between the city and its surrounding (natural) environment: both generate their own services; even the city is capable of generating ecosystem services to the benefit of the environment. Nature provides for the well-being of Man through ecosystem services: those that *provision*, in producing food, fibre, and fresh water; others that *regulate*, as in stabilising the climate and assimilating water pollutants; those that *offer cultural services* in serving mind, body, and spirit; and those deeper workings of ecosystems that *support* and undergird all three categories of the other services. Man, in return, may provide for the well-being of Nature – but does not always do so!

All is not quite what we might take it for. Indeed, it is part of the purpose of this Paper to illuminate such re-orientations of perspective.

A SYSTEMS PERSPECTIVE AND THE SCIENCE OF BIOGEOCHEMISTRY

Both Man and Nature participate in the processing functions and structuring of global material cycles, for carbon (with which we are now familiar, under the prospect of climate change), but also for nitrogen and phosphorus.[2] What goes around, comes around. These material cycles – though beneath the surface of our everyday experience and buried (away from our immediate gaze) in all the stuff that passes through our households and ourselves – are what bind Man and Nature together. Pre-consumption resources flow into the household and post-consumption resources flow out, at some point – through ecosystem services – to be renewed and returned to Man as pre-consumption resources (once again). The science of the biogeochemistry of these global material cycles is pivotal, both in acquiring an understanding of ecosystem services and in applying the knowledge so gained in developing and deploying clean technologies for the water infrastructure of cities.

It is odd, perhaps, that this Paper should start its approach to the subject of ecosystem services for *water*, by arguing (in effect) that it is not so much the water that matters, but what is in it. Yet it is an understanding of ecosystem services from the systems perspective that is at a premium in this Paper. And this will be a systems perspective at both the global scale and the intensely local–personal scale (of each and every one of us). To introduce this systems perspective, the science of biogeochemistry works best.

---

[1] "Man" connotes here humankind.
[2] As "peak food" has followed "peak oil", so too is there "peak phosphorus": see Cordell (2013) – as well as Erisman and Larsen (2013) for the corresponding case for nitrogen – in the list of References in the main body of the Paper.

URBAN FORM AND THE SCIENCE OF LANDSCAPE HYDROLOGY

Water, of course, has its own cycle in Nature. In particular, there is that arc of the cycle that connects the droplet of rain hitting the ground – notably the urban surface – and its eventual emergence as flow in a river, estuary, or other body of water. To understand the impact of the city on aquatic ecosystem services, we need the science of landscape hydrology and, again, that of the biogeochemistry of what happens in each notional parcel of water as it strikes the ground, thus to proceed on its way round to the surface flows of water in rivers and streams. The mere physical form of the conventional "grey" built environment of the city, not just the biogeochemistry of the local–regional hot-spots of urban pollution and detritus, has a profound impact on aquatic ecosystem services. Our instinct, and the science underpinning our understanding of ecosystem services, hence our technology, is being bent toward a serious "greening" of the city's (once) grey infrastructure.

ECOLOGICAL RESILIENCE IN THE NATURAL-BUILT-HUMAN ENVIRONMENTS

Man appropriates ecosystem services and, in the city, with the highest of intensity. We do so in time through the much vaunted and overwhelmingly predominant pattern of the "24–7" cycle. Nature, however, has not worked that way over geological time in evolving and assembling the flora and fauna in the bodies of water that provide what we today call ecosystem services – at least, certainly not in sympathy with Man's chosen cycle of weekly changes. The notion of frequency spectrum matters in more ways than in just the bandwidth allocated to modern wireless communications or the overwhelmingly predominant 24–7 bandwidth of modern life (with but its two frequencies extracted from the multitude). Storms happen in minutes, droughts over months, and climate change over decades, centuries, and millennia. The host of frequencies of change attaching to such disturbances – a kind of environmental chorus (or symphony) – matter for ecosystem services. And given now the words "ecology" and "ecosystem", we appropriate them to convey a sense of how Man's world should work: as in the contemporary examples of "industrial ecology", "business ecosystem", and "innovation ecosystem".

It seems, however, that we just cannot escape from one word in contemporary discourse: "resilience" – resilience in the behaviour of every thing and every system. So the Paper builds the science of resilience – of *ecological* resilience in the provision of ecosystem services and of mutually reinforcing ecological resilience in the behaviour of each of the natural, human, *and* built environments – into thinking about exactly how our clean technologies and green infrastructure should work: day-in day-out, 24–7, year-in year-out, … *and* transform themselves along the way (evolve, that is).

COSTING THE EARTH

The value of resources and services flows in a circle; and we are drawn to attaching a dollar sign to that which is valued. We can readily conceive of how value flows from Nature to Man, for example, through the harvesting of (pre-consumption) oysters from Chesapeake Bay in the USA, which are then sold to buyers. Nature generated the "good" that was sold to Man. Likewise, we can grasp how value flows from "once-removed" Man-to-Man transactions – once removed from the original sale of the oysters, that is – as in wages for restaurant employees from takings from the consumption of the oysters. In this, the restaurant owner and staff (Man) generated the good for the restaurant diners (also Man). Equally so, we can comprehend how value flows from "twice-removed" (or even-more-removed) Man-to-Man transactions, as in dividends from profits for shareholders and capital growth for investors in successful restaurants. Viewed around the reverse half of the value-flow circle, however, putting a price on some return Man-to-Nature flows can be a challenge: as in disposing of the "waste" of the (post-consumption) oyster residuals in the sewage returned back to a natural water body. Nature had no say in the Man-to-Man transaction that generated the "waste".

Beyond this, putting a price on value flows from Nature to Nature – the "existence value" of the oysters prospering in the Bay for their own sake and for the sake of their own offspring (but *not* for the sake of Man) – is often deemed impossible. This transaction (strictly among the oysters) is far removed from the familiar Man-to-Man transactions of customary economics. Its quantitative pricing would require us to reason as follows: the tangible value in some Man-to-Man transaction would have to follow with hard economic logic from the tangible value attaching to a Nature-to-Man transaction, which transaction essentially derives its tangible value (with the same iron logic) from valuations of any Nature-to-Nature transactions embedded therein. The tortuous (and torturous) complexity about the logic of such a sentence is enough to put one off trying to cost ecosystem services in the first place!

Yet we do so try in this Paper. We should, in particular, be eager to know whether a dollar sign can be attached to the value flows of ecosystem services, so that, for example, when everything is added up we might choose course of action "A" (where Nature-to-Nature value flows dominate) over course of action "B" (where Man-to-Man value flows dominate). With few precious exceptions, there is little hard evidence to satisfy any curiosity in whether such an "A" would ever be chosen over such a "B".

HAPPENING NOW – PRACTICE SHAPES SCIENCE, TECHNOLOGY, AND ECONOMICS

Insights from six case studies drive the narrative of this Paper. They are as follows:

(1) *Mayesbrook Park, Barking, London.* At £820,000 each year (US$1.3 million), cultural ecosystem services – above and beyond those of regulating, supporting, and provisioning – are the most highly valued in this park. It has been greened primarily for the regulating service of attenuating flooding, however, both from high tides and from intense rain.

(2) *City of Kent, Washington, USA.* The well-being of salmon populations in the Lower Green River, which passes through Kent, once depended on wide, shallow, "low-velocity refugia" – occasionally flooded plains, that is – now greyed, urbanised, and not available. Fish naturally need places of refuge during floods. Indeed, "bring on the floods!" might go up the cry in this case study. Small floods, jolting society occasionally out of its 24–7 routine, can be argued to be for the better (up to a point). They provide opportunities for community learning, in particular, about how to cope with the "big one", when it comes (as it will). Welcome, then, to ecological resilience and social learning in the flood-resilient – not flood-resistant – city.

(3) *Low-Impact Development.* In many countries (Korea, Germany, USA, UK, for example), building tomorrow's less grey urban form and function, from the outset, re-introduces extra bandwidth into the artificially narrowed spectrum of landscape hydrological variations, hence to reconstruct aquatic ecosystem services. "Calming measures", we might label them: to counter the frenetic (high-frequency) behaviour of today's impervious surfaces and sewerage in the city.

(4) *The Savannah Process – The Nature Conservancy and US Army Corps of Engineers.* Developed originally for the Savannah River in South Carolina and Georgia (www.conservationgateway.org), the Process amounts to operating differently – *for* the benefit of the ecosystem – "yesterday's" sunk investment in grey infrastructure: the dams, gates, sluices, and weirs imposed across rivers to create reservoirs for serving multiple facets of Man's well-being. Less prosaically, the Process is about reclaiming the evolutionary richness of the full environmental chorus of ecosystem services from their subjugation to the impoverishment of the narrow bandwidth of Man's 24–7 lifestyle.

(5) *Restoring Salmon Populations, Vancouver Island, Canada.* As the manager of the Durham (Oregon, USA) Sewage Treatment Works put it: "For 35 years, I've been removing phosphorus and ammonia from wastewater. It's hard to believe that now I'm putting them back into a river".[3] Such has been the transformation in how we view what is a pollutant and what is a support for ecosystem services: nutrient supplements for Nature, now available at your local wastewater treatment plant.

(6) *Soerendonk Sewage Works, The Netherlands.* In many ways, this case study brings together everything about ecosystem services. First, it illustrates reconstruction of the *frequency* spectrum of the environmental chorus. Second, its interventions provide the ecosystem service of fish refugia during flooding, through reconstruction of aquatic habitat and urban *landscape*. Third, and above all, it prompts the insight of this extrapolation: of the taking of our accumulating understanding of the science of the (downstream, green) natural environment and, then, the engineering of the *biogeochemistry* of this understanding back up, along the arc of post-consumption urban resource flows, into re-forming

[3]Rob Baur, senior operations analyst of Clean Water Services (CWS) at its Durham, Oregon facility, as quoted in Force (2011) – see list of References in main body of the Paper.

the (grey, upstream) core of the city's built environment – all in order to manage ecosystem services. It confuses what is city (the doings of Man) with what is environment (the doings of Nature). It confounds how we draw the sharp line between purity and impurity.[4]

WHAT NEXT?

The World Water Council and its World Water Forum might not exist, were it not for the report of the Brundtland Commission in 1987 and our enduring collective need to spark a "Sustainability Transition".[5] To strike this spark, once was the time when the prevailing sentiment was this: that what was really needed was better governance, for we already had sufficient science and technology. True, there will always be a need of better governance. It is an unending quest, as are the enterprises of science and technology – hence their inclusion (for the first time) in the 2015 World Water Forum. What we may still lack is a form of hard-nosed, pragmatic economics for the ecosystem services sector. Not for the first time has this conclusion been reached in a state-of-the-art report from the International Water Association (IWA); and what is needed is the subject of an ongoing assessment in the Association's Sustainability Specialist Group.[6]

In 2014, IWA hosted a Forum on Cleantech for Water at the World Water Congress in Lisbon. What, we should ask, was the outcome? In the face of technological "optimism" – no bad thing for cleantech and greentech innovations for managing and generating ecosystem services – the compound mix of "People–Risk Aversion–Culture", in the *water* sector, was identified as the massive barrier to innovation. So how, then, might the Sustainability Transition be sparked and ignited? An unpacking of the constituents bonding the barrier together, thus to expose the plural rationales in the nature, risk, economics, and governance of innovation, merits some sustained attention.

[4]See Thompson and Beck (2015) in the list of References in the main body of the Paper
[5]See WCED (1987) and Geels (2005, 2006) in the list of References in the main body of the Paper.
[6]See the contribution from the IWA Sustainability Specialist Group to the (2012) IWA book *Global Trends in Water Science* (cited as Beck *et al*. (2012) in the list of References in the main body of the Paper).

Applying Systems Thinking: An Outreach Paper

Prepared for the International Water Association (IWA)

UNDERSTANDING THE SCIENCE OF ECOSYSTEM SERVICES: ENGINEERING INFRASTRUCTURE FOR URBAN WATER SERVICES

An Introduction to the Science and Technology of Contemporary Practice

M B Beck

1 ECOSYSTEM SERVICES: COMING OF AGE

It has been all too easy *not* to have grasped the significance of what we call ecosystem services. To understand how the term is used today, and hence its significance, we need a brief encapsulation of the past.

Imagine the pristine landscape. As the city arrives on the ground – in an instant of geological time, as it were – the built environment of the city replaces and covers over a part of the pre-existing natural environment. The essentially *physical* nature of this first wave of change is obvious: rocks and soils are excavated and then covered over, grasses and plants are uprooted, and trees felled; undulations in the topography of the land surface are lessened or eliminated, hollows and dips filled in, hillocks flattened.

As engineered means are introduced to bring pre-consumption water from the natural environment to the city's population and industry and – after some delay (of decades perhaps) – the engineered means are likewise introduced to take post-consumption sewage and wastewater away from the city-industry and return them to the natural environment, so society perceives water pollution. In due course, the essentially latent *biochemical* nature of this second wave of change becomes obvious, eventually apprehended by our (physical) senses of sight (turbid water covered with debris and detritus) and smell (water bearing fetid and putrefying contents). Such changes in the River Thames were dramatically apparent to people's senses in 19th Century London.

Gross pollution is a manifestation of the ecosystem services provided by a body of water having been overwhelmed.

Installation of the infrastructure of sewerage and wastewater treatment in cities is what cuts water pollution back, ultimately enabling rivers, lakes, and estuaries to regain a certain purity in the "natural" environment not witnessed in living memory by citizens (Thompson and Beck, 2015). The "naturalness" of the restored environment is signalled by the return of the fish and other aquatic flora and fauna once there before the advent of the city. Things are contingent and path-dependent, of course. The "natural" environment surrounding the city will not have been put back onto the evolutionary path unfolding before the coming of the city, hence our need to wrap (here) the word "natural" in quotation marks. To a large extent, this lifting away of the obscuring blanket of historical pollution – together with the ever-expanding knowledge bases and observing capacities of science – enables us to apprehend the "emergence" of ecosystem services, in particular those delivered by the less visible biochemical functions of an aquatic ecosystem.

At the same time, progressive and successful installation of wastewater treatment – again, together with the ever-expanding knowledge bases and observing capacities of science – allows us to apprehend the significance of pollution arising from contaminants deposited on the physically changed landscape of the city, namely on the surfaces of its built environment. These contaminants may be mobilised by the flows of water stimulated by precipitation over the city and delivered through the process of drainage to the nearest body of water in the natural environment – there to compromise the effective behaviour of aquatic ecosystems. The physically altered hydrology in the urban setting has a less obvious, scientifically more subtle impact on the behaviour of those ecosystems, but a deleterious impact nonetheless.

Ecology came of age in the 20th Century, especially its later decades, when gross pollution of water had been curbed around many cities (primarily of the Global North). Appreciation of the word "ecosystem" was simply not there in all the preceding decades (especially those of the 19th Century and first half of the 20th Century)[7] to have been coupled with the word "services", and hence to coin the phrase "ecosystem services". They used to be known, in fact, as the "river's self-purification capacity".

It was not until roughly the 1980s that the word "services" was attached to the word "ecosystem" (Ehrlich and Ehrlich, 1981; as cited by Liu *et al*., 2010 (p. 61)). For some, the expression "ecosystem services" chimes with the decades-long process of gaining acceptance of the sentiment: "It's OK to make money while saving the environment" (Hawken, 1993; Hawken *et al*., 1999). For others, it is a surrender to the commodification (and the "business speak") of yet another non-monetary, more spiritual aspect of life. Either way, the recent historical trend has been towards fashioning ecosystem services as an independent sector of the economy, eventually to stand shoulder to shoulder with the sectors of water, energy, food, even banking and finance (themselves the archetypal service sectors).

One might say that ecosystem services truly came of age in 1997, when they were famously celebrated in the front-cover headline of *Nature*, the premier journal of science. Robert Costanza and colleagues had published an article on "The Value of the World's Ecosystem Services and Natural Capital", this value being anywhere between US$16 trillion and US$54 trillion per annum, with a mean value of US$33 trillion, at a time when global gross domestic product was US$18 trillion each year (Costanza *et al*., 1997).

---

[7]The word was there, however (since the 1860s, in fact), just not the widespread appreciation of it. Ernst Haeckel is credited with inventing it in 1866 (Wikipedia, under "Ecology"; last accessed 22 November, 2014).

In short, and to simplify – perhaps over-simplify – the undermining and degrading of aquatic ecosystem services by the essentially *physical* changes associated with changing the landscape through urbanisation were (we may presume) the first to occur historically. But their significance and their scientific characterisation were not revealed until much of the subsequent *biochemical* changes wrought by installing sewerage – but *not* sewage treatment – had been rectified, by the eventual installation indeed of that sewage treatment. And the technology of sewage treatment, we may observe, began empirically by mimicking the river's self-purification capacity and encapsulating it in an intensively managed and engineered system. Around the turn of the 1960s/1970s, for example, one of the very first applications of the (then) novel computational methods of *ecosystem* simulation was to the task of improving understanding and management of the sewage treatment technology of the biological trickling filter, with its remarkably complex suite of many interacting species of (microbial) flora and fauna (James, 1978).

Not until the burden of all this pollution from the city and industry was lifted off the river's self-purification capacity – a monumental righting of the wrongs of past misdemeanours – could we reveal other issues of environmental preservation and other potentially polluting "actors" on the watershed stage, in particular, agriculture. Only then could we begin to contemplate future climate change and the long-term aspiration of less unsustainability in the conduct of humanity's affairs.

Put another way, and to prime this discussion for further advances in our understanding of the science and technology of ecosystem services for water, we may conceive as follows the (very) concise history of the human-built environments of the city and their interaction with the natural environment surrounding the city:

Stage 1: The first, physical re-shaping of the landscape by construction of the city alters the way water moves across that landscape, which in turn alters the functioning of natural aquatic ecosystems.

Stage 2: The second biochemical re-shaping wrought by the arrival of the city is the creation of local hot-spots of excessive amounts of the metabolic detritus – discarded from the city's social, economic, and industrial life – in the wrong place, in proximate so-called receiving water bodies.

Stage 3: Full disclosure of the consequences of Stage 1, hence initiation of actions to rectify them, revealed historically *after* the implementation of technology to rectify the ills of Stage 2.

So now we should know better.[8]

[8]And put yet another way, if one focuses on just the flows of water through the city, our concise environmental history may be recounted as a sequence of "urban water management transitions", in five steps: from some original, rather crude "supply hydraulics" service, to the contemporary "adaptive, multi-functional infrastructure and urban design reinforcing water-sensitive behaviours" (Wong and Brown, 2008).

2 NATURE, THE CITY, AND ECOSYSTEM SERVICES

From Man's perspective, the city draws in flows of pre-consumption resources and metabolises and transforms them – as a function variously of the lives of citizens, the city's human capital, financial capital, manufactured capital, and infrastructure – into post-consumption resource flows (Figure 1). Nature receives the city's post-consumption flows of resources and *through its ecosystem services* – deriving from its stock of natural capital (and the lives of the flora and fauna constituting that capital) – transforms, processes, and returns them as pre-consumption resource flows back to the city. Just how quickly it takes Nature to prepare such returns can vary dramatically: witness the return of waste dietary carbon – in sewage – as a biofuel extracted from algae (cycling around over days, weeks, months) *versus* the incorporation of carbon into fossil fuels over aeons. In ways we can all readily appreciate, however, and absent or not a grasp of the relevant science and technology, should these ecosystem services become compromised (even extinguished), the city is somehow going to have to "compensate" for their degradation, to maintain what its citizens determine as their "well-being".

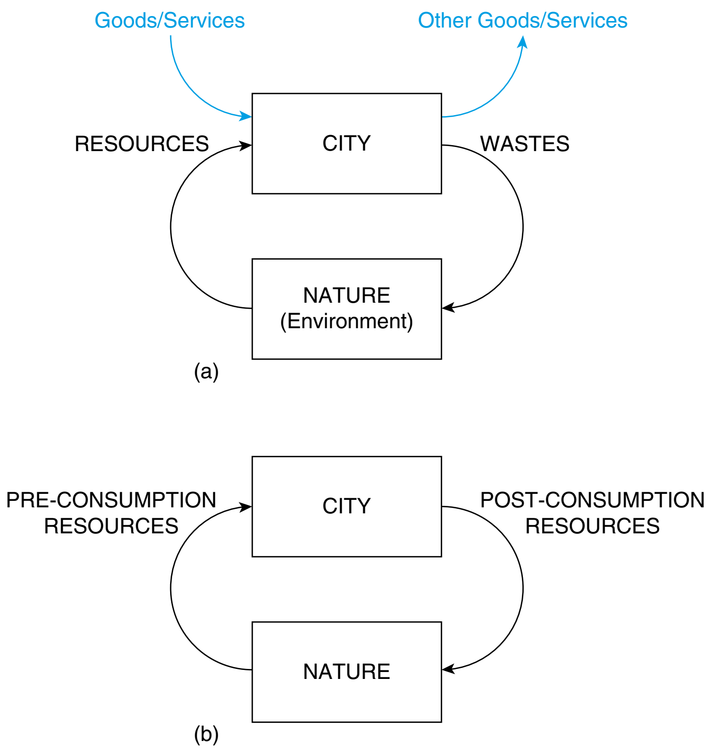

Figure 1 City–Environment Services – Symbiosis

The lower of these two "framings" is how we would prefer the reader to conceive of the relationship – the symbiosis, in fact – between the city and its environment. In particular, the flow designated "Wastes" in the upper panel can be seen alternatively as "Post-consumption Resource Flows". The blue flows of economic goods and services (in the upper panel) are implicit in this lower panel. They have been omitted simply to emphasise the circularity of resource flows, which in turn emphasises the symbiosis between the city and the environment.

Coupled in this way, one is tempted (but hesitates) to conceive of the city–environment as a duo, even as some kind of symbiosis, of Man and Nature "living off one another" (heaven forbid!). In a curious way, there *is* such a symbiosis: managing ecosystem services for water is a matter of putting the growing understanding of the science of ecosystem services in the natural environment to work in the technologies and infrastructure of the built-human environments of the city – "designed ecosystem services" (Graham and Smith, 2004). That this is happening should be no surprise. We shall come to see how the conceptual and concrete barriers we erect between what is the city (with its biological residuals of human existence) and what the environment (with its biology underpinning its ecosystems) may be gainfully dismantled.

To appreciate how the city might need to compensate for its behaviour, it is timely to introduce formal definitions of what ecosystem services are, and hence to appreciate what is lost when they are degraded, if not in due course overwhelmed. This is indeed much a case of not being able to appreciate something until it is "gone".

Thompson (2011) provides an apt point of departure, when he explains:

> Ecosystem services are the contributions that ecosystems make to human well-being – both goods, such as food and freshwater, and services, such as flood reduction and carbon-sequestration.

The (biochemical) pollution of the city's immediate water bodies, arising from Stage 2 in the concise history of the city's impact on the environment, will generally render local access to freshwater – through the loss of local ecosystem services – progressively less acceptable. The city will either have to install expensive infrastructure for accessing raw water of a near-potable quality from ever more distant sources and/or introduce ever more rigorous and expensive technology for producing wholesome, potable water from ever more compromised local raw-water sources. The (physical) modification of the city's landscape through Stage 1 in its development may undermine the ecosystem service of flood reduction (in Thompson's illustrative definition), somewhere across the city or within the watershed in which it sits. Because of the city, water from precipitation may flow markedly more swiftly and accumulate in what citizens deem as the "wrong" places, not necessarily where it once accumulated or flowed less swiftly, causing damage to property and loss of life and limb in these (now) inappropriate places. The introduction of engineered urban drainage (culverts, pipes, rectilinear concrete channels, sewers, and so forth) to insure and protect against economic flood losses in the city may displace the locus of flooding to other parts of the watershed, typically downstream of the city.

The undulations of the landscape and its hydrology, which had co-evolved with the aquatic ecosystem there before the city arrived on the ground, mattered. If a terrestrial ecosystem is altered, it is hardly surprising that the course of the co-evolving aquatic ecosystem is thereby also altered.

As for Thompson's mention of the ecosystem service of "carbon-sequestration", this has to do largely with terrestrial ecosystems locking carbon away in as immobile a biochemical form as possible and for as long as naturally possible, hence limiting its escape to the atmosphere. Typically, therefore, sequestration is achieved through forests with their trees, as opposed to industrially generated algae-based biofuel, or, for that matter, grasses and other plants.

To be more systematic, the Millennium Ecosystem Assessment grouped ecosystem services into four broad categories (see, for example, Carpenter *et al*., 2009):

Regulating, such as the control of climate, control of the spreading of disease and, in particular (for present purposes), waste decomposition and assimilation (i.e., self-purification capacity), and flood attenuation.

Supporting, such as the naturally evolving formation of soil, in which, in turn, to support primary biological production, itself serviced by crop pollination (for the provisioning service of food supply), together with the naturally evolved biogeochemistry[9] of nutrient (carbon (C), nitrogen (N), phosphorus (P), …) cycles and nutrient dispersal.

Provisioning, such as the production of food and, of special relevance here, freshwater and energy in the form of hydro-power – with other illustrations including the furnishing of naturally grown fuels (wood, peat) and fibre, and formation of the natural capital of genetic diversity. And

Cultural, such as recreational and spiritual benefits, where we know water holds an utterly special place in the affairs of mankind.

Of these, and by virtue of the word used, supporting services are generally held to have the special role of underpinning delivery of the other three services. However, the simplicity of this macroscopic fourfold classification cannot fully cater for organising our understanding of the huge variety of ecosystem functions we find in the world "out there", which are neither rigidly nor crisply differentiated one from another.

Nevertheless, according to this generally accepted categorisation, the presence of inexpensive and readily accessible freshwater is deemed a provisioning service of nature – albeit one dependent upon the regulating service of "waste decomposition and assimilation", should such freshwater access be required in the shadow of the city (with its detrital hot-spots). Flood reduction comes similarly under the category of a regulating ecosystem service. The "carbon-sequestration" to which Thompson refers (in his third illustration), might best be viewed as a supporting service, as in supporting the regulating service of control of climate, that is. To complete this introductory picture of ecosystem

[9]With the phrase "geo" now inserted to recognise the role of processes of transformation within geology and the landscape, such as, for example, the dissolution and weathering of rocks and soils.

services, services designated as cultural can yet be delivered even in the worst of circumstances: of "destroyed" supporting services, to the detriment of any regulating service and, even more surely, the loss of provisioning services. The Bagmati River is sacred to Nepalis. Yet it is currently devastated by the detritus from life in the city of Kathmandu, precisely where self-evidently the river amply and obviously meets the demand of Kathmandu's citizens for its cultural services (Figure 2).

Figure 2 The Struggle of the River to Sustain its Cultural Ecosystem Services – The Bagmati River, Kathmandu, Nepal

The sub-title of the Technical Report for which this is the cover photograph, *The Bagmati: Issues, Challenges and Prospects* (prepared for the King Mahendra Trust for Nature Conservation, Kathmandu, Nepal, by the Nepal Water Conservation Foundation), reads "You don't have to be a trained ecologist to tell the river is polluted" (also available as http://cfgnet.org/wp-content/uploads/downloads/2012/04/Bagmati2009.pdf).

3 FRONTIERS OF PRACTICE: ECOSYSTEM SERVICES AND BIOGEOCHEMISTRY

In general, the insecurities in public health brought about by the hot-spots of biochemical degradation of once-pristine water bodies – Stage 2 of the city's concise environmental history – have had to be addressed as the priority, as a matter of some urgency. Once the science behind this Stage 2 has been set out, therefore, we can review how it is being put to work at the frontiers of contemporary practice in managing ecosystem services for water (with the help of three case studies).

3.1 THE SCIENCE

The biogeochemistry at the base of (aquatic) ecosystem services can be understood as being very much a function of the *cycling* of energy and materials, in particular compounds of carbon (C) and nutrients nitrogen (N) and phosphorus (P). Crudely (very crudely for present *instrumental* purposes), and without composing an introductory text on ecology and ecosystems, we have this:

Carbon. Carbon (C) is the basis of the organic building blocks of biology and life, not least those of the trees in which we now seek to sequester it (for as long as the trees are living) to suppress its release to the atmosphere in its gaseous form, as carbon dioxide (CO_2). It is present in food, in the CO_2 each of us exhales, and in the biological residuals of our body's metabolism, thus in the water-borne sewage of a water-based sanitation infrastructure. Complex, organic C molecules are broken down into simpler end-products, such as CO_2 and methane (CH_4) (as well as water), by the action of bacteria, in both the presence and absence of gaseous oxygen (O_2) – hence the very basis of engineered wastewater treatment. Gaseous CO_2, of course, can be incorporated through the process of photosynthesis into the organic building blocks of living entities, notably algae, a biomass from which biofuels can be extracted. Algae (phytoplankton), themselves nourished by inorganic nutrients (in particular, N and P compounds, in addition to the C compounds), are a class of microscopic organisms at the very base of the food-chain of aquatic ecosystems. Their culture can be regarded as primary production in aquatic systems, namely the conversion of inorganic nutrient materials into living, organic, biomass. This, therefore, is the equivalent of the more familiar kind of primary production in terrestrial ecosystems, namely vegetation (classified above in Section 2 under the category of a supporting ecosystem service). Food-chain systems are described as comprising hierarchically arranged classes of prey and predator species ascending through generally ever larger organisms, such as zooplankton (which prey upon the algae), insects, fish, amphibians, and mammals, up to humans as (arguably) correspondingly at the apex.

Nitrogen. Nitrogen (N) is familiar to us as a key element in the composition of agricultural fertiliser. In crude terms, its cycle can be conceived here as "from the air, to the air". Unreactive nitrogen gas (N_2) can be withdrawn from the atmosphere and incorporated (fixed) into plant matter in the soil and on the ground, a terrestrial ecosystem service – in fact, that of primary production. This slow process has its much accelerated industrial counterpart: the Haber-Bosch process, for producing from unreactive N_2 (and a sizeable input of energy) the reactive forms of N found in fertiliser. Post-consumption, these reactive N forms are prominent in urine, whose degradation into non-polluting compounds of N is in due course assisted by the action of bacteria, in both the presence and absence of O_2. This occurs in a manner parallel to the degradation of polluting C compounds. The two pathways are therefore generally combined (quite deliberately) in wastewater treatment, where their accelerated implementation must be assisted by the input of energy (once more). The release of the "end-product" gaseous N_2 is a part of this treatment. But, of course, in the grand scheme of things, this is no "end" to those things, but just one arc within the circle of global N cycling. If not treated (or only partly treated), the reactive chemical species of N will undergo the same microbially mediated conversion processes in natural water bodies, as well as become incorporated into algae through photosynthesis, hence to propagate up the food-chain of the aquatic ecosystem. Conversely, when the photosynthesis of algae is engineered into a wastewater treatment plant, it will be referred to as a pollutant-nutrient removal process – on the basis of it also being "far better" to culture algae deliberately in the built environment of the treatment plant than to permit this to happen in uncontrolled ways in the natural environment, where it is referred to as eutrophication (and quite unfavourably so).

Phosphorus. Like the reactive N compounds, certain forms of (beneficially fertilising) phosphorus (P) compounds have also long been regarded unfavourably as pollutants responsible for eutrophication. This is all a matter of the concept of the "wrong" amounts of the "wrong" P compounds being in the "wrong" place at the "wrong" time. Unlike N, the cycle of P can be thought of as "from the earth, to the earth". Biologically reactive forms of P are quarried from rock. Re-distributed elsewhere in the soils of the landscape, they are incorporated through primary production into plant matter. Post-consumption, they too are prominent in urine. Again, like the biologically reactive N and C compounds, these P compounds are incorporated into the biomasses of the bacteria mediating their degradation (under specific combinations of exposure to the presence/absence of O_2), as well as expressed in simpler, soluble (but not gaseous) "end"-products. An alternative, popular form of their removal as pollutants is through chemical precipitation, returning them thus to their solid-form "origins", earth-to-earth, as it were. We may note in passing that, having been incorporated back into the biomasses of microscopic bacteria (and algae, in the case specifically of photosynthesis), these P compounds can be reduced down to economically concentrated solid forms in the ash residues of waste incineration – "to the earth", again.

The wording of this science is delightfully fraught with double meanings. Materials can be regarded in very different ways: as pollutants or resources. And what happens in the natural environment can be made to happen in the built environment of the city's infrastructure. It depends on one's perspective; and that perspective changes with time. The International Water Association (IWA) once had a Specialist Group titled "Nutrient Removal". It is now called "Nutrient Removal and Recovery" and comes under a new umbrella initiative on "Resource Recovery" – the subject of a companion science and technology Paper for the World Water Forum 2015 – together with a second Specialist Group on "Resources Oriented Sanitation".

Thus, to rewind the loop of history once more, when Streeter and Phelps were conducting their path-breaking studies on cleaning up the Ohio River in the USA, in the early 1920s, what was to be done by way of remedying such environmental injury would be conditioned on exploiting the river's self-purification capacity (Streeter and Phelps, 1925). The cleaning up was to be effected by engineering into a sewage treatment plant the capacity for microbially mediated breakdown of the C-bearing materials (primarily). This required energy to force oxygen (O_2) into the sewage to support the bacteria as the "mediators". Its success was to be gauged simply by the river's dissolved oxygen content and its closeness to saturation concentration, given that the biomasses of the bacteria no longer needed there would not be drawing down the river's limited supplies of O_2 in undertaking the degradation of the complex C molecules in the river (as opposed to the treatment facility). Today, we would describe this work as a matter of restoring the river's ecosystem services and improving its ecological health.

To put this properly in context, cleaning up rivers and other bodies of polluted water over the decades has progressed through several eras (in a slightly less concise history):

- the elimination of pathogens before discharge, for the protection, we note, of *human* health;
- the elimination of oxygen-demanding C-based pollutants, as described above;
- the elimination of N-based pollutants, initially because they too, through in-stream microbial degradation, were responsible for depressing river dissolved oxygen concentrations, hence the engineering and intensification of the processes of degradation in wastewater treatment – with the supply of additional energy for doing so;
- the elimination both of N- and of P-based substances, because they were fuelling eutrophication (especially in estuaries and lakes), with the N returned to the air as unreactive N_2 and the P to the earth; and
- the elimination of toxic pollutants, broadly categorised as substances often containing heavy metals (cadmium, chromium, and so on) and substances of a man-made, synthetic character – resistant by design to degradation not only by natural processes (ecosystem services, in fact), but also inadvertently (not by design) to degradation and elimination in the conventional processes of wastewater treatment.

These last, it was recognised, would adversely affect the activity of the species providing the aquatic ecosystem services (if not kill them) and accumulate in higher concentrations in the tissues of the higher (predator) organisms of the ecosystem. The case of mercury in commercially caught fish is, of course, all too well known.

An odd facet of the symbiosis between the ("designed") ecosystem services of the city and those of its environment rather proves the point about the interchangeable roles of the city's infrastructure and the river. Following the decades over which Europe's River Rhine was rehabilitated, it was observed that the river had lost some of its previous capacity to attenuate, hence "bounce back" from, the consequences of accidental spills of toxic substances, notably those bearing N in their composition (Malle, 1994). This was in due course attributed to the fact that, before the installation of the more advanced levels of wastewater treatment (for "complete" elimination of N therein), urban treatment facilities had been cultivating N-degrading bacteria and beneficially (as it turned out) releasing them to the river system. So there they were, ready and waiting, primed for action in the event of a spill.

Our technological capacity to observe, and hence understand the behaviour of the environment, has been ever-expanding; thus are we ever discovering other, ever more subtle ills in need of "fixing". Whereas historically it might have been engineers and planners who were setting the agenda for cleaning up rivers, members of other branches of science were beginning to hold sway. For of course, there is much more to the science of the aquatic environment than the chemical contents and biogeochemistry of the water. Understanding and managing ecosystem services depends just as much on understanding and managing aquatic habitat (see, for example, Karr, 1991; Bauer and Ralph, 1999) and likewise the spectrum of temporal disturbances to which an ecosystem is subject (see, for example, Arthington *et al*., 2006; Richter *et al*., 2006).

Things change strategically and in *quite* unexpected ways over the decades. Take, for instance, the case studies soon to be presented below as a sample of markers of the current frontiers of practice, in putting the growing science of ecosystem services to work in the technologies and infrastructure for managing them to our benefit. And to provide a frame of reference for gauging the changes these case studies illustrate, we offer the following definitions of biological integrity and ecological health (from Karr, 1991):

> ***Biological Integrity*** is the ability to support and maintain (quoting Karr and Dudley, 1981) "a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region".
>
> ***Ecological Health*** is summarised in these words (quoting Karr *et al*., 1986): "a biological system … can be considered healthy when its inherent potential is realized, its condition is stable, its capacity for self-repair when perturbed is preserved, and minimal external support for management is needed".

3.2 THE TECHNOLOGIES: CLEAN TECHNOLOGY AND GREEN INFRASTRUCTURE

The water sector has always been about cleantech. It develops and deploys technologies for providing clean, wholesome water to drink, from an environment of ever-variable quality. It develops and deploys technologies for cleaning up wastewater, to restore and maintain a clean environment.

Beyond the water sector, cleantech is for many about "doing more with less", "generating less waste", "extracting value from waste", or, taking a lead from the functioning of natural ecosystems, about solving the equation of "waste equals food" (McDonough and Braungart, 2002). And so it is; it is all of these caricatures and slogans. Many, therefore, could subscribe to the following definition of Cleantech, as (from Villarroel Walker and Beck, 2014):

> ***Cleantech.*** The set of economically competitive and socially acceptable technologies and services that use fewer resources (materials and/or energy) while causing less harmful environmental impact – even generating a positive environmental impact.

The "tech" suffix groups cleantech logically with the other familiar "techs": infotech, biotech, and nanotech. In this sense, cleantech springs from the industrial–military complex, as it were. It takes knowledge acquired essentially through laboratory science – controlled experimentation under clinically isolated conditions, and especially those sealed off from the rest of the world – and engineers this knowledge into using the processes of physics, chemistry, and biology in artificially constructed and separate volumes. Some of this qualifies as the infrastructure of the built environment. We call it "grey" because of the outward-facing, archetypal, steel and concrete support and containment structures of that infrastructure.

Green infrastructure, in contrast, can be said to have its origins in part in "community experience, practices, and knowledge" (pre-dating the industrial revolution) and in part – and much more recently – in the increasingly deeper, more systematic, direction of scientific enquiry into the workings of the natural environment, and, where possible, "segments" of that nature in their unseparated, "whole", non-reduced, *in situ* forms. We call this green infrastructure because, largely, the manifestations of nature on the land being deployed as infrastructure are predominantly (and spiritually) green.

There is not, as we shall come to see, all that much difference, if any, between the functioning of a green infrastructure and a grey infrastructure replete with cleantech. Rather, the two differ in their respective visual appearances.

Case Study 1: Promoting the Prudent Dispensation of Nutrients

Cities – and now agriculture – have been seen all too readily as nothing but "bad actors" in the watershed. For half a century, the struggle has been to curb the discharge of nutrients to water bodies. Until recently, if not still, policy and financial instruments for doing so have been referred to as nutrient *pollutant* trading programmes. Until just as recently, as already noted, IWA has had a Specialist Group on but Nutrient *Removal* (without the Recovery).

From the perspective of the aquatic ecosystem, nutrients (primarily N and P species) have generally been of interest as an environmental "bad", because their presence in excess, in readily biologically available form, causes excessive primary production of algae at the base of the aquatic food chain. The "balance", "stability", and "integrity" of the ecosystem are thereby undermined. The ecosystem does not function as expected, according to its otherwise ever-changing evolutionary trajectory (undisturbed by mankind, that is). Its provisioning ecosystem services are compromised, in the sense that customary commercial fishing (to which Man has become accustomed), the supply of potable water, and recreational use of the water body (a cultural service) are degraded to a significant extent.

Salmon fishing is one of the most prominent such industries globally. Salmon fry require the supporting ecosystem service of sufficient biologically available P in their freshwater environment, hence to incorporate the P in their metabolism and growth, thus to increase their chances of survival in migrating through the transition from a fresh- to a salt-water environment. In the absence of the P released into their freshwater environment from the rotting carcasses of adult salmon, the P they need to access is present in insufficient quantities. In streams where this is so, because of declining stocks of returning adult salmon, P may need to be added deliberately to the stream – and has been, for several years, in the streams of Vancouver Island, British Columbia, Canada (Pellett, 2010). Some 450km away, in the city of Durham, Oregon, USA, Ostara Nutrient Recovery Technologies has a P-recovery unit at the city's wastewater treatment plant (Figure 3). Some of its pellet-form, slow-release Crystal Green® P-based (fertiliser) product is bagged, shipped to Vancouver Island, and there "dumped" into the streams (Figure 4) – in the physical sense, decisively *not* the common pejorative sense of "cities dumping their sewage" – to reverse the decline in salmon populations (Pellett, 2010; Force, 2011; Beck, 2011).[10]

Figure 3 Ostara Pearl® P-recovery Process Unit, Wastewater Treatment Plant, Durham, Oregon, USA

Image from the article "Durham houses first full-scale commercial nutrient recovery facility in the nation" (http://www.cleanwaterservices.org/AboutUs/WastewaterAndStormwater/Ostara.aspx).

[10]All may not be quite how it seems, however. Adding nutrients to coastal streams in Oregon itself, for the same purpose of restoring salmon populations, is not a straightforward matter, neither scientifically nor politically (Compton *et al*, 2006). Scientifically, when the added P fertilizer is in an inorganic form, it is accessible only by algae and must pass up the food chain (through zooplankton, invertebrates, and insects) before being available for the salmon fry. Artificial increases in the supply of inorganic nutrients to the coastal streams of Oregon were not recommended at the time Compton and colleagues published their article (Compton *et al*. 2006). Politically, nutrient supplements to salmon streams might well be construed as suggesting that inappropriate chemical regimes of these water bodies are responsible for declines in salmon populations, not habitat modification through the construction of dams and other "grey" infrastructure. In a politically fraught situation, as we know in respect of climate change, money may flow in the direction of proving a scientific point on one or the other side of the controversy, not necessarily towards the higher good of their reconciliation, hence scientific progress.

Figure 4 Issue of Nutrient Supplements for Reconstruction of Declining Salmon Populations in Vancouver Island Stream, Canada
Bagged, slow-release Crystal Green® P-based fertiliser product (recovered from the Durham Wastewater Treatment Plant (Figure 3)) is placed in a Vancouver Island stream.

The city of Durham is, in effect, supplying an ecosystem service to its (or rather, Vancouver Island's) environment, by way of manipulating the chemical content of stream water. To be precise, if not pedantic, about this:

> The ecosystem service sustained in this instance is the investment and re-investment in future stocks of salmon populations – both a supporting and a provisioning service, in fact. It is occasioned by the prudent dispensation of recovered urban nutrients to the salmon-spawning stream.

Today, we are coming around to referring to the nutrient pollutant trading programmes of former times in the neutral, if no longer negative (but yet not positive), phrasing of Nutrient Credit Trading markets.[11]

Case Study 2: Dismantling the Conceptual Divide between the City and the Watershed

By convention, we have conceived of cities and industries, and their potential to generate environmental harm, as being encircled (metaphorically) by an infrastructure, on the downside of the city or industry, designed to suppress and curtail its polluting potential. We categorise this infrastructure (of sewerage and wastewater treatment) as belonging to the built environment, to distinguish it from the complementary categories of the natural and human environments. The colour we would choose to give it, for the sake of argument, would be grey (as opposed to green, for example). Its functioning and services are those quite deliberately engineered and *controlled* by the hand of Man. We should be correct to conclude this grey infrastructure demands a great deal of external support, decidedly over and above the "minimal external support" conferring the status of well-being in Karr's foregoing definition of ecological health.

By convention, we have conceived of the city's surrounding watershed as the green, rural, extensive, unconfined space in which other activities take place: ones quite different from those of the city and industry; those, notably, of agriculture. Absent from this rural landscape is the grey infrastructure of the city.

What is done in the city, surely, is *not* what is done in the city's environment and *vice versa*. The two are sharply cleaved conceptually, one from the other. Yet, agriculture has become an industry and therewith its activities deeply intensified. There are confined animal feeding operations (CAFOs) and, as in the city, increasingly there is their attaching and deliberately engineered, if not grey, infrastructure for restraining their potential to pollute the water environment.[12]

By convention, it was not possible to conceive of the city doing good things for the environment, only less bad things. The city had to be bounded physically and kept separate from the environment. The wrong things should not escape from it

---

[11]The US state of Pennsylvania has one of the first such successful Nutrient Credit Trading programmes (see http://www.portal.state.pa.us/portal/server.pt/community/nutrient_trading/21451).
[12]We may think conversely, if not with flattery, of cities as confined human feeding operations (or CHFOs) – and there is much insight to be gained from adopting such an unappealing take on the city (Beck, 2011; Villarroel Walker and Beck, 2014).

(polluting substances). Other things, of particular importance for understanding and managing ecosystem services, should not be permitted to gain access, specifically flood waters from the surrounding environment.

The recently renovated sewage treatment works at Soerendonk in The Netherlands tramples wonderfully across this conceptual distinction, between what the city does and what the environment does. It is hard to better the original account of the change, itself almost one of those "shifts in paradigm", of which we hear so much.

To begin, The Natural Step's (TNS) news bulletin (www.naturalstep.org; accessed 7 August 2010) asked simply:

> [C]an a sewage facility actually help to enhance the health of natural systems?

and then responded, recording these changes:

> These new possibilities are now on display at the sewage treatment plant at Soerendonk today. The facility now includes a 9 hectare, €1.2 million (22 acre, US$1.4 million) addition that consists of ponds, marshes and canals filled with aquatic vegetation that blends into the existing river ecosystem. The final pond along the riverbank is designed to be inundated during floods, and during dry seasons, a fish ladder provides a way for fish to spawn in the sewage facility's final pond. In this way, the line between the "treatment plant" and the "natural ecosystem" is intentionally blurred, providing a benefit to both systems.

The bulletin went on to observe (www.naturalstep.org; accessed 7 August 2010):

> The change has been a deep one, as Hans van Sluis, senior advisor on vitalization of water at DHV [Engineering Group] notes. "The effect of this change in our way of thinking about sewage treatment has been fundamental. We now look at sewage treatment not as a necessity to reduce pollution and safeguard health but as a chance to enhance ecosystems and the related service provision."

And to continue, DHV's own briefing note on "Revitalizing effluent for STP Soerendonk" revealed the kernel of something more (www.dhv.nl; Figure 5):

> A three-stage ecological filter [daphnia ponds, reed marshes, fish pond] – based on the *water harmonica* principle – removes the last remaining bacteria and pathogens and inoculates the treated effluent with appropriate surface water flora and fauna species.

Figure 5 Plan View of Soerendonk Wastewater Treatment Plant, The Netherlands

Services are drawn from three ecosystems: a flea pond, or daphnia pond (Zone 1); reed marshes (Zones 2); and a fish pond, or biotope (Zone 3) (http://www.paul-van-dijk.com/nieuws/application-of-flowform-technology-in-the-sewage-water-treatment-plant-soerendonk-nl).

Upstream of the first of these stages

> [a] flowformcascade is placed between the 'concrete' sand filters and the Daphnia ponds of the 'green' section [of the STP]. Flowforms … evoke a rhythmical flow, which mimics a meandering river. … [A] stimulating effect on the downstream ecosystems development is expected.

The ecosystem service provided by the city's wastewater treatment plant is that of enhanced riparian aquatic habitat, admittedly in ways we can recognise in the now classic wetland treatment system, but in ways that positively, deliberately, and actively go beyond such systems. Unsurprisingly, the Soerendonk plant is what we would describe as grey–green urban infrastructure.[13] Again, to be precise:

> The ecosystem services sustained in this instance are twofold, respectively a regulating service and a supporting service: the attenuation of flood impacts somewhere in the watershed; and seeding of the river with its native flora and fauna. They are occasioned by the reconstruction of riparian habitat, including the insertion of a meandering (rhythmic) spatial pattern of channel flow through that habitat, itself contained within a space customarily designated as an urban wastewater treatment plant (Figure 6).

Figure 6 The "Flowformcascade": Design for a Meandering Stream Pattern – Other Artistic Designs Based on This Theme Can Be Found at the Studio of Paul van Dijk (www.paul-van-dijk.com)

Image taken from the article: http://www.paul-van-dijk.com/nieuws/application-of-flowform-technology-in-the-sewage-water-treatment-plant-soerendonk-nl.

Case Study 3: Planning for an Environment Not at Steady State

Throughout much of the mid- to late 20th Century, and indeed guided by the classical work of Streeter and Phelps (1925), planning and constructing urban infrastructure to clean up polluted rivers were driven by the regulatory goal of maintaining in-stream dissolved oxygen concentration above some critical lower bound under *steady* low-flow stream conditions. Wastewater treatment plants were built (and operated) as though the watershed was in a steady state, its behaviour unchanging over time. This was not bad policy. It was not bad to plan for a (near) "worst-case" scenario. Ecosystem services were to be restored to an "acceptable" level, subject to a given level of risk of their failing from time to time, since

[13]Like all such matters, if one enquires deeply enough, the distinction between grey and green infrastructure can appear somewhat arbitrary. The conventional (grey) part of a wastewater treatment plant seeks by design to replicate the biologically mediated "self-purification capacity" of a natural river in an intensified, accelerated, confined, engineered unit process. This activated sludge process is a highly complex microbial ecosystem, but one controlled (unlike "natural" ecosystems) by "external" artificial and automated interventions. In contrast, too, the operation of constructed wetlands is celebrated precisely because such systems are left more or less to their own devices (Karr's "minimal external support"), without much deliberate manipulation of their day-to-day behaviour, but instead *with* almost complete internal self-control. Being highly complex and nonlinear, however, the risk is of this self-directed behaviour evolving into something that is not at all what was desired – by the (external) ecological engineer – when the wetland was first set up. The risk in this "hands-off" policy is a bit like the risk of having children maturing into wayward teenagers.

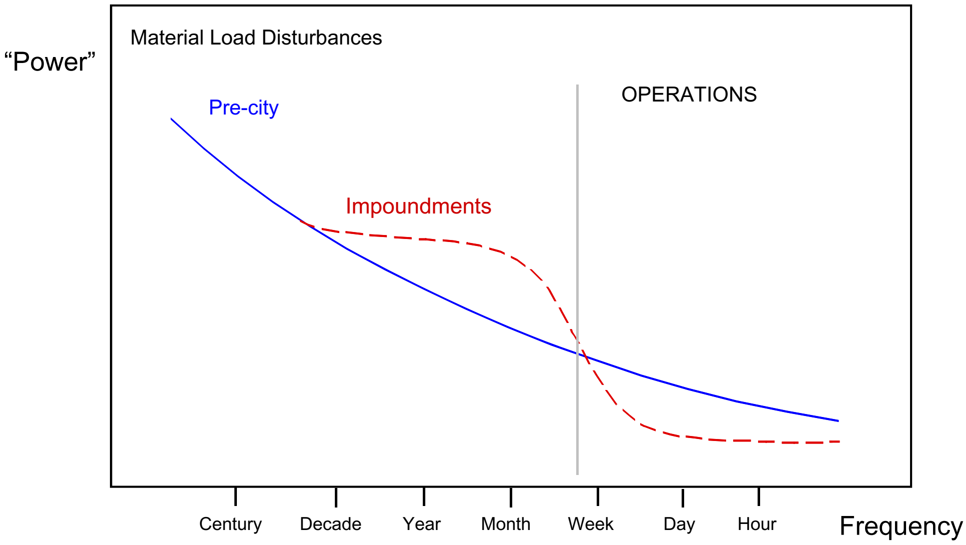

Figure 7 Frequency Spectrum as a Representation of Variations in Streamflow in a River: A Summary Impression of the Impact of Constructing Impoundments (Reservoirs) (Dashed Line) on an Otherwise Naturally Flowing River, Before Arrival of the City (Continuous Line) in "Geological Time"

Think of the variation in time of stream flow (or sediment flow, or nutrient flow) – namely material flow/load in the river – as a combination of many idealised sinusoidally varying components, each with a specific frequency of oscillation, which may lie anywhere (in principle) between a fraction of a nanosecond and beyond multiple millennia. Impoundments have the effect of concentrating more of the river's downstream flow variations (its "power") within the span of relatively slower monthly and annual fluctuations (frequencies) and reducing their concentration ("power") within the span of relatively faster daily and hourly fluctuations (frequencies).

the world is not in a steady state. This would be superior to having previously had either substantially degraded or no ecosystem services.

The very success of such a strategic policy not only then enables apprehension of the growing significance of transient, highly unsteady-state (dynamic) pollution from agricultural and urban runoff, it also makes the restored ecosystem services much more vulnerable to disruption – and to the public's perception thereof. Think of the cultural ecosystem service of a recreational fishery painstakingly reinstated over the years in a previously polluted waterway, which is then wiped away by a sudden failure in the wastewater treatment plant's operation (Beck, 1996, 2005).

Perceptions and the responsibilities of management change over the decades.

Nothing epitomises better this fact of life – of the environment *not* being in a steady state – than what is brought to mind by the now rampantly popular word "resilience": needed in all systems (so it appears) to cope with transient disturbances, shocks, shifts, surprises, and changes of strategic significance; and a matter to which we shall return in much more detail in Section 4.[14] Something of the same is apparent in the two foregoing definitions of biological integrity and ecological health.

The world is not constant, even though we might imagine we seek this in the popular phrase "the city never sleeps". Parts of the world, conspicuously the city, *are* indeed locked into the narrow bandwidth of the "24–7" frequencies of variation. A very great deal of what happens in the city's watershed (and beyond) is appropriated to service (ultimately) just this narrow segment of the frequency spectrum. In many places, all the rich breadth of dynamic variation in the spectrum of disturbances and fluctuations to which an environment is naturally subject (from seconds to millennia) – and which define how that environment has evolved over the aeons – has been subjugated to just the 24–7 bandwidth of socio-economic life in the city. Thus works, for such appropriation of nature's resources, all manner of built (grey) infrastructure imposed across and alongside rivers, to afford Man water for irrigation, potable supply, recreation, and flood protection.

On the one hand, and of greater concern to stream ecologists, we have the following. The infrastructure of dams, sluices, weirs, and locks spanning rivers, to create impoundments (reservoirs) of water for various societal uses, has the overall impact of shifting "power" out of the high-frequency oscillations in streamflows downstream of the infrastructure (over minutes, hours, days, and weeks) and into the mid-frequency fluctuations (with periods of months, possibly years) (Figure 7). On the other hand, creating impervious surfaces in cities and then fast-reacting conduits (sewers) to attenuate pluvial urban flooding, has shifted power out of the mid-frequency fluctuations and into the higher-frequency components of the streamflow spectrum.[15] By association with these two strategic changes in the spectrum of streamflow variations, so we can

[14]For a good inter-disciplinary account of the extent of the current fascination with resilience, see Martin and Sunley (2015).
[15]The effects of the two (stream impoundments and urban sewerage) do not cancel each other out, however. The system is far less straightforward than just that (Beck, 1996, 2011).

assume like changes in the corresponding spectra of sediments and C-, N-, and P-based nutrients. This indeed is apparent in Liao's (2014) analysis of the impacts of (grey) infrastructure on the Lower Green River Valley in Washington state, USA (which we examine in greater detail in Section 4).

The concern of stream ecologists is that we have the ecosystems and their assemblages of organisms "naturally found" around the world (or once found) as a result of the *full* spectrum of environmental perturbations with which they have co-evolved. The ecosystem services we have inherited from these evolved ecosystems (and benefit from) are exquisitely attuned to the spectrum of environmental perturbations to which they have "naturally" been subject. Mankind, with its built environment of grey infrastructure, has wrought all manner of distortions in that spectrum and now reaps accordingly a diminution in the volume and quality of the associated ecosystem services. Think – though we believe there is no instance to be found – of a natural ecosystem, namely one undisturbed by Man, that has co-evolved over the aeons with an environmental perturbation with a *weekly* periodicity (one of the now dominant 24–7 couple of cyclical components).

Yet there is redemption in that very same grey infrastructure. It can be manipulated in an operational manner, to reconstruct, in part, the once complete spectrum of temporal disturbances of the now degraded river environments. Hence too, in a self-interested manner, Man derives benefits from the restored ecosystem services.

Stream ecologists recognise both the problem and the solution in what they refer to as the provision of "environmental flows" (Arthington *et al*., 2006; Richter, 2010). Practical implementations follow a so-called "Savannah Process" (as in Savannah River, USA) for site-specific environmental flow assessment. Its prescription amounts to reconstructing a sampled approximation of the spectrum comprising the following elements (Richter *et al*., 2006) (Figure 8):

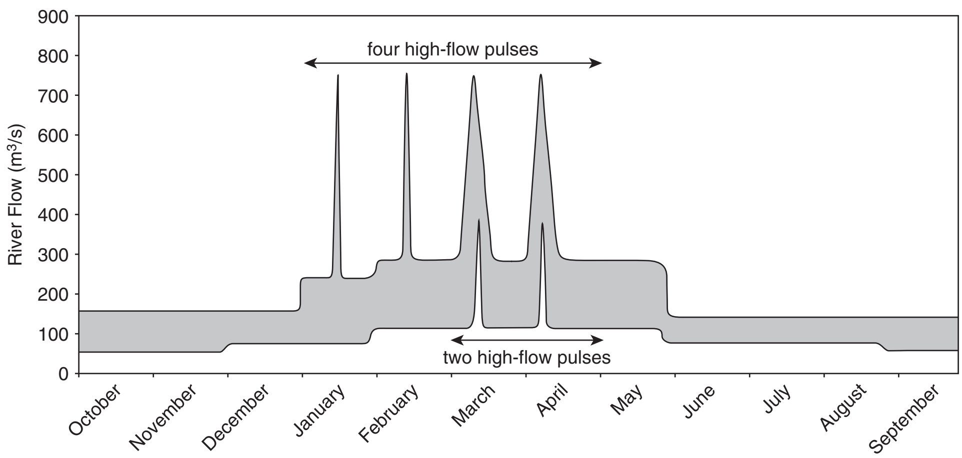

Figure 8 The Savannah Process for Reconstructing More "Natural" Streamflows in a River with Impoundments/Reservoirs

These are idealised patterns in time of the variations in streamflow to be generated within a river by deliberate manipulation of an upstream sluice-gate in a dam (from Richter *et al*., 2006). The two pairs of shorter-duration "spikes" (shaded and unshaded) would "contain" the highest-frequency components of sinusoidal oscillations reflected in the summary frequency spectrum of Figure 7; those in the slightly longer-duration "spikes" (shaded) would contain slightly fewer of the highest-frequency components. The "steps" of varying durations in both the shaded and unshaded idealised patterns would contain (primarily) relatively more of the mid-frequency components of fluctuations – focused on weeks for the shorter steps and months for the longer steps.

(1) "floods", or higher-amplitude, high-frequency[16] events;
(2) "high flow pulses", or lower-amplitude, high-frequency events;
(3) "low (base) flows – normal", or low-amplitude, low-frequency events; and
(4) "low (base) flows – drought", lower-amplitude, lower-frequency events.

To be precise about the message from this third case study:

The ecosystem service sustained in this instance is the prosperity of a native fish assemblage, as "originally" found in the river. It is occasioned by the prudent manipulation of the (grey) civil engineering infrastructure of the built environment. If one has to classify it, supporting service would best fit the bill.

[16]"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.

3.3 INTRODUCTORY LESSONS LEARNED

From a "systems perspective", within the framework of Karr's definition of ecological health, what might we learn about ecosystem services for water from the three foregoing case studies?

First, each of the three categories of the science of the aquatic environment are exemplified: (1) water *biochemistry*, in the case of the Vancouver Island streams; (2) aquatic *habitat*, at the interface between the Soerendonk treatment plant and the receiving river; and (3) the *spectrum of environmental disturbances* co-evolving with the aquatic ecosystem, in the Savannah Process of The Nature Conservancy and the US Army Corps of Engineers (Richter *et al.*, 2006).

Second, the Vancouver Island and Soerendonk case studies complement each other, in a way that echoes and elaborates further the city–environment symbiosis. The former (Vancouver Island) takes the material outcome of what is generally thought of as the city's conventional grey infrastructure (nutrient fertiliser) and puts it to work at the base of the food chain of an aquatic ecosystem in a natural environment. The latter (Soerendonk) takes what has been understood of the services of a natural system and grafts them – as the upper echelons of an ecosystem (interactions among flora and fauna) – on to conventional grey infrastructure.

Third, two of the case studies illustrate active, deliberate, and operational *external* support for their respective ecosystem services: dumping of the bagged, slow-release P fertiliser (Vancouver Island); and manipulation of the grey infrastructure (dam releases, specifically) in the Savannah Process. The third, constructed riparian habitat (Soerendonk), is in contrast in line with Karr's minimal external support, namely minimal operational support, for the behaviour of the associated ecosystem, once constructed and put into operation (and presumed, therefore and ever thereafter, to be in good ecological health). The style of management of the former pair might be classified as active, that of the third as passive.

Fourth, both the Vancouver Island and Soerendonk studies exhibit facets of the Savannah Process. The bagged slow-release P fertiliser recovered from the city of Durham is not just dumped at any old time in a Vancouver Island stream (nor should it be; see Compton *et al.*, 2006), but after the peak stream-flows of the late spring. And – to quote from the Savannah Process for *water* flows – the slow-release properties of the fertiliser create not a wasteful, short "high flow pulse" of *nutrient*, but more a "low (base) flow – normal" flux. Soerendonk's "flowformcascade", which evokes a "rhythmical flow", which therefore "mimics a meandering river", provides a space-time interpretation of the spectrum: that of meandering (in space) and of rhythmic flow (in time), albeit possibly at merely a single frequency in the spectrum.

3.4 HISTORY *NOT* REPEATING ITSELF – CHANGE AFTER 200 YEARS

Back in the 1830s, two patents were registered in London: for Thomas Crapper's water closet and the Reverend Henry Moule's earth closet. We know only too well which achieved overwhelming success in its adoption.[17] Some of us, schooled in the conventional water infrastructure of the mid-20th Century, gave not a thought to the notion of dry sanitation until the approach of the second millennium.

In those many parts of the world where the conventional infrastructure of wet sanitation (the WC, sewerage, and wastewater treatment) is not in place, it can only but be said that *not* installing it *may* be of the greatest service to the aquatic environment, subject to public (human) health in the city being secured, and kept secure (Larsen *et al.*, 2013). In any paper on science and technology for the water sector, such as this, we would be seriously remiss in not standing back from the detail of that sector, thus to take in the broader perspective, above and beyond just what is needed for water. Indeed, the less water there is passing through the urban metabolism, the better things might altogether be, socially, economically, and technologically (Thompson and Beck, 2014, 2015; Villarroel Walker *et al.*, 2014; and Beck, 2015).

On the ground, in practice, we note therefore that forging an urban sanitation–agriculture nexus is being promoted through the use of urine-diverting *dry* toilets, in Ouagadougou, Burkina Faso (Dagerskog *et al.*, 2010).

[17]And think how the English language might have been forever otherwise changed, had the Reverend Moule's device won in the mid-19th Century technological stakes.

4 FRONTIERS OF PRACTICE: LANDSCAPE AND HYDROLOGY

Picking up on the way in which the Soerendonk case study dismantles the conceptual distinction between what takes place in the city and what in the city's environment, we turn now to address the progressive "greening" of the customary grey urban infrastructure. This greening may come broadly in two forms: first, in the physical substitution of manufactured materials (concrete, steel) by natural, non-manufactured materials (plants, grasses, soils, rocks); second, and less obviously (and much less easily), in adapting the grey infrastructure so that it may be operated – not rebuilt or substituted – with progressively more *ecological* resilience in its behaviour (Beck and Villarroel Walker, 2013a,b).

4.1 THE SCIENCE

Let us begin by providing a more scientific account of the colloquialisms already introduced above under Case Study 3 on the Savannah Process: those of the "city never sleeps" and the "24–7 bandwidth of socio-economic life in the city". They have to do with the technical concept of *frequency spectrum*.

Hydrology. Water on the earth's surface and in the landscape is evaporated into the atmosphere, is transported around the globe, and delivered back to the surface as precipitation, whence it flows over and under the earth's surface. Some of these flows in the landscape drain to surface water bodies, some to sub-surface groundwater, and the remainder return to the atmosphere. This is familiar to us as the hydrological cycle.[18] Our present concern is with the arc of this cycle between precipitation (as stimulus) and, in particular, the surface water flows in response: in streams, rivers, impounded reservoirs, lakes, and estuaries, each with its own distinctive aquatic ecosystem, from which the city is expecting to derive some services.[19] The features and properties of those services are distinctively a function of the particular ecosystem, hence a function of the distinctive way in which the structure and composition of that ecosystem have co-evolved over the aeons with the evolving patterns in time of precipitation and water flows. Stretches of rivers whose flows vary relatively little over the year, from year to year, and from decade to decade, will exhibit ecosystems with types of fish and other species different from those whose flows vary dramatically, from even one hour to the next. Fish species that have evolved to populate the latter will, in principle, be mal-adapted to survive and prosper in the former and *vice versa* (hence indeed the Savannah Process). The impact of the city on the temporal patterns of water flows in the environment – in particular, from Stage 1 in the city's concise environmental history – is akin to requiring an aquatic ecosystem to switch from functioning under one hydrological regime to functioning under another. Of the essence for appreciating the nature of the green infrastructure described below, is the summary shape of the frequency spectrum of water flow at a given location in the landscape (as depicted in Figure 7). Any quantity (such as water flow) varies with time. The pattern of this variation can be represented as a combination of a host of oscillations deriving from many ideal sine-waves, each with its own characteristic amplitude and frequency of oscillation: from cycling with periods below nanoseconds to beyond millennia. A river at steady state – or the metaphorical "constancy" in the exaggerated image of a city that "never sleeps" – is displaying a kind of (non-)variation over time equivalent to a single sinusoid with an infinitely long period: a frequency spectrum with but a single peak, somewhere technically off the end of the spectrum, well beyond the period of an aeon. The strange case of a river flow beating to just the two metaphorical 24–7 "pulses" would have a frequency spectrum with two peaks, at one cycle per day and one cycle per week.

In practice, righting the wrongs of the city's impact on its environment (especially those from Stage 1), through the greening of its water infrastructure and built environment, is to reconstruct in theory the original spectrum of water flow variations before the advent of the city. The framework of the Savannah Process of Case Study 3 illustrates well how this is

[18]As a parallel, water in the human body circulates substances and heat. Evacuation from the body occurs after the water has been re-cycled and re-used some 20 times. About 5% of the water inside the body, therefore, must be replenished with fresh intakes on a day-by-day basis. Tambo (2004) has likened this to an "urban metabolic system for water". YouTube is replete with video clips explaining water re-use and re-cycling in the urban context. A sample can be found at www.youtube.com/watch?v=GVm-d-zOxJs&feature=player_embedded (last accessed 15 April 2015).

[19]Focusing on this arc alone, Fletcher and Walsh (2007) show how urbanization of a landscape may triple the volume of water flowing from precipitation across the landscape to surface water bodies and increase tenfold the rate at which water falling onto the landscape will be apparent as additional surface runoff into those water bodies – as opposed to precipitation "disappearing", or being "earthed", as it were, into the ground (and atmosphere).

to be achieved, ideally not merely by adapting what has already been built – and, in fact, risking repeating the "mistakes" of the past – but by design *before* construction.

In part, such design goes under the heading of low impact development, or LID (see, for example, Dietz, 2007) – or water sensitive urban design (in other schools of thought; see, for example, Wong and Brown, 2008). LID, however, has implications beyond reconstruction only of the pattern of physical water flows across the urban landscape. We need some more (and more subtle) science, along the lines of the biogeochemistry set out in Section 3.

Landscape. At the small-scale, the fate of the notional drop of precipitation that hits the ground warrants closer inspection. It brings with it some biogeochemistry. Acid rain is a conspicuous example thereof, with its dissolved N and sulphur (S) constituents. The falling droplet of precipitation picks up other substances, from the surfaces with which it comes into contact, and further biogeochemical transformations occur within it. Some of the surfaces will be those of soil particles and rock. Others will be surfaces of the built environment and urban infrastructure (notably road transport), on which substances generally regarded as contaminants will be deposited. Yet other surfaces will be those on trees, plants, aquatic vegetation, and their below-ground root systems; hence the droplet nourishes the ecosystem service of primary production, in a wetland as much as through urban agriculture. Both the water and the materials it carries with it pass into the vegetation. Some of the water exits as vapour transpiring back to the atmosphere. Some of the contaminant materials (including heavy metals) are rendered innocuous when incorporated into the plant matter, typically the reeds in a wetland. Exploited more generally as a technology of "pollutant elimination", the process has become known as phyto-remediation (see, for example, Meagher, 2000). Having previously silted up over the decades – a consequence of soil erosion from changing patterns of surrounding land-use – the Kis-Balaton (small Balaton) wetland, located at the mouth of the Zala River tributary of Lake Balaton in Hungary, was re-flooded in the 1980s. The goal of this restoration (1986–1995) was to entrap nutrient P materials and have them incorporated into the plant matter of wetland reeds, instead of allowing them to pass into the lake, there to sustain (undesirable) eutrophication (Zalewski, 1999).

In short, the impacts of Stage 1 in the concise history of the city and its interactions with the ecosystem services of the aquatic environment can be summarised as follows:

(1) Acceleration of the speed with which water is transferred from its point of first contact with the ground as precipitation, to its participation in the duly responding flow of the receiving water body, with this speed being accelerated yet further by the artificial conduits (sewerage) introduced under the city's (initial) built environment for the purposes of urban drainage and the avoidance or attenuation of flooding in the city – thus the distortion wrought by the city in the frequency spectrum of variations in streamflow.
(2) Re-distribution of the eventual fate of the incoming precipitation among the three outflows of surface water, groundwater, and evaporation/transpiration (to the atmosphere), hence again altering the pre-existing patterns of streamflow variations in surface water bodies.
(3) Compression of the time "parcels" of water reside in the landscape between input precipitation and output streamflow, i.e. compression of their "residence times" in chemical engineering terms, and change in the surfaces with which they have contact, hence change in the extent[20] and nature of the biogeochemical transformations wrought over this arc in the hydrological cycle, between precipitation and streamflow.

It was not just the undulations in the topography of the landscape that mattered for aquatic ecosystem services before the coming of the city. It was also the presence of the vegetation: the plants to be uprooted and the trees subsequently felled, *ergo* the loss of pieces of pre-existing terrestrial ecosystem habitat. And it was the pervious (permeable, porous) surfaces of this foregoing natural landscape in which the vegetation was rooted that mattered too, perhaps only really to be appreciated (much later) once they were "gone" – replaced by the hard, impervious surfaces of the city's built environment and in due course its grey infrastructure.

It was *not* solely that the pristine flows of water once exhibited an all-important "natural" spectrum of fluctuations over time. It was also that fluxes of nutrients and sediments across the landscape – albeit fluxes obviously dominated by the patterns of water flows – bore equally important natural spectra (along the lines of that depicted in Figure 7), with significant implications for the ecosystems of the receiving water bodies. And it was *not* that the landscape was solely some

[20]Residence time is important, because it determines the extent to which two or more interacting biogoechemical entities will be changed by their contact or the number of reactions in a chain/sequence of biochemical transformations that can be brought to completion.

Figure 9 Low Impact Development (LID): A Small Retention Basin for Temporarily Storing and Treating Flows of Urban Surface Runoff, Freiburg, Germany

glorified aqueous biogeochemical reactor, whose reactions and their approach (or not) to completion, hence the mixture of biochemical components delivered to a river, were altered by the developments of Stage 1 in the city's coming. For such narrowness of concept would be to repeat the same limitations Karr (with his emphasis on habitat) illuminated in the way engineers and planners had approached curbing the hot-spots of water pollution from Stage 2 of the city's concise environmental history. Here now, he would point out, the impacts of Stage 1 were very much a matter of alterations to habitat in terrestrial (as opposed to aquatic) ecosystems.

How we put this understanding to use, in developing and applying technologies for a greener infrastructure, should be rather obvious: lessen the speed of water travelling across the urban landscape; reduce the area of impervious surfaces; and maximise the duration of exposure of the water and its contents to plant surfaces.

4.2 THE TECHNOLOGIES: GREENING OF THE GREY BUILT ENVIRONMENT

Over the decades and centuries of urban development, the city's counter to precipitation events, has been (to put it figuratively): "Shift this incident, pluvial water away from the urban landscape a.s.a.p!". The strategy has the air of having put in place a piece of infrastructure with a rather frenetic response. The "calming" measures of LID are called for.

Case Study 4: Hydrological "Calming Measures" – Restoring Urban Terrestrial Ecosystems for Restoring Aquatic Ecosystem Services

Rainwater harvesting from roof runoff and rock-filled cisterns alongside housing are rudimentary devices in the LID toolkit for temporarily storing and delaying water on its journey between precipitation and receiving stream. Equally rudimentary (in ecological terms) are permeable pavements and infiltration trenches, both intended to divert surface water flow into the (natural) sub-surface environment. These four tools all work to slow the transfer of water through the urban landscape. One of them, permeable pavement, will enhance the flux of water into the ground at the expense of its flux to the atmosphere. It does so because it nullifies the increases in evaporation from *im*pervious surfaces, with their elevated temperatures arising from greater heat absorption from solar radiation (a feature of the "urban heat island" effect).

In addition to slowing water transfer, and stepping incrementally up in terms of complexity of ecological function, vegetated swales, green roofs, bioretention basins, and tree-box filters seek to place water in contact with plant-root surfaces, and hence to mobilise some biogeochemical manipulations of the water's contents[21] and re-partition its eventual destination, in particular to the atmosphere (through transpiration). Figure 9 shows a small retention basin. In the sense that these re-introduced terrestrial ecosystem services are brought back to restore aquatic ecosystem services, they might arguably be called "supporting services". Of course, they can also provide "cultural services": as amenity spaces, or spaces

[21]The functional mechanisms of the likes of tree box filters, bioretention basins, and rock-filled cisterns should remind us (quite appropriately) of the scientific principles used originally in the biological trickling filters of conventional, grey sewage treatment.

Figure 10 Computer-generated Image of the Roof Garden at the Top of the "Walkie-Talkie" Tower in the City of London. Image taken from the article "First view of Europe's highest roof garden – an oasis on top of the Walkie Talkie tower"; *Evening Standard*, posted 6 June 2013, www.standard.co.uk).

for recreation in the urban setting. The garden-park now placed on top of the 38-storey "Walkie-Talkie" building (20 Fenchurch Street), open to the public in the heart of London's central business district, is a dramatic realisation of this kind of cultural ecosystem service (Figure 10).[22]

The constructed wetland is the icon of complex ecosystem devices available from the LID toolkit. Not intended solely as an embodiment of LID for stilling the water flows of urban drainage, however, we have already seen how such technology has been incorporated into the Soerendonk wastewater treatment plant (in Case Study 2). The new 11-storey headquarters building of the San Francisco Public Utilities Commission has a wetland too, for the on-board, on-site treatment of its sewage (Harrington, 2012).

In short, many are the successful applications in practice of these LID devices and green infrastructure technologies (Dietz, 2007).

As before, there are lessons to be learned from this case study:

First, calming the frenetic pace of the conventional (grey) means of draining the urban landscape – with its consequences for reconstructing the once "natural" spectrum of streamflow variations, hence reconstructing aquatic ecosystem services – also re-creates more time for the biogeochemistry of the terrestrial ecosystems of nature to work its transformations, thereby ameliorating the impacts of contaminants and redistributing the portfolio of nutrient forms delivered to the aquatic ecosystem (with their altered spectra of temporal variation).

Second, all this expansion in residence times notwithstanding, there is yet not enough time – in confined spaces – for deliberately engineered aquatic ecosystems such as constructed wetlands to put their biogeochemistry to work fully on the post-consumption resource flows of everyone in the city. Their slower, more naturally paced biogeochemical transformations can succeed, given either the relatively dilute distributions of substances in urban drainage water (here) and already well-treated sewage water (in Section 3 above), or the sufficient residence times afforded by the availability of large spatial areas and volumes for their accommodation in the urban landscape. Conventional (grey) wastewater treatment plants are as they are, because of the intensity of their deliberately engineered functioning, which must be completed under conditions of massive compression in space and time (and with the input of not-insignificant amounts of energy).

Third, from the perspective of putting our increasing understanding of the scientific basis of ecosystem services to work in various designs of technology, bring together (in the mind's eye) the Soerendonk case study and these LID

[22]"First view of Europe's highest roof garden – an oasis on top of the Walkie Talkie tower"; *Evening Standard*, posted 6 June 2013, www.standard.co.uk; last accessed 9 December 2014).

devices, and imagine the following. Begin downstream with the physical re-engineering of once heavily culverted, piped, and canalised urban rivers (their greening and "daylighting"; Wild *et al*. (2011), Everard and Moggridge (2012)). From there, extrapolate step-by-step back upstream, first through the physical technology of Soerendonk's flowformcascade (recreating a meandering streamflow); and then on to the importation of more natural habitat and "sacrificial" flooding areas into what we have conventionally called the sewage treatment plant. Continuing, pass over Soerendonk's ecologically more complex three-stage "ecological filter" (made up of fish pond, reed marshes, and daphnia ponds), which comprises the downstream "polishing" processes of wastewater treatment; and so on back upstream into the much more heavily engineered and intensively managed microbial ecosystems of the activated sludge process of conventional wastewater treatment. The "complexion" of the technology running along this line of thought, from the natural environment (green) back upstream into the heart of the city (grey), passes from nurturing the physical circumstances of an ecosystem, through ecosystems themselves at the interface between landscape and water – the reed marsh or wetland, with its constituent higher organisms – and into an aqueous ecosystem comprising essentially lower organisms (bacteria) and their pre-consumption, nutrient resources, namely the city's post-consumption resource flows.

Like the breakdown of the sharp conceptual divide between the city and the watershed of its surrounding environment, the crispness of contrast between what is green infrastructure and what grey infrastructure is blurring further. To reiterate, there is this curious symbiosis: managing ecosystem services for water is a matter of putting the growing understanding of the *science* of ecosystem services in the natural environment to work in the *technologies* and infrastructure of the built-human environments of the city. This is why this Paper bears the title it does.

In fact, a challenge is emerging: to push the blurring yet further; and to unfold and elaborate the complexities of the curious symbiosis. Inasmuch as we can discern ecological thinking and ecological systems being thrust back into the core of the city, can this extrapolation carry with it *ecological* (as opposed to engineering) resilience into the behaviour of the conventional engineering systems of (grey) infrastructure we encounter there? Truly green infrastructure will display ecological resilience in its behaviour. Surely, in the spirit of biomimicry – technology inspired by nature[23] – should we not want some of this in the behaviour of conventional grey urban infrastructure?

But what exactly is this ecological resilience and how does it compare and contrast with engineering resilience?

Towards Some More Science: Engineering Resilience, Ecological Resilience, and Transformation

Consider a river with good ecological health. According to the definition of Karr *et al*. (1986), its condition would be notably "stable" and its capacity for self-repair when "perturbed" would be preserved. Consider one indeed rather like the rehabilitated River Rhine. Everyday perturbations are always occurring, just as they would in a river in pristine, pre-city condition. Nothing is at steady state. Understanding, designing for, and managing resilience are quintessentially about the dynamic, time-varying nature of a system's behaviour. In many ways, this is about coping with change – and deliberately orchestrating it too (Thompson and Beck, 2014).

Let our system of the healthy river be subjected to the abrupt, transient disturbance of an accidental spill of polluting (biodegradable) substances, through failure in the control of a wastewater treatment plant, for instance. Assuming the spill is not catastrophic, the river's dissolved oxygen concentration might fall some distance from its "equilibrium" saturation value and then recover to that (desired) level. Under these circumstances, dissolved oxygen concentration and the river ecosystem might be said to "bounce back" (see also Martin and Sunley (2015) for an account of the same in economics). Thus:

> ***Engineering resilience*** is generally understood to be about bounce-back, as gauged by the magnitude of the but transient displacement of the system's behaviour away from equilibrium; and the speed with which normal (equilibrium-proximate) behaviour is recovered – here, the time taken to re-attain saturated dissolved oxygen concentration.

Even a severely stressed, unhealthy river, such as that in a polluted hot-spot during Stage 2 of the city's concise environmental history, could be said to exhibit such engineering resilience. It will return to its ambient, chronically degraded (undesired) status after the acute, transient, additional injury and insult (Beck, 2005). We should expect the nature of the bounce-back and the everyday, high-frequency flutter about equilibrium in these two quite different "stable" regimes (desired and undesired), namely their engineering resilience, to differ markedly, even to identical disturbances and perturbations.

---

[23]Brought to the public's wider attention in Benyus's (1997) book.

Desired behaviour does not have to be technically invariant over time. It may change with the low-frequency variations of the season and the year. And we all certainly expect high engineering resilience in the behaviour of a city infrastructure intended to deliver services 24–7, which is to say the following: to track the called-for daily and weekly oscillations of life as closely as possible; and to restore the normal, expected services just as quickly as possible in the event of any disturbance or interruption. These, we hope, would indeed be small-amplitude, quite transient, incoming disturbances and corresponding deviations from the desired – things happening, therefore, with a speed (frequency) higher than the "24" of the 24–7.

Expressed in scientific terms (those of nonlinear mechanics and control theory), engineering resilience captures the widespread and welcome desirability of the transient excursions in the ever-dynamic behaviour of a system – river ecosystem (natural environment); green and grey infrastructure (built environment); or social governance (human environment) – to remain in a given "basin of attraction", namely one of Karr's stable regimes, or a domain of stable behaviour. The risk with engineering resilience, as systems ecologist C. S. Holling first observed (Holling, 1973, 1978), is that the pursuit of perfection therein may make the system's behaviour brittle and fragile, ever more prone to failure and collapse, quite the opposite of what in everyday language we would understand as resilient. Holling himself cited the example of the optimised and technologically locked-in methods of farming on the north American prairies to illustrate his concern.

Building on the ideas of catastrophe theory developing at the time (the turn of the 1960s/1970s), resilience came to be associated conceptually with the presence of multiple basins of attraction in a system's behaviour and of transition (or transformation) between one and another such basin. While subject to and exhibiting (relatively) high-frequency fluctuations in any one basin, other subtle, "latent", low-frequency, slowly evolving variations in the mechanics of the system's behaviour would cause it (in theory) to "flip" from one to the other "stable" regime. Or, more obvious and palpable, struck by an incoming high-amplitude shock, collapse (change) from a desired to an undesired regime of behaviour would be occasioned.

Regimes, or basins of attraction, and transformations–transitions between them, are at the same time familiar to us from our common experience of the world, yet quite difficult to pin down more formally in terms of the nonlinear dynamics and mathematics of catastrophe theory. The stable regimes of a Stage 2 river in the shadow of a city hot-spot and of a transformed, rehabilitated Stage 3 river will suffice familiarly, if not being entirely satisfactory from the perspective of theory, as exemplars of basins of attraction (with their respective scopes for transformation) from the perspective of theory.[24]

Beyond the facet of engineering resilience, the nub of resilience (like that of sustainability) is remarkably elusive to capture in a one-sentence definition. The so-called Resilience Alliance group of researchers, taking its lead from Holling's seminal work (Holling, 1973), has defined the term resilience as (see, for example, Walker *et al*., 2006):

> the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks.

This conveys some more of what we need to say here of resilience. It begins to help us elucidate the idea of what Holling called *ecological resilience*, as something *not* in the nature of engineering resilience (and much more than it) – a distinction he introduced in his contribution to a 1996 book entitled (significantly for us) *Engineering Within Ecological Constraints* (Schulze, 1996; Holling, 1996). For one thing, by virtue of the anthropocentric origins of the kind of resilience that is *engineered* into the behaviour of a system, engineering resilience is yoked to the human-centric expression of what is desired, and what not. In contrast, left to its own devices, no sense of any desired or undesired regime of behaviour can be assigned to itself by an ecosystem in the natural world. Frustratingly, however, the oft-quoted definition from the Resilience Alliance is still not enough (as the Alliance would have been the first to acknowledge; see Gunderson and Holling (2002) and Walker *et al*. (2006)).

Something further can be teased out by saying that resilience in the behaviour of a system is its ability to cycle endlessly through a number of different basins of attraction. Thus, to engineering resilience and ecological resilience can be added the idea of strategic change and *transformation* (passive, or deliberate and active) as part of what constitutes resilience. This would be something demonstrable, moreover, not only in the behaviour of ecosystems of the natural environment (as Holling showed us; Holling, 1986), but also in the behaviour of the social systems of the human environment, in concert with and through their managing the ecosystems of the natural environment – as brightly illuminated in a seminal paper by anthropologist Michael Thompson (Thompson, 2002) (see also Beck *et al*. (2011) and Thompson and Beck (2014) in respect of cities, their built environments, and their infrastructure). Something of the same, however, has yet to be demonstrated for the case of the built environment and the grey infrastructure of the city, to which we now turn. The science, meanwhile, we acknowledge, must continue to advance the frontiers of our understanding of resilience, in respect

[24]It should be noted, however, that some of the most successful enquiry into the nature of resilience has been conducted on the recovery of polluted, eutrophic lake ecosystems to regimes of behaviour more akin to something considered "natural" (as illustrated in the restoration of Lake Veluwe, The Netherlands; Ibelings *et al*. 2007).

of ecological resilience and transformation, for neither of which is any single-sentence definition offered (see Text Box: The Trouble with “Bounce Back”). They are conspicuous by their absence.

The Trouble with “Bounce Back”

In some technocratic quarters, the yearning for a singular, succinct, and “mechanical” operational definition of sustainability is palpable. The present author (MBB) set out in pursuit of this goal in 2002. Nine years, six re-drafts, and over 160 pages of dense reasoning later, no such definition was to be found (Beck, 2011). The same yearning for an operational definition of resilience is now emerging too. This may be just as troublesome.

The power and influence of Holling’s seminal ideas are evidenced in the establishment of the Stockholm Resilience Centre in 2007 (www.stockholmresilience.org). In Holling’s concept – augmented both by his own subsequent contributions and by many others since (Holling, 1973, 1986, 1996; Peterson *et al*., 1998; Holling *et al*., 2002; Thompson, 2002; Salingaros, 2005; Walker *et al*., 2006; Lietaer *et al*., 2009; Smith and Stirling, 2010; and Martin and Sunley, 2015) – resilience is both bounce-back and, much more so, these things:

- first, and above all, the ability of a system to cycle endlessly through a number of different and ever evolving basins of attraction, each differentiated by possibly quite different ways in which the system bounces back from disturbance;
- where (in social systems) these differentiated ways of coping in the different basins of attraction – of acting in the world – are determined primarily by likewise differentiated sets of beliefs about the way world works and correspondingly differentiated attitudes towards risk (Thompson, 2002; Thompson and Beck, 2014);
- with yet, in all this cycling, the system still having a recognisable structure of cohering components and providing recognisable functions deemed broadly similar, even if degraded *or* markedly enhanced relative to what they were before (substantial) disturbance – enhanced, for example, in the “bounce forward” of an economy moving to a growth trajectory yet higher than would have been possible before disturbance (Martin and Sunley, 2015);
- the capacity also – in systems with capacities for self-observation and self-reflection – for learning and adapting, precisely because of disturbance and disorder, hence anticipating (up to a point) how to cope with future disturbance, which disturbance may (or may not) prompt change from one basin of attraction to another;
- with yet the enduring capacity to be transformed and to effect change and transformation from one basin of attraction to another, even inventing a novel basin of attraction, in ways mostly deemed for the better – continuing to develop, that is, for the greater good;
- and, finally, with this capacity for transformation itself being grounded in the (seeming) redundancies of structure and function in the system and the (in)efficiencies of those functions, all in turn determined by the strengths and weaknesses of the links among the cohering components and the duplication (or not) of these links.

It is not at all hard to sense the frustration of another 9 years passing and another six re-drafts of a lengthy tome coming on. And this is exactly the point: the essence of resilience is no easier to capture than that of sustainability.

One of the great difficulties, therefore, is to make work in the systems of the *built* environment what we can imagine of ecological resilience and transformation in the *natural* and *human* environments (courtesy of Holling and Thompson, respectively; and see, accordingly, Beck and Villarroel Walker (2013b)).

Author Nicholas Taleb, famous for his use of the phrase “black swans” in the worlds of banking and finance, has more recently published his book *Antifragile. Things That Gain From Disorder*. There, based on his experience of London’s Heathrow Airport, he provides us with the most succinct distinction of what we should wish for of engineering resilience *vis-à-vis* ecological resilience (Taleb, 2012; p. 283):

> smooth functioning at regular times [delivered within engineering resilience] … rough functioning at times of stress [bestowed by ecological resilience].

The “rough” functioning here would, we submit, mimic that of an ecosystem. For unlike the archetypal optimised but fragile engineering system, so the argument would run, in which *all* functioning may be altogether lost (as in the closure of Heathrow in the event of perhaps but modest snowfall), some “degraded” level of functioning would be maintained. It would be discernible in the desired service – otherwise not provided – of at least a few flights taking off and landing at the airport. The title of Taleb's book reveals something of how Taleb believes we might attain such a wonderful combination of smooth and rough functioning in the behaviour of a system: by permitting, even seeking, behaviour towards the very edge of stability, at the very rim of a basin of attraction; by observing these perturbations and the resulting excursions to the margins of our discomfort; from which experience crucially to learn, to forearm ourselves and the system for resilience, survival, and transformation in the face of the big shock (the "black swan") when it comes – and it will. Holling (1996) should have great sympathy with this view (see the review of Taleb's book posted at www.cfgnet.org/archives/1329; also Beck and Villarroel Walker, 2013b).

Case Study 5: Urban Flooding – Inviting in Resilience and Learning

Whereas the historical purpose of urban drainage was to remove "unwanted" water from the urban landscape, by speeding it on its way to a distant stretch of downstream river, the task of other facets of conventional flood control infrastructure has been to stop equally "unwanted" water gaining access to the city from a rising tide or a flood wave approaching from rivers upstream in the watershed (worse still, to deal with the combination of the two, from within and without the city).

K-H Liao has embarked on developing a blueprint for a change of paradigm: to transform thinking, away from flood-*resistant* cities, with the increasingly fragile engineering resilience of ever more conventional flood control infrastructure, towards flood-*resilient* cities, exhibiting resilient behaviour more in the ecological sense (Liao, 2012). If realised in practice, this would properly qualify as a quite deliberate "transformation" – no passive matter of just coping, or putting up, with change. It would be a move from one basin of (social) attraction to another. Working with several officers of the Department of Natural Resources and Parks of King County, Washington, USA, Liao has envisaged alternatives for adapting the entire city of Kent (situated in the Lower Green River Valley; Figure 11), to restore some of the watershed's ecosystem services, as once they were, before European settlement (Liao, 2014).

The progressive installation of the grey, built environment of customary flood control infrastructure in Kent affects, and is affected by, flow and sediment changes in the Lower Green River. The unfolding consequences of this causal loop are compromised ecosystem services in the natural environment and, in the human environment, the changing perceptions of citizens of their security and the risks of flooding to which they believe they are exposed. In short, the health of the river's ecosystem is impoverished through, variously, the following (Liao, 2014): reduced habitat availability, specifically low-velocity refugia for juvenile Chinook salmon, i.e. the equivalent of what has been engineered into the Soerendonk wastewater treatment plant; reduced habitat complexity; floodplain disconnection; reduced flow variability, or the "impoverishment" of its frequency spectrum; and the loss of cues for life-cycle behaviour. Ecosystem services have been degraded through changes to all three factors (in our phrasing): of the chemical content, habitat, and spectrum of the system. In particular, the river's self-purification capacity is diminished through the reduction in floodplain wetland areas and the degraded riparian zones. Salmonid populations in this particular watershed, furthermore, have been declining for reasons similar to those of the Vancouver Island populations of Case Study 1 above. Drawing upon the work of Naiman *et al.* (2009), Liao (2014) observes:

> the oligotrophic [river-reservoir] system is no longer subsidized by marine-derived nutrients and organic matter borne by spawning salmonids

where (technically) "oligotrophic" is the opposite for a water body of being eutrophic.

Like the great works of restoration, in ridding rivers of the pollution from cities and industries, Liao envisages an unwinding of the historical loop of accreting (grey) flood control infrastructure and diminishing ecosystem services – accreting and diminishing, that is, over a century and more. The radical alternative of floodplain restoration, hence an "ecologically functioning floodplain and riparian zone", "could bring a host of ecosystem services" (Liao, 2014). Actions would be implemented in the built and natural environments (as indicated in Figure 12). In the human environment, unlearning of a false sense of flood-free security would be needed. It would suitably be provoked by the learning opportunities of non-catastrophic flooding entering the city, with socio-economic life from time to time being jolted (instructively, Taleb-style) out of its narrowed experience of just the 24–7 bandwidth (Liao, 2014; see also Liao, 2012).

Taleb (2012), we presume, would indeed see this as the city becoming less fragile through such disorder, even anti-fragile (see further, again, the review of Taleb's book posted at http://cfgnet.org/archives/1329). We know that ecological and social systems – respectively, the natural and human environments – can exhibit the kind of resilience and transformations we are seeking in restoring ecosystem services for water. What exactly might Taleb's "rough functioning"

Figure 11 Plan View of Urban Area of City of Kent (Lower Green River Valley), Washington, USA, Earmarked for Ecological Restoration in the Desk-top Design Study of **Liao (2014) for a Flood-resilient City**

Area not shaded is where an integrated collection of green-infrastructure interventions might be made (as illustrated in more detail in Figure 12).

amount to, and how could it be engineered into water and wastewater infrastructure, not just for cities, but also for confined animal feeding operations in the non-urban environment? Might it be similar to the clever transposition from "fail-safe" to "safe-fail" infrastructure, as first conceived four decades ago, and bearing the authorship of Holling (Jones *et al*., 1975)? What do "rough functioning" and "safe-fail" mean in terms of the provision of ecosystem services, as opposed to business services? How much better, as we have said, might be the whole of the coupled human–built–natural environment of city–watershed systems, if it could benefit from mutually reinforcing ecological resilience in each of its environments: the human, the natural, *and* the built (Beck and Villarroel Walker, 2013a,b; Thompson and Beck, 2014)?

Our working definitions of ecological health and biological integrity (taken from Karr) are beginning to fail to encompass and contain all that we might wish for of resilience in the provision of ecosystem services for water. Karr's definitions capture something of what is needed in his phrase "capacity for self-repair". Indeed, this has already been appropriated for thinking about the re-engineering of electrical infrastructure, so that it might become "self-healing" (Amin, 2001).

Now we can imagine the even more curious, but "reverse", symbiosis: of the business and technologies of city infrastructure provoking questions to be put to the science of ecosystems and their services. These are questions for the future, however. Yet we stand already on the threshold of change, heralded by the kinds of changes in outlook and *practice* illustrated in the five case studies presented so far. It is time (once more) for something essentially pragmatic, that of how to shape policies and assemble the *economics* of managing ecosystem services for water – time indeed for pragmatism, except for one last brief reference to what might motivate change, in the "big conceptual picture".

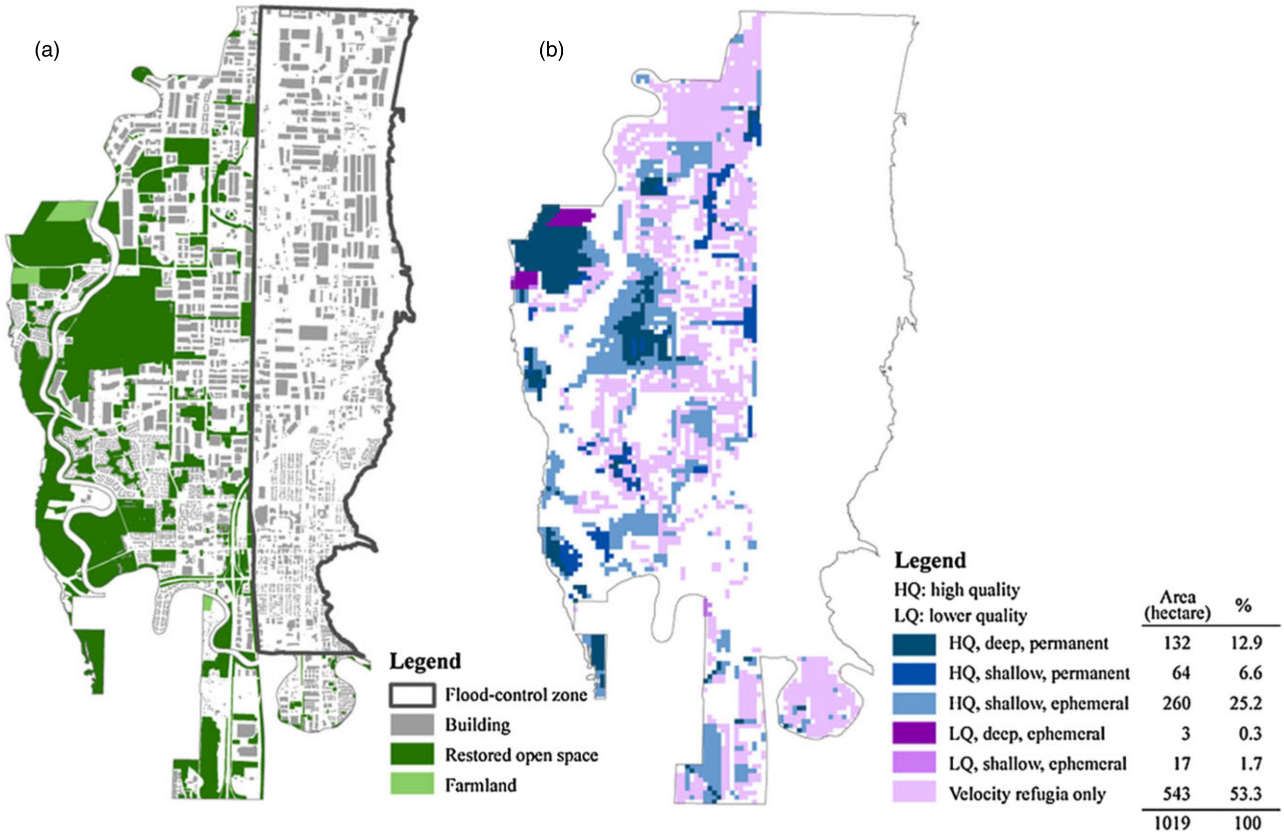

Figure 12 Detailed Plan Views of Green-infrastructure Interventions for Restoring the Ecology and Ecosystem Services of the Lower Green River as it Flows through the City of Kent, Washington, USA

Left panel (a) distinguishes between restored open spaces and buildings and farmlands; right panel (b) distinguishes between six types of refugia for stream fish, such as juvenile Chinook salmon (from Liao, 2014).

4.3 FROM "BAD ACTORS" TO "NET GENERATORS OF ECOSYSTEM GOODS"

Consider the words we have been using hitherto: a "historic righting of wrongs"; "unlearning"; and "bad actors". They convey a sense of looking to the past and, in looking to the future, a moral compass pointing policy instruments towards those enabling our becoming "less bad". Lightening the urban ecological footprint, for example, can only head from its negative imprint towards but zero.

Let us recognise that the world is *far* from everyone enjoying the happy circumstances of a restored, reasonably vibrant environment around them. And for the moment, let us put aside puzzling over the ethics of policies seeking to intervene in the environment, not for mankind's extraction of ecosystem services from it, but for the sake of the environment *itself* – that this generation of oysters in Chesapeake Bay be granted the "right" to expect that its next generation of oysters will fare no less well than it has. Might we not go beyond becoming just "less bad", then, to follow a moral compass of "becoming good"? Might the city not "walk on air" (Beck, 2013), to break therefore through the zero reference-barrier of the urban ecological footprint, to become a "net generator of ecosystem services"?

There are at least three programmes of research pursuing such lines of reasoning:

(1) Jonathan Fink, based at Portland State University, Oregon, but previously with Arizona State University in Phoenix, Arizona, writes of cities as "positive forces for climate repair" (Fink, 2012, 2013);[25]

(2) Herbert Girardet has for some time been conceiving of the "regenerative city" and has now brought this work together in his book *Creating Regenerative Cities* (Girardet, 2015; see also World Future Council (www.worldfuturecouncil.org)); and

[25]Portland is widely celebrated for its thinking, leadership, policies, and actions in respect of cities and the environment, such as its promotion of urban eco-districts (www.ecodistricts.org).

(3) the international network on Cities as Forces for Good in the Environment (www.cfgnet.org; Beck, 2011).

The first of these self-evidently seeks to restore the regulating ecosystem service of climate “stability”. Girardet’s regenerative city “reuses resources and restores degraded ecosystems”. The outcomes of the third programme are exemplified by the prudent dispensation of recovered nutrients for the purposes of enhancing in-stream ecosystem services – just as in the Durham–Vancouver Island case study, along with quite distinct echoes of the Soerendonk and Savannah Process case studies.

Some of this may smack of “mission impossible”.[26] It is time surely, then, to turn to the economics of ecosystem services and their anchoring of our discussion in the pragmatism of how change actually does, or might, come about (as it has in the five preceding case studies).

[26]Not that that is so bad. Sustained bearing down on the “mission impossible” may yield good questions that *can* be answered, but which would never otherwise have come to mind, had the mission impossible not been confronted in the first place.

5 ECONOMIC VALUATION OF ECOSYSTEM SERVICES

Our sixth and final case study bears the hallmarks of both the LID toolkit and (more so) Liao's work for the city of Kent (Case Studies 4 and 5 above). Its significance, however, is the economic message it conveys and the motivation it then provides for generalising from the particulars of practice back to the more conceptual bases of the economic valuation of ecosystem services.

Case Study 6: Some Pragmatic "Green" Economics for Urban Flood Attenuation

The open urban space of Mayesbrook Park in the London Borough of Barking and Dagenham lies some 3km upstream along the Mayes Brook from the tidal section of the River Thames. Its restoration has been hailed as "designed to produce the UK's first climate change adaptation public park" (Everard *et al*., 2011). And it will indeed need to function so: it stands (metaphorically) at the increasingly vulnerable intersection between sea-level rise and the changing patterns of precipitation. In less grand terms, re-engineering of the Park was a deliberate, prototypical exercise in reconstructing a variety of ecosystem services.

More completely (Everard *et al*., 2011):

> The restoration of an urban river within a barren park landscape is also a good example of an approach that combines flood storage, biodiversity enhancement and adaptation to climate change within a city environment.

The intent of replacing aged, grey, hard infrastructure for flood management by softer, green infrastructure is clear (Everard *et al*., 2011):

> The Environment Agency [for England and Wales] owns a number of flood management assets on site (sluices, pumps and so on), many of which are reaching the end of their useful lives. This includes a large flood control sluice gate immediately downstream of the lake inlet channel which is controlled automatically at times when high tides and high flows coincide. Flood control mechanisms include telemetry, a pumping station and related infrastructure, which would cost millions of pounds to replace. This creates a further reason to explore other options for management of the Mayes Brook in the Mayesbrook Park.

More specifically, one item of the restoration work is expressed as (Everard *et al*., 2011):

> excavating a one-hectare floodplain around this new winding channel, creating brook and riparian habitat and improving the resilience of the river to climate change.

Seeking to generate ecosystem services under three of the four Millennium Ecosystem Assessment categories (Section 2) was the express motivation of this project. From the perspective of the Environment Agency for England and Wales (Everard *et al*., 2011):

> The urban setting means that improvements will contribute to '*regulatory services*' (regulation of air and water quality, microclimate and flood risk) affecting the local community. Enhanced recreation and tourism (*cultural services*) are also likely to bring benefits, since many people in the borough lack gardens or ready access to other green spaces. [emphasis added]
>
> The benefits of '*supporting services*', which are hard to quantify but important in maintaining ecosystem functions, are significant in terms of nutrient cycling and providing habitats for wildlife. This latter ensures there are animals and plants capable of colonising the wider landscape as the habitat improves. These improved habitats also serve as 'stepping stones' for wildlife to move across and between limited and fragmented suitable habitat in the urban landscape. [emphasis added]

Category by category, the following were the hard economic values placed on the Park's various ecosystem services (to be derived on an annual basis):

Cultural – US$1.3 million (£820,000)
Supporting – US$49,000 (£31,000)

Regulating – US$45,000 (£28,000)
Provisioning – US$0.

Re-introducing services under this last category was judged to be beyond a system in such a highly urbanised context, although the reuse on site of tree and other park trimmings as biomass fuel or mulch would be practised (Everard *et al.*, 2011).

5.1 SERVICE CATEGORY BY SERVICE CATEGORY

Without entering into the detailed calculus of exactly how the foregoing valuations were obtained by Everard *et al.* (2011), this Mayesbrook Park case study affords us a convenient vehicle for organising some of the many methods for valuing ecosystem services, as follows:[27]

Provisioning. This, we suggest, strikes us as the easiest of categories of services to evaluate, or monetise. The methods to be used would come under the rubric of "revealed preferences", such as, for example:

(1) "market methods", in which the sale of timber from a forest, or dockside sales of oysters harvested from Chesapeake Bay, will be tangible enough; or
(2) "production approaches", as in the monetary value of increased yields of shrimp deriving from increasing the area of a wetland (Liu *et al.*, 2010).

Regulating. Mayesbrook Park, with its reference to climate change and its express design for flood attenuation, exemplifies a "replacement cost" approach to valuing the ecosystem services of regulation (replacement cost is again a revealed preference method). In this, nature – in the forms of meandering streams, the floodplain, riparian habitat, and reedbed filtration – is to provide the services once provided by the alternative and relatively *easy-to-cost* built, grey infrastructure. It has been estimated that if Melbourne, Australia, did not have the good geographical fortune of immediate access to the (cleansing) ecosystem services of Port Phillip Bay, it would have to pay AUS$6 billion (US$4.5 billion) for the replacement infrastructure.[28] Likewise, as in the Soerendonk case study, the wetland providing the ecosystem services of the alternative easy-to-cost tertiary (polishing) wastewater treatment plant is the archetype of how regulating ecosystem services may be valued. Another revealed preference approach, of "avoidance cost", may also serve the present purpose of giving tangible value to a regulating ecosystem service: clean, potable water delivered by a healthy aquatic ecosystem, for example, reduces costly incidents of diarrhoea (Liu *et al.*, 2010).

Cultural. We ascribe a "benefits transfer" to valuing this category of service. It is classified as neither a revealed nor "stated preference" method.[29] Thus, given a prospective project – let us say a barren open space in the city of Kent, Washington – the value of cultural benefits to accrue from renovating that space would be estimated from a statistical (regression-like) relationship for observed cultural services deriving from the existing (now renovated) Mayesbrook Park in London. The "transfer" is that of the extrapolation from one *past* project in one location to a *future* project in some other location.[30] To one side of this approach might lie that of the revealed preference approach using "hedonic methods". It might have been, for example, that the prices of houses arrayed around the perimeter of the Mayesbrook Park rose faster than those of houses elsewhere in Barking, as a direct consequence of the green infrastructure of the Park simply being more attractive than the previous grey infrastructure it replaced. The property price differential would reveal the ecosystem service valuation.

Supporting. Crop pollination ought to be capable of valuation by some of the foregoing methods of revealed preferences. There are commercial pollinating enterprises for whom farmers pay a clear unambiguous market price for the services of the bee colonies of these enterprises. In contrast, the supporting service of the biogeochemistry of nutrient cycles lies beneath, and obscured by, the obvious and immediate headline values of the salmon fishing industry, to which these cycles are critical (as we have seen) in the

[27]In general, we follow the terms and classification of ecosystem services valuation set out in Liu *et al.* (2010).
[28]Personal communication: Francis Pamminger, Yarra Valley Water (2015).
[29]The distinction between revealed and stated preferences is this. The former is found in the "real world", whereas the latter is estimated in a "hypothetical or laboratory world". These are our phrases. Nevertheless, they are based on the definitions of Liu *et al.* (2010).
[30]This places a burden on getting the original statistical relationship reasonably "right" for the past case study and attaching suitable confidence bounds to the projected cultural benefits to flow from the future project.

Pacific north-west of North America (Compton *et al.*, 2006). If the biogeochemistry is not to be valued through the surrogate of the value of the associated fishing industry, it might be subjected to analysis through another revealed preference approach, namely that of "travel cost". Think of the value placed on a locale, such as a national park, as revealed through the travelling, accommodation, sport fishing licences, and subsistence costs, all of which add up to what we call eco-tourism. It may be these tangible (travel) costs that contribute to the US$49,000 (£31,000) annual value of the supporting ecosystem services for Mayesbrook Park.

There are non-monetising valuations of ecosystem services, of course, and Liu *et al.* (2010) name several of them. Such valuations, however, do not seem to be forces of economic nature. Francis Pamminger, of Yarra Valley Water, Australia, has paraphrased one of Churchill's many memorable quotes on the practice of democracy, to sum up (gruffly speaking!) the predominant urge to "monetise" Nature (as opposed to "democratise" nations):

> Money … is the worst way of valuing nature … except for all those other failed ways we've already tried.

5.2 VALUE FLOWS: NATURE TO MAN; MAN-TO-MAN TRANSACTIONS; AND NATURE TO NATURE

A cursory review of all the illustrative ecosystem services sprinkled about the six case studies of this Paper reveals that any given service has been portrayed as something valued by Man as a result of his interaction with Nature. Value flows from Nature to Man; that value is monetised by the ecosystem service valuation, i.e. quantified according to the various mechanisms set out in the foregoing discussion; and enumerated thus, these value flows from Nature to Man are to be enfolded into Man-to-Man transactions, namely society's monetised, economic exchanges.

Man-to-Man Transactions

It may occur, of course, that what one Man values from his interaction with Nature another will value not at all.[31] Or, more to the hard-nosed economic point, one Man's flow of value from Nature may be cutting off the flow of value from that same piece of Nature to another Man. Markets for buying and selling ecosystem services may be established, by government stipulation or on a voluntary (or some other) basis.

Payment for ecosystem services in the buyer-seller (Man-to-Man) exchange has been defined as (Liu *et al.* (2010) quoting Engel *et al.* (2008)):

> a voluntary transaction where a well-defined environmental service is being bought by a service buyer from a service provider if and only if the service provider secures service provision

The oft-cited case study of such a transaction is that of the one agent, Vittel (Nestlé Waters), paying for the ecosystem services of land cover to be progressively reinstated by the second agent, a farmer in north-eastern France (Perrot-Maître, 2006). The quality of the (downstream) groundwater of value to Vittel was being compromised by the (upstream) agricultural production of value to the farmer. The ecosystem service was that of the water-cleansing capabilities of a certain form of landscape cover, which was otherwise being successively degraded by the steadily intensifying agricultural practices. In fact, the mineral water bottler and supplier (Vittel) engaged in our notional Man-to-Man transactions with several farmers, with the payment customised for each individual farmer. The arrangement was voluntary.

The International Institute for Environment and Development – the institutional home of the Perrot-Maître study – has a central interest in the study and promotion of payment for ecosystem services. It argues that, in general, downstream agents in a watershed should pay upstream agents for the (downstream-flowing) ecosystem services they preserve and nurture (Bond and Mayers, 2010). In the Sarapiqui watershed in Costa Rica, for example, the Man-to-Man transaction is as follows: a hydropower company pays US$48 per hectare annually to upstream landowners for forest management and restoration (Krchnak *et al.*, 2011). The ecosystem service at stake is no increase in the flow of suspended sediment into the company's reservoir. Valuation of the service is calibrated to the avoidance cost of (otherwise) dredging the reservoir to

[31]Thompson's (2002) article on "Man and Nature as a Complex but Single System" is especially enlightening in this respect.

remove the excessive silt deposits, along with the operational benefits (to the company) of a "more reliable streamflow" (Krchnak *et al*., 2011).

Not all such Man-to-Man transactions require payment; and the precise amount of the payment does not have to be set by any of the methods of ecosystem services valuation (ESV). Observing on the then fast-emerging concept of payment for ecosystem services, Liu *et al*. (2010) concluded that, "ESV results have rarely been applied in setting payment amounts". This may have been somewhat premature in the specific case of payment for ecosystem services, but it is in line with their conclusions on the entire field of ESV (Liu *et al*., 2010):

> [T]he contribution of ESV to ecosystem management has not been as significant as hoped nor as clearly defined

> ESV research has to become more problem-driven rather than tool-driven.

Value Flows: Nature to Nature

Only once have we questioned the way in which the word "service" inclines our thinking towards flows of value from Nature to Man. And, with reference earlier to the oysters of Chesapeake Bay (for specificity of argument), we put aside there such puzzling over the ethics of policies seeking to intervene in the environment. Now, with the assistance of Figure 13, we must resolve some of this "puzzling".

We can conceive of value flowing from Nature to Nature: of value flowing to today's (m) generation of oysters through their ecosystem enabling tomorrow's ($m + 1$) generation of oysters having their offspring (generation $m + 2$) come into being and prosperity, and so on (Figure 13d).[32] Put notional Man into the picture and we can conceive value flowing to Man from the concept – and actuality – of this Nature-to-Nature flow of value.

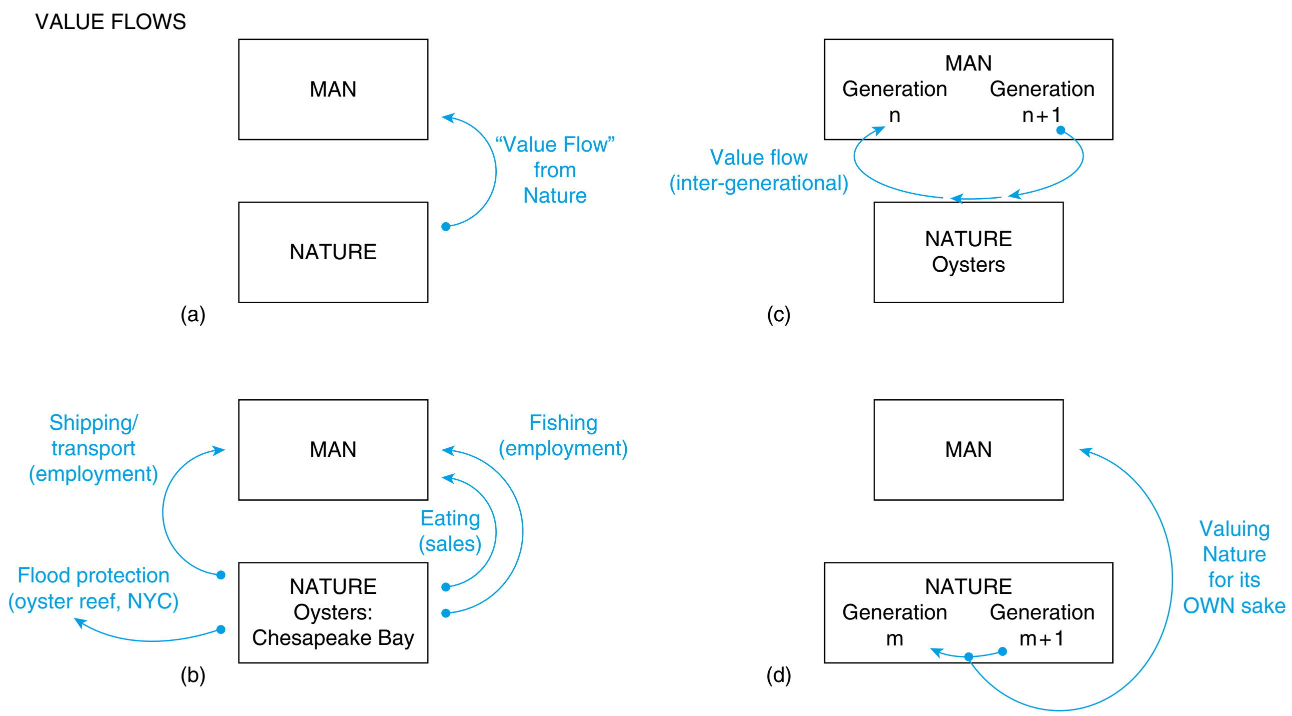

Figure 13 How to Conceive of the Logic of Value Flows between Nature and Man

In panel (a), think of Man and Nature in the two blocks of the diagram and then depict the flow of value – from Nature to Man – as the blue arrow: its arrowhead points to the entity (Man, in this case) that derives the value; and its base denotes the entity (Nature, in this case) that is the origin, or source, of the value flowing along it. Using the logic of this principle, therefore, a specific illustration of the various streams of value – tangible, conventional, economic, monetary value, in fact – flowing from the presence of oysters in Chesapeake Bay on the Atlantic coast of the USA, is given in panel (b). This is a specific instance of a Nature-to-Man flow of value. In panel (c), we conceive of an inter-generational flow of value: to our (n) generation from knowing that the next ($n + 1$) generation – our children – will be able to value the presence of oysters in the Bay (just as we ourselves do today). This Man-to-Man flow of value lies at one remove, as it were, from Nature. Panel (d) introduces the additional device of conceiving of how Man derives value from supposing that Nature derives value from Nature in the current (m) generation of oysters in Chesapeake Bay "knowing" that their offspring, generation ($m + 1$) of oysters, will be able to prosper in the Bay. This, at base, is a Nature-to-Nature flow of value, from which – at one remove – Man derives value.

Contrived though this example might be, it establishes the point: value flows to Man – at one remove – from witnessing or believing value to be flowing from Nature to Nature. One suspects, however, this would be a very difficult, once-removed flow of value from Nature to Man to monetise.

5.3 THE ONCE- AND TWICE-REMOVED HANDS OF INVESTORS AND CONSUMERS

There can be Man-to-Man transactions over the flows of value from Nature to Man, namely ecosystem services. Life is yet more complicated, however, and we are obliged to think of Man-to-Man transactions, the subject of which is other Man-to-Man transactions, in particular those regarding (at bottom) Nature-to-Man flows of value, if not Nature-to-Nature value flows. In short, we must bring to mind transactions once-removed, or twice-removed (if not more so), from the focus of our concern, namely the ecosystem services for water.

Sustainable Asset Management, now Sustainable Asset Management (SAM) Group (www.sustainabilityhq.com), was founded in 1995. It was the first to appeal to the instincts of high net-worth individuals and institutional investors, to direct their funds preferentially into business leaders (as opposed to laggards), in respect of their appetite for "doing well by the environment". The Man-to-Man transaction is all about the flow of value from an enterprise that values the flow of value from Nature to Man in its business.

Trucost, founded in 2002 (www.trucost.com), works with the United Nations Environment Programme's Finance Initiative and the Principles of Responsible Investment (PRI) Association to have the formation (and destruction) of natural capital and environmental profit-loss accounts incorporated into company annual reports (Trucost, 2013). Here again, the prospect is of Man-to-Man transactions, for example purchasing stock in a company, as a function (in part) of how that company is performing in valuing Nature-to-Man value flows. The thrust of this alternative argument – in contrast to that of SAM (which accentuates the positive in seeking out "leaders") – is directed at "targeting the laggards" (PRI Association, 2010). Both, rather like the archetypal, military "pincer movement" (or the "carrot and stick"), have considerable merit and demonstrated success (in SAM's case).

The Carbon Tracker Initiative (CTI; www.carbontracker.org) has enjoyed an uncommonly rapid rise to prominence. The popular headline concept of a "Carbon Bubble" has arisen. Here, governments may well eventually take action to bound rises in average, global temperatures to no more than 2 degrees Celsius. If such actions are taken, they imply that only some 20–40% of the world's currently proven reserves of fossil fuels can be burned; 60–80% of the reserves of fossil fuels currently held by businesses in the fossil-fuel prospecting and extraction sector are, in effect, worth $0.0 (or so the argument runs). What institutional investors can do about this – no matter their status as once- or more-removed from the flow of value from Nature to Man – is the punch line of CTI's *Unburnable Carbon 2013: Wasted Capital and Stranded Assets* (CTI, 2013). If investors were to divest *en masse* (a Man-to-Man transaction), stock exchanges around the world could suffer significant falls in their indices, depending upon their exposure to the volumes of fossil-fuel sector stocks quoted on those exchanges. The "carbon bubble", therefore, is already with us: in the latent run-up in stock prices of fossil-fuel companies. There is some anticipation, therefore, of the bursting of this bubble.

What we are discerning is not so much hard, pragmatic decisions being determined by some monetising of the value of natural-capital assets and the profit streams of their ecosystem services, but rather decisions guided by what pension funds, for example, judge will – or should – eventually generate the incomes of those of us fortunate enough to have a pension to cover our retirement. "Universal owners", namely "large, diversified institutional investors such as pension funds, mutual funds and insurance companies" "that have a financial interest in the wellbeing of the economy as a whole", have a special role to play, argues the Principles of Responsible Investment Association (PRI Association, 2010).

Taking a similarly long view, insurance companies have been factoring climate change into the formation of everyday insurance policies for two decades or so. Significantly, in a recent "Thought Leadership" piece posted under the ClimateWise 2012 Discussion Group of the Cambridge Sustainability Network – and entitled "The Value of Ecosystem Resilience to Insurers" – Ian Kirk, Chief Executive of the South African based Santam Group, has made the following argument (http://www.climatewise.org.uk/issue-two/; last accessed, 11 November, 2012):

[32]Like sustainability, value flows to today's (m) generation from "knowing" that the next ($m + 1$) generation will fare at least as well as it has. In the context of the ecosystems of Nature, continuation of the very existence of species (other than Man) is being valued *per se* – "existence value", in other words.

We produced 3 key findings with significant implications for the insurance industry:

1. Climate changes are driving risks higher
2. Changes to ecological buffering capacity [are] as important as climate change
3. Real risk on the ground is the end result of many factors in a dynamic complex system

These findings point out that human-induced impact on the ability of a given ecosystem to absorb weather events (i.e. its ecological buffering capacity) [has] an equal or greater impact on risk, as compared to future climate change predictions.

On a macro level, this project allowed us at Santam to better understand the system dynamics between risk and resilience in a socio-ecological landscape and the role of the insurance industry in shaping societal behaviour. On a micro level, it will eventually impact certain decisions that we make in terms of underwriting and risk exposure.

Embedded now in the once-removed Man-to-Man transaction of buying an insurance policy is a valuing (by the insurance company) of the regulating ecosystem service of flood attenuation nurtured by attention to landscape cover and riparian habitat (the "ecological buffering capacity" of a watershed).

6 CONCLUSIONS

Ecosystem services are those “entities” generated on a continuing, everyday basis by the natural capital of the world about us and expressly valued in some way by humankind. They are services that nourish the body, the mind, and the spirit. They are services of renewal, both material and metaphorical. As we expand and change the science base of our understanding of them, so we may green and clean the technologies and forms of the built environment and urban infrastructure that mediate the interaction between society (in the city) and nature. We may indeed conceive of bringing elements of the green natural environment back into the functioning of the once grey core of the built environment, which itself sustains the human environment and economic life of the city.

This Paper has obliged its reader to glide back and forth, ever just below the surface of all manner of specific, but superficially quite different types of system, and hence to appreciate the undergirding of the generic *systems perspective*, which reveals the common, shared essentials of their behaviour. Words and phrases rise and fall in their popularity in a language, especially in respect of political and policy discourse and (doubtless) Ministerial Declarations: witness “ring-fencing”, “cherry-picking”, “going forward”, and “evidence-based”, or – much more to the point in respect of the systems perspective – “resilience” and “ecosystem”. This last pair, joined together as “ecological resilience”, sums up what we shall need to understand much better and in much greater depth in the future (going forward, that is):

- in developing a different style of enterprise risk management, for the small cleantech entrepreneurial startup company as much as for a new product or service from a large corporation;
- in orchestrating the governance and behaviour of the innovation ecosystems in which those startups and corporations all participate – along with government agencies, venture capitalists, asset managers, philanthropic foundations, community activists, and other institutions – with the common aim of sparking the breakout of a sustainability transition; and on up
- to assessing the hard empirical evidence for an ecosystems services sector warranting its own free-standing status in those city-regional economies, to which the innovation ecosystems of cleantech and greentech entrepreneurship – and the ecosystems of the natural and (green-grey) built environments – all contribute.

Assessments and recommendations to these effects can be found in Villarroel Walker and Beck (2014) (see also www.cfgnet.org/archives/1528; Thompson and Beck (2014); Beck (2015)).

REFERENCES

Amin, M (2001), "Toward Self-Healing Energy Infrastructure Systems", *IEEE Computer Applications in Power*, (January), 20–28.

Arthington, A H, Bunn, S E, Poff, N L, and Naiman, R J (2006), "The Challenge of Providing Environmental Flow Rules to Sustain River Ecosystems", *Ecological Applications*, **16**(4), 1311–1318.

Bauer, S B, and Ralph, S C (1999), "Aquatic Habitat Indicators and Their Application to Water Quality Objectives Within the Clean Water Act", *Report* EPA-910-R-99-014, US Environmental Protection Agency, Region 10, Seattle, Washington.

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

Beck, M B (2005), "Vulnerability of Water Quality in Intensively Developing Watersheds", *Environmental Modelling and Software*, **20**(4), 381–400.

Beck, M B (2011), "*Cities as Forces for Good in the Environment: Sustainability in the Water Sector*", Warnell School of Forestry and Natural Resources, University of Georgia, Athens, Georgia, (ISBN: 978-1-61584-248-4), xx + 165pp (online as http://cfgnet.org/archives/587).

Beck, M B (2013), "Sustainability and Smartness: A Tale of Two Slogans", *Sustainability of Water Quality & Ecology*, **1–2**, 86–89.

Beck, M B (2015), "Cleantech – All a Matter of People-Risk-Culture", *Water21* (in preparation; from a Report on the Water & Cleantech Forum, IWA World Water Congress, Lisbon, 2014).

Beck, M B, and Villarroel Walker, R (2013a), "On Water Security, Sustainability, and the Water-food-energy-climate Nexus", *Frontiers of Environmental Science & Engineering*, **7**(5), 626–639.

Beck, M B, and Villarroel Walker, R (2013b), "Nexus Security: Governance, Innovation and the Resilient City", *Frontiers of Environmental Science & Engineering*, **7**(5), 640–657.

Beck, M B, Thompson, M, Ney, S, Gyawali, D, and Jeffrey, P (2011), "On Governance for Re-engineering City Infrastructure", *Proceedings of the Institution of Civil Engineers, Engineering Sustainability*, **164**(ES2), 129–142.

Beck, M B, Davis, C, Kenway, S J, Porro, J, Matsui, S, Crawford, G, Hilger, H, and Zhang, H (2012), "Sustainability in the Water Sector", in *Global Trends in Water Science, Research and Management*, (H Li, ed), IWA Publishing, London, 79–82.

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

Bond, I, and Mayers, J (2010), "Fair Deals for Watershed Services: Lessons From a Multi-country Action-learning Project", *Natural Resource Issues*, **13**, International Institute for Environment and Development, London.

Carpenter, S R, Mooney, H A, Agard, J, Capistrano, D, DeFries, R S, Diaz, S, Dietz, T, Duraiappah, A K, Oteng-Yeboah, A, Miguel Pereira, H, Perrings, C, Reid, W V, Saruhkan, J, Scholes, R J, and Whyte, A (2009), "Science for Managing Ecosystem Services: Beyond the Millennium Ecosystem Assessment", *Proceedings National Academy of Sciences*, **106**(5), 3 February, 1305–1312.

Compton, J E, Andersen, C P, Phillips, D L, Brooks, J R, Johnson, M G, Church, M R, Hogsett, W E, Cairns, M A, Rygiewicz, P T, McComb, B C, and Shaff, C D (2006), "Ecological and Water Quality Consequences of Nutrient Addition for Salmon Restoration in the Pacific Northwest", *Frontiers in Ecology and Environment*, **4**(1), 18–26.

Cordell, D (2013), "Peak Phosphorus and the Role of P Recovery in Achieving Food Security", in *Source Separation and Decentralization for Wastewater Management* (T A Larsen, K M Udert, and J Lienert, eds), IWA Publishing, London, 29–44.

Costanza, R, d'Arge, R, de Groot, R, Farber, S, Grasso, M, Hannon, B, Limburg, K, Naeem, S, O'Neill, R V, Paruelo, J, Raskin, R G, Sutton, P, and Van Den Belt, M (1997), "The Value of the World's Ecosystem Services and Natural Capital", *Nature*, **387**, 253–260.

CTI (2013), "Unburnable Carbon 2013: Wasted Capital and Stranded Assets", Carbon Tracker Intiative (CTI) and The Grantham Research Institute, London School of Economics, London.

Dagerskog, L, Coulibaly, C, and Ouandaoga, I (2010), "The Emerging Market of Treated Human Excreta in Ouagadougou", *Urban Agriculture Magazine*, **23**, 45–48 (April).

Dietz, M E (2007), "Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions", *Water, Air, and Soil Pollution*, **186**(1–4), 351–363.

Ehrlich, P, and Ehrlich, A (1981), "*Extinction: The Causes and Consequences of the Disappearance of Species*", Random House, New York.

Engel, S, Pagiola, S, and Wunder, S (2008), "Designing Payments for Environmental Services in Theory and Practice: An Overview of the Issues", *Ecological Economics*, **65**, 663–674.

Erisman, J W, and Larsen, T A (2013), “Nitrogen Economy in the 21st Century”, in *Source Separation and Decentralization for Wastewater Management* (T A Larsen, K M Udert, and J Lienert, eds), IWA Publishing, London, 45–58.

Everard, M, and Moggridge, H (2012), “Rediscovering the Value of Urban Rivers”, *Urban Ecosystems*, **15**(2), 293–314.

Everard, M, Shuker, L, and Gurnell, A (2011), “The Mayes Brook Restoration in Mayesbrook Park, East London: An Ecosystem Services Assessment”, *Report*, Environment Agency, Bristol, UK.

Fink, J H (2012), “Cities as Geoengineering Building Blocks”, in *Earth Systems Engineering 2012: A Technical Symposium on Systems Engineering for Sustainable Adaptation to Global Change*, (R J Dawson, C L Walsh, and C G Kilsby, eds), Centre for Earth Systems Engineering Research, Newcastle University, UK, 59–64.

Fink, J (2013), “Geoengineering Cities to Stabilize Climate”, *Proceedings of the Institution of Civil Engineers, Engineering Sustainability*, **166**(5), 242–248.

Fletcher, T D, and Walsh, C J (2007), “Formulation and Assessment of an Allotment-scale Flow Objective for Protecting Waterways”, *Technical Report*, Benchmark Environmental Consulting, Melbourne, Australia.

Force, J (2011), “The Ultimate Recycling”, *Treatment Plant Operator*, 12–17, (September).

Geels, F (2005), “Co-evolution of Technology and Society: The Transition in Water Supply and Personal Hygiene in The Netherlands (1850–1930) – A Case Study in Multi-level Perspective”, *Technology in Society*, **27**(3), 363–397.

Geels, F (2006), “The Hygienic Transition from Cesspools to Sewer Systems (1840–1930): The Dynamics of Regime Transformation”, *Research Policy*, **35**(7), 1069–1082.

Girardet, H (2015), “*Creating Regenerative Cities*”, Routledge, London.

Graham, D W, and Smith, V H (2004), “Designed Ecosystem Services: Application of Ecological Principles in Wastewater Treatment Engineering”, *Frontiers in Ecology and Environment*, **2**(4), 199–206.

Gunderson, L H and Holling, C S (eds) (2002), “*Panarchy: Understanding Transformations in Human and Natural Systems*”, Island, Washington, DC.

Harrington, E (2012), “Building a Coastal Wetland in the Heart of a City”, *Nature*, **486**, 189.

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

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

Holling, C S (1973), “Resilience and Stability of Ecological Systems”, *Annual Reviews of Ecological Systems*, **4**, 1–23.

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

Holling, C S (1986), “The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change”, in *Sustainable Development of the Biosphere*, (W C Clark and R E Munn, eds), Cambridge University Press, Cambridge, 292–317.

Holling, C S (1996), “Engineering Resilience Versus Ecological Resilience”, in *Engineering Within Ecological Constraints*, (P Schulze, ed), National Academy Press, Washington DC, 31–44.

Holling, C S, Gunderson, L H, and Peterson, G D (2002), “Sustainability and Panarchies”, in *Panarchy: Understanding Transformations in Human and Natural Systems*, (L H Gunderson and C S Holling, eds), Island, Washington, DC.

Ibelings, B W, Portielje, R, Lammens, E H R R, Noordhuis, R, van den Berg, M S, Joosse, W, and Meijer, M L (2007), “Resilience of Alternative Stable States During the Recovery of Shallow Lakes from Eutrophication: Lake Veluwe as a Case Study”, *Ecosystems*, **10**, 4–16.

James, A, (1978), “An Ecological Model of Percolating Filters”, in *Mathematical Models in Water Pollution Control* (A James, ed), Wiley, London, 303–318.

Jones, D D, Holling, C S, and Peterman, R (1975), “Fail-safe vs. Safe-fail Catastrophes”, *Working Paper*, WP-75-093, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Karr, J R (1991), “Biological Integrity: A Long-neglected Aspect of Water Resource Management”, *Ecological Applications*, **1**(1), 66–84.

Karr, J R, and Dudley, D R (1981), “Ecological Perspective on Water Quality Goals”, *Environmental Management*, **5**, 55–68.

Karr, J R, Fausch, K D, Angermaier, P L, Yant, P R, and Schlosser, I J (1986), “Assessing Biological Integrity in Running Waters: A Method and its Rationale”, *Special Publication* **5**, Illinois Natural History Survey, Champagne, Illinois.

Krchnak, K M, Smith, D M, and Deutz, A (2011), “Putting Nature in the Nexus: Investing in Natural Infrastructure to Advance Water-Energy-Food Security”, *Background Paper*, Bonn2011 Conference on “The Water, Energy and Food Security Nexus – Solutions for the Green Economy”.

Larsen, T A, Udert, K M, and Lienert, J (eds) (2013), “*Source Separation and Decentralization for Wastewater Management*”, IWA Publishing, London.

Lietaer, B, Ulanowicz, R, and Goerner, S (2009), “Options for Managing a Systemic Bank Crisis”, *S.A.P.I.E.N.S.* [Online], 2.1, Online since 6 April 2009. Available from: http://sapiens.revues.org/747.

Liao, K H (2012), “A Theory on Urban Resilience to Floods: A Basis for Alternative Planning Practices”, *Ecology & Society*, **17**(4), 48 [online]. Available from: www.ecologyandsociety.org/vol17/iss4/art48.

Liao, K H (2014), “From Flood Control to Flood Adaptation: A Case Study of the Lower Green River Valley and the City of Kent in King County, Washington”, *Natural Hazards*, **71**, 723–750.

Liu, S, Costanza, R, Farber, S, and Troy, A (2010), “Valuing Ecosystem Services. Theory, Practice, and the Need for a Transdisciplinary Synthesis”, *Annals of the New York Academy of Sciences*, **1185**, 54–78.

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

Martin, R, and Sunley, P (2015), “On the Notion of Regional Economic Resilience: Conceptualization and Explanation”, *J Economic Geography*, **15**(1), 1–42.

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

Meagher, R B (2000), “Phytoremediation of Toxic Elemental and Organic Pollutants”, *Current Opinion in Plant Biology*, **3**(2), 153–162.

Naiman, R J, Helfield, J M, Bartz, K K, Drake, D C, and Honea, J M (2009), “Pacific Salmon, Marine-derived Nutrients and the Characteristics of Aquatic and Riparian Ecosystems”, in *Challenges for Diadromous Fishes in a Dynamic Global Environment* (A J Haro, K L Smith, T A Rulifson, C M Moffitt, R J Klauda, M J Dadswell, R A Cunjak, J E Cooper, K L Beal, and T S Avery (eds)), 69, Proceedings Symposium, American Fisheries Society, Bethesda, Maryland, 395–425.

Pellett, K (2010), “Salmon River Watershed Enrichment for Fish Habitat Restoration”, *Report* (Project # 09.CBR.03), British Columbia Conservation Foundation, Nanaimo, British Columbia, (March).

Perrot-Maître, D (2006), “The Vittel Payments for Ecosystem Services: The “Perfect” PES Case?”, *Report*, International Institute for Environment and Development, London.

Peterson, G, Allen, C R, and Holling, C S (1998), “Ecological Resilience, Biodiversity, and Scale”, *Ecosystems*, **1**, 6–18.

PRI Association (2010), “*Universal Ownership. Why Environmental Externalities Matter to Institutional Investors*”, PRI Association and UNEP Finance Initiative, (October).

Richter, B D (2010), “Re-thinking Environmental Flows: From Allocations and Reserves to Sustainability Boundaries”, *River Research & Applications*, **26**(8), 1052–1063 [DOI: 10.1002/rra.1320].

Richter, B D, Warner, A T, Meyer, J L, and Lutz, K (2006), “A Collaborative and Adaptive Process for Developing Environmental Flow Recommendations”, *River Research and Applications*, **22**, 297–318.

Salingaros, N A (2005), “*Principles of Urban Structure*”, Techne Press, Amsterdam.

Schulze, P (ed) (1996), “*Engineering Within Ecological Constraints*”, National Academy Press, Washington, DC.

Smith, A, and Stirling, A (2010), “The Politics of Socio-ecological Resilience and Sustainable Socio-technical Transitions”, *Ecology & Society*, **15**(1), 11 [online]. Available from: www.ecologyandsociety.org/vol15/iss1/art11.

Streeter, H W, and Phelps, E B (1925), “A Study of the Pollution and Natural Purification of the Ohio River. III Factors Concerned in the Phenomena of Oxidation and Reaeration”, *Public Health Bulletin* **146**, Public Health Service, US Department of Health, Education and Welfare, Washington, DC (reprinted 1958).

Taleb, N N (2012), “*Antifragile. Things That Gain From Disorder*”, Random House, New York.

Tambo, N (2004), “Urban Metabolic System of Water for the 21st Century”, *Water Supply*, **4**(1), 1–5.

Thompson, M (2002), “Man and Nature as a Single but Complex System”, in *Encyclopedia of Global Environmental Change*, 5 (P Timmerman, ed), Wiley, Chichester, 384–393.

Thompson, B H (2011), "Background and History: Ecosystem Services", *Seminar* **1**, Ecosystem Services Seminar Series, Gordon and Betty Moore Foundation, Palo Alto, California (available from http://www.moore.org/ecosystemservicesseminar.html).

Thompson, M, and Beck, M B (2014), "Coping with Change: Urban Resilience, Sustainability, Adaptability and Path Dependence", *Working Paper* 13, Foresight Future of Cities, UK Government Office for Science (GOS), December, p 45.

Thompson, M, and Beck, M B (2015), "Not So Much the Water as What's In It. Engineering Anthropology for Beginners", in *Purity and Pollution in the 21st Century*, (D Weiss, S Schnall, and R Duschinky, eds), (submitted).

Trucost (2013), "*Natural Capital at Risk: The Top 100 Externalities to Business*", Trucost, London, (April).

Villarroel Walker, R, and Beck, M B (2014), "Nutrient Recovery. Nexus Innovation Impact Analysis", *Insight*, **1**, BeCleantech Initiative, Sustainability Specialist Group, International Water Association, www.becleantech.org, August, (2014), p 30 (see also www.cfgnet.org/archives/1528).

Villarroel Walker, R, Beck, M B, Hall, J W, Dawson, R J, and Heidrich, O (2014), "The Energy-water-food Nexus: Strategic Analysis of Technologies for Transforming The Urban Metabolism", *J Environmental Management*, **141**, 104–115.

Walker, B H, Gunderson, L, Kinzig, A, Folke, C, Carpenter, S R, and Schultz, L (2006), "A Handful of Heuristics and Some Propositions for Understanding Resilience in Socio-ecological Systems", *Ecology & Society*, **11**(1), 13 [online]. Available from: www.ecologyandsociety.org/vol11/iss1/art13.

WCED (1987), "*Our Common Future*", World Commission on Environment and Development, Oxford University Press, Oxford.

Wild, T C, Bernet, J F, Westling, E L, and Lerner, D N (2011), "Deculverting: Reviewing the Evidence on "Daylighting" and Restoration of Culverted Rivers", *Water and Environment*, **25**(3), 412–421.

Wong, T, and Brown, R (2008), "Transitioning to Water Sensitive Cities: Ensuring Resilience through a New Hydro-social Contract", *Paper*, presented at 11th International Conference on Urban Drainage, Edinburgh, UK.

Zalewski, M (1999), "Minimizing the Risk and Amplifying the Opportunities for Restoration of Shallow Reservoirs", *Hydrobiologia*, **395/396**, 107–114.

the international water association

IWA Global Operations

address Anna van Buerenplein 48,
11th Floor
2595 DA The Hague
The Netherlands
phone + 31 703 150 792
email water@IWAhq.org

inspiring change

www.iwa-network.org