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RESEARCH ARTICLE

Nexus security: governance, innovation and the resilient city

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Abstract Nexus security is a compound mix of ideas: reconciling human needs and wants with access to multiple resources; diversity of access to those resources and services; resilience in the face of weather- and climate-related variability; resilience likewise in the face of infrastructure failure; and the personal, individual sense of belonging. At the level of Systems Thinking there is a very close relationship between resilience in the behavior of natural (ecological) systems and resilience in the social dynamics of governance within communities, where such resilience establishes the viability of these communities over centuries, which in turn entails successful stewardship of the man-environment relationship. We use insights from this cross-system mapping — across natural, built, and human systems — to assess, first, the role of city governance in achieving nexus security (or not) and, second, the role of technological innovations in serving the same purpose. More specifically, eight principles, covering resilience and diversity of access to resources and services, are used to gauge security-enhancing features of city buildings and infrastructure. Case studies include new designs of resilient office blocks, nutrient (nitrogen and phosphorus) recovery systems for sanitation and waste-water treatment, and the reconstruction of urban parks for the provision of ecosystem services. Throughout the paper, matters of risk in the face of meteorological variability are prominent. We do not conclude, however, that the presence of risk implies nexus *in*security.

Keywords cities as forces for good, climate variability, ecosystem services, energy and nutrient recovery, infra-structure failure, urban metabolism

1 Introduction

What, we may ask, is a "sense of security"? Standing back from the burgeoning literature on water security [1–6], and focusing rather on security around the water-food-energy-climate nexus as viewed from the perspective of the city [7], does a sense of security equate to:

"Making ends meet", i.e., reconciling needs with the resources to meet them, as in sustainable development, and with a diversity of strategies for doing so, the merits of which will vary over time according to circumstances [8]?

Not being dependent upon a single point of access (or no access at all) to the resources (means) required to "make ends meet"?

Resilience in the face of "too little" of the accessible resources and "too much" exposure to the extremes of meteorological and climate variability?

Resilience likewise in the face of technological or infrastructural failure (which is absent, in general, from definitions of water security)?

A sense, in the individual, of belonging?

We assert that security resides in all of these everyday-language attributes. Our purpose is to evaluate this conjecture.

We do so from the perspective of the city and its hinterland, as a coupled human-built-natural system [9]. Our evaluation is further made from the perspective of nexus security, as opposed to the mono-sectoral perspective of water security, or of food or energy security alone. Given the broad, multi-sectoral aspects of the water-food-energy-climate nexus, we treat the metabolism of the city [10] in terms of the flows of energy and materials (water, nitrogen (N), phosphorus (P), and carbon (C)) into the city from its surrounding environment, around and through the city, and back into the environment, i.e., back into the city's hinterland [11]. Cities are, after all, where the water, food and energy sectors interact with the very highest density of intersections and inextricable interdependencies. They are the origin of many of the demands for resource flows from and to the environment and around the globe. Cities require us to balance assessments of nexus security over the many flows of pre-consumption resources into the city *and* of post-consumption resources out of the city.

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Section 2 begins by summarizing our provisional criteria for gauging nexus security [7]. In Section 3, we use these criteria to examine nexus security from the perspective of the human environment, i.e., in respect *inter alia* of the individual's sense of belonging, and of institutions and governance (thus building on the previous work of Beck et al [12]) with brief consideration given to economics and finance. Section 4 employs the same criteria to evaluate security-enhancing technological innovations in city buildings and infrastructure. This is, then, nexus security from the perspective of the built environment. The paper concludes with a discussion of nexus security and the resilient city in the context of city-hinterland relationships, i.e., from the over-arching stance of coupled human-built-natural systems (Section 5).

2 Assessment criteria

As argued elsewhere [7], we have chosen to gauge nexus security in terms of the diversity of an agent or entity's access to resources and services, and of resilience in the metabolism of resources in the social and economic life of the city. Of the two — diversity and resilience — the latter is the more subtle, deep, and complex concept (at least for the present paper). We therefore provide a brief recapitulation of the ways in which we have previously interpreted resilience in the setting of cities as forces for good in the environment [13,14]. This introductory conceptual "caricature" of resilience forms the foundation for our subsequent discussion in Section 3 of risk and a sense of belonging, as well as what appears to be key in the endurance and prosperity of vibrant communities.

2.1 Notions of resilience

To begin with, Holling has drawn a significant distinction between "engineering resilience" and "ecological resilience" [15]. The former is epitomized by the goals of disciplines dealing with automation and control engineering, whose purpose is to maintain the behavior of a system within some acceptable domain, or at some desired set-point (or goal), in the face of all manner of disturbances that tend to push the state of the system away from the set-point and out of the acceptable domain. For the city, this is summed up in the popular phrase of the 24h-7d beat (or pulse-rate) of the city, or even the implied constancy of the "city never sleeps". The pulse-rate of the city has been organized to our liking and comfort, irrespective of all the surrounding fluctuations in the city's environment, with their periods of seconds, minutes, hours, days, years, decades, centuries, millennia, and so on [7,14]. Holling argues that such engineering resilience is brittle in quality, not least when the city (in our case) is struck by a shock or disturbance of abnormal properties and proportions, for instance a hurricane making landfall. The system may lose all its capacities to provide life-sustaining services.

Ecological resilience in the behavior of a system, as first described in Holling's seminal paper of 1973 [16], has in contrast the quality of the system surviving, if not in fact benefitting from, such extraordinary disturbances. Its overall behavior may no longer be gravitating around any previously comfortable set-point. Yet it continues to function fruitfully in some way throughout the disturbance and its aftermath, albeit with possibly reduced levels of those services previously considered desirable — but *not* with a complete absence of services. In his book *Antifragile — Things That Gain from Disorder*, Taleb [17] describes his experience of the infrastructure of London's Heathrow Airport in these terms: "smooth functioning at regular times is different from rough functioning at times of stress". The former is indicative of engineering resilience, the latter of ecological resilience.

Second, Holling goes on to equate sustainable development — the "release of human opportunity" — with the evolutionary advantages of warm-blooded animals (endotherms). Advantages for such animals derive from their having multiple means of regulating their body temperature, i.e., multiple means of meeting their ends (first and foremost, survival). None of these means is notably efficient or unique. These are systems with inefficiencies and redundancies in their ways of working ([15]; see also [7,14], with respect to cities). Holling notes how effective control of internal dynamics at the edge of instability — seemingly under imminent *in*security — generates opportunities for endotherms to achieve things other species cannot. In the present discussion, these internal dynamics would be those of the metabolism of the city.

Third, picking up on the ideas of the city's pulse-rate and the frequency spectrum of disturbances to which it and its environment are subject [7,18,19], what is considered "normal" for the city is focused on the daily and weekly frequencies of the spectrum. "Abnormal" is a matter attaching, on the one side of the norm, to lower-frequency fluctuations (as in droughts, which extend over months and years) and, on the other, to higher-frequency fluctuations, as in the hours and minutes of the flood, or the loss of electrical power in an instant. This way of conceiving of the separation between the normal and the abnormal will be referred to here as a "frequentist outlook" (which is different in this context from the way this phrase is used in Statistics). Clearly, this facet of resilience — of surviving the shocks and privations resulting from meteorological events and infrastructure failures — is strongly associated with the way in which Grey and Sadoff [3] address issues of countries achieving basic water security under conditions of substantial hydrologic variability. The prominent periods of such variability (in hydrology) are hours, days, weeks, intra-annual, inter-annual and so on, down to very low frequency fluctuations over centuries, millennia, and beyond (themselves below even the long intra-generational and inter-generational periods typically associated with considerations of sustainability).

Fourth, all of the above facets anchor resilience as something associated with change and variation over time. Holling himself talks of fast and slow variables and their *interaction* [15]. Here, we would equate fast with being dominated by oscillations with predominantly high-frequency components, and slow with low-frequency components. But it is the interaction across the spectrum that is important, hence our subsequent use of the phrase "cross-spectrum interactions". This is the same as the nature of interactions across the life cycle of projects and infrastructure, most obviously between design and construction for the long-term and operations in the short-term. Indeed, it has been the historical neglect of considering the nature of short-term variability, and how it will be managed — some significant distance into the long-term future — that brought our own frame of thinking around to using the electrical engineering concept of spectrum [13,14,18,19] (see also [7]).

Fifth, these cross-spectrum interactions have their counterparts in the spatial dimension, with respect to spatial scale, hierarchical organization, and networks. Ecological resilience has therefore companion interpretations with respect to cross-scale interactions [20]:

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

Such insights will be referred to as "cross-scale interactions". The prominence of the attribute of diversity within them should also be noted.

2.2 Criteria of nexus security

The broad framework for understanding nexus security, from the starting point of water security, has been set out in a companion paper [7]. It comprises four facets each of the notions of resilience and diversity. Our purpose is to employ them for gauging security within the human environment of the city, e.g., with respect to governance (in Section 3), and within its built environment (in Section 4), e.g., with respect to the merits of adopting some given technological innovation or strategy of infrastructure re-engineering. These principles of diversity and resilience are not mutually exclusive nor are they strictly distinguishable. The one entails something of the other, as indeed is the case for the definitions of nexus security and resilience themselves. Security and resilience differ, however, in their conceptual provenance. In the abstract terms of systems thinking, the former (security) is an "atomistic" human agent-centered notion. The latter (resilience), given its origins in the study of ecological systems, is a nature- or system-centered property, where the system is decisively a collection of multiple, interacting agents.

Consider, then, the city as the system. It acquires inputs of resources from its environment; it generates post-consumption outputs as returns to its environment (as well as economic goods and services). Access, hence diversity of access, as understood in any of the more prominent definitions of water security [1–4,7], is taken to be access to options for either an input-supply or output-return service by an individual, household, office-block, ward/district of the city, or the city itself. Since the concept of output-return option is perhaps somewhat unfamiliar, this will typically be an option for sanitation, for example, or for access to a facility for receiving household (food) "waste". Much of the discussion on enhancing security thus far (in the literature as a whole) has been biased toward enhancing access to input resources (as means to ends), with resources generally understood to be scarce. The manner in which scarcity is taken for granted in mainstream economics, in reconciling supply with demand, has been challenged by Mehta [21]. The criteria for diversity below are fully cognizant of this challenge [7].

In short, our eight principles ((D1) through (D4) and (R1) through (R4) below) are intended to structure the assessment of enhancing nexus security in the following qualitative senses (as arrived at and introduced in [7]):

Diversity. Inspired by metabolism, diversity of input-supply and output-return options should be increased through: (D1) Increasing options for access from *outside* the city; (D2) Reducing consumption of resources *within* the city to enable better sharing of access to those resources; (D3) Decentralizing, again within the city, i.e., multiplying the numbers of potential input-supply and output-return options; and (D4) Increasing resource recovery and recycling, within the city, and likewise creating new (i.e., more) input-supply options. From a system's perspective, the distinction between (D1) and (D2)–(D4) is significant.

Resilience. Inspired (in part) by the pulse-rate of the city (and the frequentist perspective), increasing (ecological) resilience should derive from considering: (R1) Increasing diversity of species, agents, and agencies within the city-system (as the complement of the facets of diversity in all the (D) above); (R2) Creating a richer hierarchy in which to exploit cross-scale interactions; (R3) Tolerating, if not celebrating, redundancy and inefficiency of function; and (R4) Being more mindful of cross-spectrum interactions.

We now examine nexus security according to these criteria from the perspective of the human environment (Section 3) and the built environment (Section 4), given our over-arching view of the metabolism of the city as being that of a coupled human-built-natural system.

3 Human environment: governance

We perceive insecurity and seek to move away from it, just as we acknowledge unsustainability and wish to have less of it. There is some urgency about achieving both. Given economic feasibility, the pace of such change, even simply embarking upon a path toward change, is essentially dependent upon the degree to which any proposed innovations are accorded social legitimacy [9,12] (see also the discussions of sustainability transitions [22,23]). The global water crisis has long been defined as a crisis in governance, not of the appropriate technologies. Thus, the World Economic Forum (WEF) book — *Water Security: The Water-Food-Energy-Climate Nexus* [24] — has a penultimate chapter on "New Economic Frameworks for Decision-Making", albeit not frameworks that are likely to challenge the orthodoxy of neoclassical economics [7,21]. "Innovative Water Partnerships", however, are the culmination of the book in its final chapter.

How then does (and should) governance affect nexus security?

3.1 Plural rationalities: security, risk, and belonging

Good governance has intrinsic merits with respect to enhancing a sense of personal and collective security within a community. The converse is also true. In other words, apart from appreciating that security may be enhanced through technological innovation and the material world of physical infrastructure (the subject of Section 4 below), it may be likewise enhanced through the social infrastructure of governance.

In his seminal theory of human motivation, Maslow [25] elaborated a hierarchy of needs for the individual at a strictly personal level. They passed from basic physiologic needs; up to safety needs, including health, hygiene and employment; then love/belonging and social needs; further up to esteem needs; and beyond all these there was a yet higher level of growth needs. We can deduce from this that the quality of community governance should have a bearing on the individual's security in respect of his/her perception of "belonging" to that community. Arnstein, in her landmark paper on "A Ladder of Citizen Participation" [26], would suggest citizen control as the climax of participation. A definition of this would amount to the very opposite of the vastly inferior practice of tokenism, in which government agencies hold all the power and act decisively, but merely inform, consult or placate the individual citizen and his/her community. What level would be the more nexus-secure: the bottom or the top of this ladder of participation?

Matters are probably somewhat more subtle and complex [12,14,27]. While we do not here equate security with the absence of risk (as we shall see), let us consider the plural attitudes toward risk we can find in society. This will reveal a theory of plural rationalities, *ergo* plural ways of seeing the world, of organizing, and of managing the man-environment relationship. As elsewhere, the assertion is that resilience is interwoven with nexus security [7]. In fact, our argument will proceed in reverse historical order: backward, as it were, from the notion of resilience in the man-nature relationship, hence resilience in social ("man") dynamics of the human environment [28]; to resilience in the behavior of ecological ("nature") systems [16,29], with reference ultimately back to the foundations of Holling's seminal work.

Very briefly, and cryptically succinct, there are (first) four attitudes toward risk (see [28,30] for the full discourse). As archetypes, these are: the risk seekers and takers, whose outlook we shall style as (*I*), for reasons that will shortly become apparent; others who believe they know how to manage risks (*H*); those who abhor risk (*E*); and yet others who are the absorbers of risk (*F*). Under water *in*security — in the absence of water development as the platform for subsequent self-sustaining (more general) development — Grey and Sadoff observe that high levels of "risk aversion" will constrain growth and diversification [3]. For them, this is the one, specific attitude toward risk that is of predominant concern.

Second, the four categories reflect four ways of organizing competition, each occupying a quadrant of the 2-D plot, as it were, of an equality-inequality axis of symmetric-asymmetric social transactions and an axis of unfettered-fettered competition. They are [31,32]:

a) The individualists (*I*), or free-marketeers, who are convinced of the rightness of unfettered competition on a level playing field (symmetric transactions) and who privilege the creation of private goods;

b) Hierarchists (*H*), who prize public goods and a commitment to regulation in a world organized according to asymmetrical transactions (inequality) and fettered competition;

c) Egalitarians (*E*), who favor a world of common-pool goods and equality (symmetric transactions), and from which unfettered competition is absent; and finally,

d) Fatalists (*F*), who perceive themselves as inhabiting a world made up of club goods, from which they are excluded, and who are unable to organize themselves in any way that might affect any outcome, i.e., individuals with a world view consistent with unfettered competition and inequality.

The focus of Mehta's book [21] — *The Limits to Scarcity:*

Contesting the Politics of Allocation — is that scarcity, in reconciling means and ends and in balancing supply and demand, was long ago assumed to be a "natural" "fact of life" by mainstream economics, which is *solely* the economics of the overwhelmingly dominant free-marketeers (*I*). There is more to dealing with scarcity, she argues, than merely this one view of it [7].

Third, (*I*), (*H*), (*E*) and (*F*) each have their own rationales, which is to say, there are plural rationalities. What may seem quite rational to one may appear utterly irrational to another. In principle, there would not be just the one "rational economic man" of computable general equilibrium models [33], but several. For Thompson, "rational economic man" acts in a world where ends (needs) and means (resources) are managed ever upwards and as high as possible [8]. For Fine [34] rational economic man acts as though he is an optimizing "automaton" [7].

Fourth, each of the four so-called solidarities has its own world outlook (*Weltanschauung*), in particular on the man-environment relationship, and hence its own style of managing that relationship, i.e., in large part reconciling ends with means [7,8]. Technically, however, the archetypal fatalist (*F*) has no say in any such matters of management or policy formation; by definition, s/he is disengaged from the process of debating, voting and community decision-making.

Given these four briefly stated steps, taking us (in effect) from individual, personal attitudes toward risk to collectively organized styles of stewardship of the man-environment relationship, we can at last express the one-to-one mapping, from Thompson's theory of plural rationalities [31] to Holling's four Myths of Nature [29], as achieved in [28]:

(*I*) holds to Holling's Myth of "Nature Benign";
(*H*) to "Nature Tolerant But Perverse";
(*E*) to "Nature Ephemeral"; and
(*F*) to "Nature Capricious".

By way of orientation on these Myths, "Nature Benign" would be precisely the necessary state of affairs for the city to proceed comfortably on its way, with everything around it subjugated to the dictates of comfort and the 24-7 beat.

Overall, our highly abbreviated logic has proceeded from a person-centric, single-agent outlook — with its origins in Maslow's [25] theory of human motivation (and hence personal attitudes toward risk) — to a multiple-agent systems perspective.

Security for the individual might now be seen to be a matter of his/her belonging to one of the ways of thinking about the man-environment relationship ((*I*), (*H*), (*E*) or (*F*)), having these convictions confirmed by observation and experience over time, and witnessing policy and technological interventions being tailored to serve their personal aspirations for the future (instead of those of the others). If this is so, security resides in all four attitudes toward risk. The presence of risk and its harms is not identical with a sense of *in*security.

3.2 Governance at the core of nexus security

Governance, it is argued [27], entails the recognition of this 4-fold typology. High quality governance entails granting access to the debate — in this case, how to manage the man-environment relationship — by each of the three actively engaged parties (*I*), (*H*), or (*E*). (Members of solidarity (*F*), we may recall, give themselves no voice, by definition.) Each of the three will have a voice in the debate. It will be the role of those responsible for governance to ensure that the voice of each is heard, and responded to, by each of the two other parties at the metaphorical table of the debate ([27]; see also [12] and [14] with respect to cities, sustainability, and governance). Security for the "whole", as opposed to the individual (or one of the solidarities), may come in the form of a grudging acquiescence: that those not currently most satisfied by the direction of policy and technological interventions, not least because they cater to the aspirations of others, will nonetheless tolerate the status quo — for a while [14]. In particular, they may well do so because it is apparent that current policy does not necessarily foreclose the possibility of their eventually attaining *their* cherished hopes for the more distant future [9]. Think, for instance, of how members of solidarities (*H*) and (*E*) would view a policy they believe serves presently the aspirations of solidarity (*I*). For a start, each holds to their own view of how to reconcile means and ends, hence (arguably) differing views on security, where the conviction of each is in fact defined in opposition to those of the others [8,31]. (*H*) and (*E*) would thus be obliged to go along grudgingly with the (*I*)-catering policy for a while, before returning to attempt to disrupt it. Security derives from retaining such impassioned debate over contending aspirations *within* the deliberative processes of good governance, which themselves might better thrive on dispute.

According to the World Economic Forum (WEF), the nub of the water security challenge, itself the kernel of nexus security, is this: in 2030 a 40% gap between the global demand and supply of water is forecast [24]. Increases in water supply under a business-as-usual (BaU) scenario, i.e., one that simply extrapolates past trends, will be very modest. So too will be BaU increases in the efficiency (or productivity) of water use as it flows through the systems of agriculture, industry and commerce, hence to reach people and the city. The looming insecurity and scarcity associated with a sizeable gap between demand and supply is forecast to remain. It dominates thinking, which very dominance itself, to the exclusion of other arguments *not based* on scarcity, would be of concern to Mehta [7,21]. Using illustrative results for India, the new economic framework for decision-making — of "making ends meet" [8] — ranks the options for closing the gap according to their unit costs of supply and the additional volumes they promise to yield, including through wastewater reuse [24]. Enabling (or disabling) implementation of any of the options will be a function of governance, summarized under the heading of innovative water partnerships, defined *inter alia* as follows: an "institutional commons" is to be created and funded for collective sharing of ideas on how to resolve collectively shared challenges. This commons is to be a multi-stakeholder platform, itself encapsulated in a public-private-community partnership (PPCP) [24] — possibly a partnership, we might say, that recognizes and gives a voice to those who hold stakes in private goods, public goods, and/or common-pool goods. All discussions and activities of the platforms are assuredly to be "fact-based" [24]. "Innovation vectors", i.e., leaders and proponents skilled in the arts of collaboration and motivation, are to be assiduously cultivated [24].

In these ways, as elaborated by the WEF book (*Water Security: The Water-Food-Energy-Climate Nexus*) [24], nexus security should indeed be understood as ultimately a function of governance and therefore in line with the arguments of Cook and Bakker in their review of water security [1].

3.3 Considerations of economy and finance

The four criteria of diversity ((D1)-(D4)) are about enhancing security through diversifying access to more (i.e., multiple) options, conventionally understood as options essentially for accessing flows of energy, materials and resources.

There are quite other kinds of non-material resources to which we might need (or want) access, as we can now appreciate, such as the resources of *wisdom* and *experience* — with respect to man getting along with nature and his fellow man. The theory of plural rationalities, or Cultural Theory [31], doubles in a single stroke the number of such sources; diversity of access to wisdom and experience is doubled, in other words. The mere duo of markets (*I*) and regulation (*H*) is an impoverished representation of the ways of managing our affairs, wrote Thompson, shortly after the global financial crash of 2008 [35]:

> Beyond boom and bust. Swinging between the regulations of government [(*H*)] and the excesses of the market [(*I*)] has proven flaws ... [C]ultural theory can offer a new economic paradigm.

That paradigm would acknowledge the 4-fold typology of (*I*), (*H*), (*E*) *and* (*F*), for there is something of value to policy-making in the experience of the disengaged risk-absorbers (*F*), giving thus a total of four quite different sources of wisdom and experience. Guided by a prevailing attitude toward risk, asset managers display this same 4-fold diversity in their investment strategies, each perhaps being "right" at any given time, as market conditions change, evolve and fluctuate [36]. In other words, and in general, the system — be it the stock market, the economy, or the environment — may move (unpredictably) through various regimes of strategically quite different patterns of behavior. Matters are not necessarily confined to just two such regimes, nor regimes whose behavior is best managed by strategies of just the free-market or government regulations. Greater security for society in coping with these plural regime shifts should derive from having a four-fold repertoire of management styles, as opposed to merely two. Great ingenuity would then be required, of course, to spot a change of regime and to determine which style of management might be best suited to coping with and prospering under the new regime.

Also writing in the wake of the 2008 economic crash, Lietaer et al [37] have proposed that ecological resilience in national financial systems would be improved by introducing "diverse complementary currencies": to circulate around networks, and sub-networks within networks, of national financial systems, thus mimicking the spatial-hierarchical patterns of material and energy flows that imbue ecosystems with their evident coherence and capacity to endure shocks. Since 1934 a currency known as the WIR, or Wirtschaftsring, has circulated around a sub-network of businesses in Switzerland in parallel with the circulation around other networks of the Swiss national currency, the franc. The volume of WIR flows (and transactions) increases in times of national economic recession and decreases in better times. Operating together, in different networks (i.e. different parts of the whole), the two currency flows act to provide counter-cyclical stabilization of the whole and hence greater security for a greater number of citizens than might otherwise have been the case [37]. Based on analyses of the networks in ecological systems, the theoretical principle to be set to work here is one that tries to formalize (even in mathematical and numerical terms) where viability for a system lies, in the trade-offs between system efficiency and system resilience. It makes something of a virtue of applying principles (R1), diversity of agents (here currencies), (R2), cross-scale interactions (between regions and nations), and (R3), soft redundancy and inefficiency, in serving (R4), i.e., benefitting from cross-spectrum interactions for stabilizing behavior. Yet perhaps more importantly, the network theory upon which it builds is fundamentally one of connectivity in a system, i.e., security deriving from the principles of diversity (D) of access to material-energy flows. In the past, objections to diverse, complementary currencies have focused notably on the economic taboo of their *in*efficiencies [37].

To summarize, access to the diversity of human experience and wisdom, and access to the perhaps surprising idea of a diversity of currencies, ought to enhance resilience and security.

3.4 Enduring and viable communities

"Clumsiness" and "clumsy institutions" [28] are Thompson's choices of words for the structures of governance we should cherish. They are meant as the sharpest possible contrast to the elegance and efficiency customarily sought in the workings of governance [12]. We infer from this that inefficiency should not merely be tolerated, but almost celebrated. The enduring viability of communities may rest upon it.

Resilience is fundamentally about how things change with time. Our dimension (R4) captures this in its principle of "being more mindful of cross-spectrum interactions". Drawing upon his training in anthropology, Thompson gives us the following account of how village-environment systems have endured, in order to retain their identity over the longer sweep of time, in the face of the comings and goings of shorter cycles [28]:

> Himalayan villagers parcel out their transactions with their physical environment into four distinct solidarities, each of which is characterized by a distinct management style.
>
> Viability can only be achieved, therefore, by covering all the bases: by the villagers ensuring that they have the full 4-fold repertoire [diversity] of management styles, and by their being prepared to try a different one whenever the one they are relying on shows signs of no longer being appropriate. The Davosers [villagers of the Davos Valley, Switzerland], like their Himalayan counterparts, have now been in their valley for more than 700 years, without destroying either themselves or their valley in the process. This achievement would not have been possible if they had opted for just one management style, or even for the two [those of (*I*) and (*H*)] that the prevalent orthodoxy allows!

This — the way in which the two illustrative village-environment systems have retained their identity — is at the heart of the definition of resilience according to the Resilience Alliance (www.resalliance.org), as quoted by Moddemeyer [38] (and also [7]).

Change is the only constant in life. Oddly enough, the constancy of an identity is metaphorically associated with very low-frequency variation (technically, it is variation with an infinitely long period). According to Thompson's account of "Man and Nature as a Single but Complex System" we have the following [28]. Surviving shortage and surfeit (famine and flood), being viable, and retaining identity over the longer term (centuries, say), are all a function of decisive change, learning, and adaptation over shorter-term cycles of relatively higher frequencies, be they inter- or intra-generational, inter- or intra-annual, weeks, days or even higher. In short, survival, even prosperity, *ergo* enhanced security, derive from the workings of principle (R4), the appreciation of cross-spectrum interactions.

Could we now substitute "nexus security" for "viability"? Will what has been good for village-environment systems be just as good for the coupled human-built-natural systems of cities and their hinterlands?

3.5 Experimentation, learning, and adaptation

We are prompted to think about resilience in governance on two further accounts.

First, in proposing a new theory of urban resilience in the face of floods, Liao [39] promotes the arresting idea of floods as beneficial learning opportunities and suggests that ecological resilience in the coupled built-human environments of the city resides within the community of people, i.e., in society, not the city's infrastructure. Clearly, we might raise the minor objection that elements of such resilience are, in fact, vested in *green* infrastructure for managing stormwater and tidal surges (as we shall see [40]), even if they are presumed to be absent from the conventional *gray* infrastructure of sewers, barrages and other man-made ("hard", engineered) defenses. Significantly, Liao's proposal of society benefitting collectively from the harms to some citizens of urban flooding resonates with Taleb's recently proposed notion of antifragility [17]. A city could be said to be antifragile when it seeks to learn from the buffeting-and-muted-response couples of partial flooding. Its collective human-built-natural sub-systems then function so much the better to prepare — even over-compensate — for surviving the eventual catastrophic flood. The city and its citizens gain strength, i.e., a greater sense of security, in facing future disturbance and disruption from the stresses of disorder, randomness and volatility in the present, i.e., from the inconstancy and discomfort of being occasionally jolted out of the regular, monotonous beat of the 24-7 routine. Liao [39] would concur. So might Holling, since the concept of antifragility also resonates with his description of the epitome of sustainable development as [15]: the release of human opportunity when affairs are being conducted at the edge of instability (the parallel being that the evolutionary opportunities for endotherms comes with their operating at body temperatures close to lethal, as noted above). We shall return to examine further Liao's new theory in Section 4.5 below.

Second, these ideas of learning and adaptation from experimentation are prominent in Gatzweiler's work on governance [41]. He proposes "borrowing from the organization of public economies in *metropolitan* areas" (emphasis added) in order to suggest design principles for polycentric, multi-level governance in a coffee forest conservation project in rural Ethiopia. This he labels a "public ecosystem service economy for sustaining biodiversity" and goes on to say [41]:

> Other hypothesized benefits of multi-level governance are that it provides more complete information of constituents' preferences, is more adaptive in response to changing preferences, is more open to experimentation and innovation, and that it facilitates credible commitments.

The importance of such "plasticity" in city governance — and of the diversity (D) implied in the attributes of *poly*centric and *multi*-level — has not escaped our attention in writing elsewhere on technological innovation and governance for re-engineering cities so that they may become forces for good in the environment [14].

Community learning and adaptation are integral to resilience; they have a bearing on a community's sense of security and its viability over the longer term. At the same time, the scope for such learning and adaptation is enhanced by diversity in the scales and loci of governance and decision-making in the city.

4 Built environment: innovation

We now assess some case studies of such innovations in the forms of the built environment from the perspective of their capacity to enhance nexus security within the city, using again the criteria of diversity of access ((D1) through (D4)) and resilience ((R1) through (R4)). By the end of this assessment (in section 4.5) our discussion will have returned to the subject of risk, but this time from the perspective of human, technological and institutional failure (which has hitherto not been prominent in discussions of water security, for instance).

4.1 The nexus and disruptive entrepreneurship

We know from its advertising campaign during 2010/11 that the energy company Exxon-Mobil has an algae biofuel research and development (R&D) program. Conceivably, given the rising prominence of the nexus, Exxon-Mobil might, through and because of the nexus, develop more readily a new and successful line of business in recovering from sewage (in the traditional water sector) the N and P precursors it needs for biofuel production. In other words, the nexus itself may facilitate the entry of more diverse business actors into what are for them non-traditional sectors. Exxon-Mobil is not normally thought of as a water business. Security may thereby be enhanced, specifically through the principles of increased number and enhanced diversity of business agents within the water sector, i.e., (R1), and of enhanced diversity of resource-supply options (renewable energy in this case), i.e., (D4).

Writing on a blog posted at www.exxonmobilperspectives.com on 21 April, 2011, Emil Jacobs, Vice President for R&D at the company, stated the following[1]:

> In the nearly two years since we first announced our alliance with Synthetic Genomics Inc. (SGI; www.syntheticgenomics.com), we've made good progress in our research aimed at developing next-generation biofuels from photosynthetic algae.

SGI, in the words of its founder J Craig Venter (from a 2007 BBC Dimbleby Lecture)[2], describes the company in these terms[3]:

> I believe the best examples of disruptive technologies that could change our future are in the new fields of synthetic biology, synthetic genomics, and genome engineering. These fields can change the way we think about life by showing that we can use living systems to increase our chances of survival as a species. Simply put: this area of research will enable us to create new fuels to replace oil and coal.

At SGI's partner, the not-for-profit J Craig Venter Institute, researchers are already in vigorous pursuit of technology for generating electricity from sewage through a fuel cell exploiting genetically modified bacteria (as reported in New Scientist[4], 29 March, 2012; see also [42]).

One does not have to look far at all, therefore, to find prospective new entrants into the business of the water sector. This will diversify the number of business agents as well as access to resource flows other than water (such as biofuels), and hence enhance overall nexus security, in principle. If, more specifically, water security and the water sector *are* privileged, then this is especially significant, because the water sector, by its own admission, is conspicuous for its unusually low-rate of technological innovation [14]. The assumptions of low rates of efficiency and productivity gains in the business-as-usual (BaU) extrapolations to 2030 of WEF [24] should therefore be no surprise. They lie at the heart of *in*security associated with the forecast scarcity caused by the supply-demand gap.

1) available online at http://www.exxonmobilperspectives.com/2011/04/21/algae-biofuels-update/ (accessed February 6, 2013)
2) Available online at http://www.bbc.co.uk/pressoffice/pressreleases/stories/2007/12_december/05/dimbleby.shtml (accessed May 6, 2013)
3) available online at http://www.syntheticgenomics.com/about/ (accessed February 6, 2013)
4) available online at http://www.newscientist.com (accessed November 21, 2012)

From a governance perspective, in particular, through that element of governance which increases diversity for resilience (R1), we might better welcome the arrival sooner than later of disruptive, newcomer businesses, as start-ups, or "cross-sectoral insurgents" (such as Exxon-Mobil entering the water sector). A well functioning "whole system" encompassing the water-food-energy-climate nexus enhances the scope for such diversity and variety. Science creates the potential for new technologies that are (beneficially) disruptive. Governance, among other social and economic factors, creates the scope for new businesses to be beneficially disruptive. In whichever single, constituent sector the greatest promise of such beneficial "disruption" might be discerned — water, food, energy and so on — it should be the responsibility of governance to facilitate its accelerated emergence hence to improve nexus security through a greater diversity of businesses and an expanded diversity of access to resource options, when these new businesses are engaged in resource recovery and recycling.

Novelty, hence innovation, may spring from other developments, themselves well attuned to the nexus. Grounded historically in the water sector, Veolia Environnement has for some years rightfully described itself as a Multi-Utility Service Company (or MUSCO), recognizing the added business value deriving from the fact that its services cover water, waste-handling, transport, and energy [14,43]. Water may indeed be privileged within the nexus; and Growing Blue, therefore, might be the fastest route to the more diversified Growing Rainbow[1)]. Security, however, may rise or fall as a result of the advent of the MUSCO. It may enrich the hierarchy and scales of businesses by adding an uppermost tier through cross-sectoral consolidation, thereby increasing the number of potential input-supply and output-return options (D3) and enhancing resilience through more cross-scale interactions (R2). Yet the elimination of other business entities (hence options for supplies of services), which tends to accompany the creation of an upper-tier business through this kind of merger — not least, to eliminate redundancy — would work to reduce security according to (R3) (with its redundancy-tolerant sentiment).

Credit as leaders in their class should therefore be given to those businesses that have fractured the traditional sectoral boundaries and hence been arguably "disruptive". This should be done tangibly and publicly, through the ratings and investments of asset managers [44]. Becoming a "best in class" or highly ranked in a league table matters. Given all other such tables, it is probably only a matter of time before a security league table is created (it probably exists already!). In setting out his green agenda for Atlanta (on 1 June 2012), Mayor Kasim Reed recognized his predecessor's achievement for improving the city's sustainability ranking among U.S. cities from 38^{th} to 18^{th} and committed himself to taking the city into the Top 10.[2)] Rankings matter.

4.2 Resource recovery

The strategic principle of resource recovery in the city (D4) enhances nexus security by multiplying the number of input-supply options to which an agent has access.

To gauge the potential of recoverable "resource-rich" flows in a city's metabolism, consider indeed that part of the city of Atlanta lying within the Upper Chattahoochee Watershed (which is home to 1.4M people [11,45]). How much of the city's currently wasted N, P, and C resources might be available for biofuel and fertilizer production? From which particular flows might they be accessible and in which of the various sectors of the nexus (energy, water, of food)? For example, and perhaps surprisingly, each year more than 50,000 tonnes of N presently enter the energy sector of the Atlanta-Chattahoochee system in fuels for transport, energy and industry. This is the largest single flow of N. Presently, however, 90% of it ends up unproductive and inaccessible in gaseous atmospheric emissions from combustion [46,47]. In a non-fossil fuel future — thus a low-C future — this N resource flow would simply not be available for recovery.

Lesser options elsewhere, although in fact more familiar, will have to be exploited: in the residual flows from food consumption (sewage) and food waste. Thus, of the just under 10,000 tonnes of N per annum in the city's input food supply (to those 1.4M citizens of Atlanta living in the Chattahoochee watershed), slightly more than 1,000 tonnes are lost as food waste, while about 6,400 tonnes exit households in sewage, of which 60% ought to be readily recoverable for various beneficial purposes [47]. This is not a novel proposal. In 1913, 40% of human dietary N was being recovered from the city of Paris and recycled as fertilizer for the surrounding agricultural hinterland [48,49] (see also Section 5 below). With respect to P, estimates of a companion recycle rate of about 20–25% have been made [50,51]. Of necessity, the security of the city was mutually dependent upon the success (and security) of its immediate hinterland. It may be less so now, a century later, as we shall observe in Section 5 below.

Two case studies from very different social and developmental settings demonstrate the principle of (D4) at work today, i.e., increasing resource input-supply options through urban resource recovery and recycling.

1) The city of Ouagadougou (capital of Burkina Faso) is the site of one of several field trials in establishing and benefitting from the "Nexus of Sanitation and Agriculture at Municipal Scale" [52]. Security is to be achieved on two fronts: the installation of an output-return option for basic

1) available online at http://growingblue.com/2012/11/07/growing-blue-to-grow-rainbow/ (accessed February 5, 2013)
2) available online at http://www.saportareport.com/blog (accessed November 11, 2012)

sanitation in the form of Urine-Diverting Dry Toilets (UDDTs); and increased reliability, if not greater variety, in the input-supply options for urban agriculture [53]. The trial is taking place in a somewhat de-centralized format, in four of the city's 30 administrative districts. Placed in between the output-return and input-supply locations are "eco-stations" to which urine and dried feces collected from the UDDTs are transported and where, after adequate storage, the recovered "human fertiliser" is then sold to the urban farmers [53]. To realize this potential for enhanced security, minimal distances between the output and input locations, hence the costs of transport, are critical.

2) Ostara Nutrient Recovery Technologies is a small start-up company and forms one element of an interesting tripartite institutional arrangement of a private, public and not-for-profit partnership (the other two partners are Clean Water Services and the Clean Water Institute™, based in Durham, Oregon, USA [14]). Ostara's technology recovers slow-release, crystalline granules of P-based fertilizer, i.e., an additional input-supply option for the food sector, from an otherwise conventional, centralized wastewater treatment plant [54]. It happens, however, that some of the recovered resource is directed toward the ecosystem services sector, a latent but significant element of the water-food-energy-climate nexus, precisely as argued elsewhere [55]. In this instance, the fertilizer is used for the purpose of restoring salmon populations in the rivers and streams of Vancouver Island in British Columbia, quite some distance away — over the border in Canada, in fact [14,56]. Timing, a frequentist outlook, and principle (R4), i.e., being more mindful of cross-spectrum interactions in seeking resilience, are evident in this practice, albeit subtly [14].

From a more abstract systems perspective, the Ouagadougou case study illustrates how the city (system) might re-arrange the internal structure of its metabolism to serve the goal of enhanced person-centric nexus security. An additional output-return option has been introduced, as indeed it would tellingly be expressed in detached, objective, abstract terms; in the hard messiness of subjective reality, it is the basic UDDT. In the Ostara case study, the city is seen to be intervening constructively in nature, as opposed to destructively (the popular perception), i.e., in the system's external environment. But in what ways, we should ask, might this be a modern-day realization of the (presumably) security-enhancing city-hinterland symbiosis of Paris a century ago, which was focused pragmatically on person-centric food security, as we have seen above [48,49]?

4.3 Buildings and scale

Progressing upwards from the small and local to the citywide scale, we have the following five case examples upon which to test further our provisional criteria of nexus security.

3) The autarkic house, pushed to the very extremities of its logic, exemplifies *par excellence* (D2), reducing net consumption, (D3), de-centralization, and (D4), resource recovery and recycle, possibly even the resilience of increasing the diversity of agents acting within the city system (R1), where such autonomy at the household-scale is unusual. Germany is generally cited as having hosted the most prominent salients in developments along this dimension [57,58]. According to Truffer et al [58], the key driver for this has been maximizing water-use efficiency and water recovery and recycling. Blueprints exist for houses consuming as little as 80 L of water per person per day, and even as low as 30 L per person per day [58]. For Londong [57], self-sufficiency has a somewhat more rounded interpretation:

> The Lambertsmühle [demonstration project] involves urine source separation and full recycling of nutrients from faeces and urine.

Achieving autarky appears to be favored in dwellings that are relatively isolated in space, if not rural in their settings. The Lambertsmühle demonstration project requires the complementary ecosystems of agriculture, gardening and wetlands, which fulfill vital roles in the recycle loops around the house [57]. At the limit, complete self-sufficiency will have substituted access to one set of community-furnished input-supply options (for water, food and energy), and one output-return option (for wastewater), by one-for-one corresponding household-focused options. Technically this therefore affords no net increase in nexus security, i.e., no increase in the number of options accessible from the house. Feeling secure, however, is person-centered, as we have already seen above in Section 3. Those drawn to living in the archetypal autarkic house are most likely "independent types" (acting out, perhaps, some blend of the (*E*) and (*I*) rationales of Cultural Theory), possibly seeking to detach themselves from society, possibly deliberately courting a riskier existence, even to become more antifragile thereby [17]. And they might indeed need to be so. On the other hand, in a relatively more isolated rural setting, failure of the output-return (sanitation) sub-system in the house may be quite acceptable, without compromising perceptions of security among fellow members of the community. For they, living quite some distance away, might not perceive *their* own personal health as being threatened by pathogen propagation from the failed autarkic house.

4) The Headquarters Building of the San Francisco Public Utilities Commission (SFPUC) exemplifies primarily principle (D2), reducing consumption (of water and energy), (D3), de-centralization to the scale of a partly autonomous 13-storey building, (D4), resource recovery and recycle (for water), and something of (R1), as in the resilience of a constructed wetland in the recycle loop for water recovery. The following extracts from Harrington's

[59] account of the project capture the essence of how nexus security is being enhanced:

> Water reuse was a central concern, but we quickly discovered that many decentralized water-reuse technologies were too energy-intensive for our building's energy budget. My team proposed that we pursue ecological sanitation methods inspired by wetlands, and challenge ourselves to defy the conventional wisdom that the space such methods demand is too big for dense urban areas.
>
> In our low-energy solution, wastewater treatment, which is usually buried in the basement, is visible — in the atrium and from the pavements where thousands walk every day. And we've done it in one of the highest-density neighborhoods in one of the highest-density cities in the United States.
>
> The process begins and ends with low-flow toilets.

In spite of the burgeoning autonomy identifiable in this project, security through a multiplicity of output-return options is nonetheless implicit in the following observation [59]:

> [F]iltered solids such as faeces are pumped periodically to the municipal sewage system.

The building cannot be entirely cut free from the customary centralized, citywide arrangement, access to which output-return option is surely retained for reasons of security.

5) The Barclay Tower in New York City illustrates the merits of security and autonomy distinctively (but not solely) through (R4), i.e., being more mindful of cross-spectrum interactions. According to a post at SustainableBusiness.com[1)] (notably less than 4 weeks before the occurrence of Hurricane-superstorm Sandy):

> The next time New York City suffers a blackout, residents of the 58-story Barclay Tower will still have their lights on — thanks to an on-site energy storage system providing 225 kW (kW) of alternative power to the building.
>
> The luxury high rise near the new World Trade Center is using the Joule System, developed by Demand Energy Networks that houses batteries made by C&D Technologies.

Operation of the Tower currently takes economic advantage of the 24-7 cycles in electricity tariffs to store cheaper energy for times of more expensive energy or of no energy input (i.e., failure). In the longer term, however, C&D Technologies plans to exploit the know-how thus gained from tariff-juggling to develop batteries for converting the vagaries (stochasticity) of high-frequency energy inputs, i.e., those of wind and solar radiation, into the comfort (and predictability) of the 24-7 rhythm of the building. Indeed, Glenwood Management, which manages the Barclay Tower, has its eye on exploiting spatial variability, of hedging against failure in but one of several locations (or parts) to enhance security for the whole. The whole here would be the cluster of networked, partially-autonomous buildings (such as the Barclay Tower) across the city. If anything, this would approximate principle (D3), i.e., creating a richer hierarchy to better exploit cross-scale interactions, where the more nexus-secure cluster is higher in the hierarchy than any single building.

6) Westfield Stratford City, London, billed as "Europe's largest urban shopping centre" [60] achieves many of the now demonstrable water and energy savings, not least through security-enhancing access to the additional input-supply option of rainwater harvesting, i.e., the exercise of principle (D1). Significantly, with respect to food waste, this building complex "is aiming to be 100% recyclable within five years" [60]. There is even a hint of the complex becoming a force for good [14] in its local city environment (again, [60]):

> Green roofs have been planted ... and have been designed by ecologists to enhance local biodiversity ...

This multi-building sub-system, we might conclude, is intended to enhance the resilience of the larger-scale city system and beyond (given the mobility of the roof's fauna, its bird populations).

7) Moddemeyer's "Whole City" presents an overarching vision of an entire city that would, above all (we assert), celebrate (R2) as first among the otherwise equals of all the attributes of resilience, i.e., the realization of a richer hierarchy within which to exploit cross-scale interactions [20,38]. Assembled from various parts of his text, this is how resilience through such beneficial cross-scale interactions would be brought about [38]:

> The resilience of the cloud computing platform is based on the *global* network of highly interconnected nodes and servers that helps to avoid downtime in local emergency situations. [emphasis added]
>
> At the *district* scale, planners and urban designers are implementing nested semi-autonomous districts [which] work with an

1) available online at http://www.sustainablebusiness.com (accessed October 4, 2012)

> astute blend of onsite renewable strategies, semi-closed loops for water and energy, intelligent operational systems, incorporation of natural systems into the urban fabric, and a design aesthetic that creates memorable places that people want to care for over time. [emphasis added]
>
> At the *building* scale, green buildings of all kinds such as the Zhome in Issaquah, US, become vital building blocks to the success of these sustainable and resilient districts. [emphasis added]

He cites other case studies illustrating how the whole might eventually be approached from the progressive agglomeration of the nascent resilient parts, notably Hammarby Sjöstad and Värtahamnen port, both in Stockholm, Sweden.

Writing from a largely conceptual perspective, Salingaros [61] substantiates the theoretical underpinnings of Moddemeyer's argument. Indeed, he expands them. For Salingaros (a mathematician-*cum*-architect), intervening to change the connectivity among a diversity of socioeconomic agents across space in a city would be key. "Living cities have intrinsically fractal properties, in common with all living systems," he argues. They are a system of self-coherent sub-networks within larger-scale self-coherent sub-networks. Each sub-network is self-similar and nested, graduating scale by scale up to the level of the city as a whole. Living cities exemplify principles (R1), a diversity of agents, and, in particular, (R2), benefitting from cross-scale interactions.

What we therefore see in this sequence of five case studies, from the autarkic house to the whole city, is nexus security being enhanced through a broad multi-faceted strategy of, first, increasing diversity — through increasing degrees of autonomy at several scales within the city, i.e., creating quasi-autonomous, self-reliant agents and clusters of such agents (where these did not exist before) — and, second, increasing diversity within a progressively more variegated hierarchy. Together, these may hint at the workings of principle (R3), i.e., greater resilience through a tolerance of redundancy, but somewhat coincidentally in these particular case histories, i.e., not by deliberate intent or forethought.

4.4 Green infrastructure

The following are familiar instances of green infrastructure: using trees to provide shade to mitigate urban heat islands; planting green roofs in a manner designed to enhance urban biodiversity (as above, in the case history of the Westfield Stratford City complex); introducing grassy bioswales, ephemeral retention ponds and wetlands to attenuate stormwater runoff (not to mention tidal surges); and restoring linear, canalized, culverted, urban streams to a meandering, more natural, daylight-receiving condition, again for the purpose of stormwater management. These are all instances of nature being "imported" into the city — instances of incorporating "natural systems into the urban fabric" (as expressed by Moddemeyer [38]) — to bestow resilience ((R1) through (R4)) upon various aspects of the behavior of the city. Perhaps more accurately, they seek to restore the natural capital and ecosystem services of the landscape to conditions approximating those prior to the city's initial occupation of that landscape [14,62].

They are also motivated in significant part by the threatening insecurity of climate change and climate variability. Thus we have the following case study in green infrastructure to assess.

8) The Mayesbrook Park in the London Borough of Barking and Dagenham has been "designed to produce the UK's first climate change adaptation public park" [40]:

> 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 intention of replacing aging, gray, hard infrastructure for flood management by such softer, green infrastructure is clear [40]:

> 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 [40]:

> 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

Nothing in this case study is motivated by any principles of diversity insofar as they relate to enhancing nexus security, i.e., (D1) through (D4). Relative to the present gray infrastructure, the added "provisioning" functions of the ecosystem services sought from this particular piece of green infrastructure — fresh water, food, fiber and fuel — are negligible. No additional input-supply options will be created. In fact, these provisioning functions for the Mayesbrook Park restoration are valued at $0 per annum. In contrast, those of regulation, including additional flood risk attenuation, are valued at $44,000 (£28,000) each year; those of supporting services, such as nutrient cycling and wildlife habitat creation, at $49,000 (£31,000); and the cultural services of recreation and tourism dominate at $1.4M (£820,000). How we assess any increase (or decrease) in nexus security here is not straightforward, as we shall see.

4.5 Failures and insurance

The Mayesbrook Park case study, along with other examples of contemporary innovations in green infrastructure [63,64], may well inject greater resilience into the behavior of the city, but do they increase an agent's awareness and appreciation of nexus security? Does the enhanced security provided by an individual's greater sense of belonging to a community derive from the cultural services so highly valued for the Mayesbrook Park? Some of us may *feel* more secure knowing of the existence of "hard", "fail-safe" conventional flood defenses, not least in the face of climate change. Others might feel less secure, especially when confronted with the prospect of their neighborhoods being subjected to flooding by design, as it were, in order for society collectively to learn how to cope with increased rates of flooding, hence adaptation toward flood-resilient cities [39]. To paraphrase (and augment) somewhat, the argument in Liao's work on the concept of the flood-resilient city runs as follows.

Climate change and increasing rates of occurrence of extreme meteorological events will render pursuit of the flood-free city prohibitively expensive (if not plain futile). We should therefore embark upon a historic transition toward flood-resilient cities, in which enhanced resilience is to be approached with a three-pronged strategy: first, retention of the often useful, if yet brittle, engineering resilience of the customary, conventional, hard, gray infrastructure of flood defenses; second, progressive recombination of conventional infrastructure with the somewhat more ecologically resilient green infrastructure; and, third, a growing volume of explicit appeals to the ecological resilience of urban communities of people. People have the capacity to continue to function and learn lessons to improve their survival strategies in the face of one flood after another [39], now perhaps in the relatively "safe" space of the green infrastructure exemplified by London's Mayesbrook Park. Enhanced nexus security, however, somehow seems starkly incompatible with the notion of welcoming floods as social learning opportunities.

Such expected failures are known risks to security, as discussed above in shaping principle (D4), which is defined by its attachment to considerations of the divide between normality and abnormality. For two decades insurance companies have been factoring climate change into the formation of everyday insurance policies. Significantly, in a recent "Thought Leadership" piece posted under the ClimateWise 2012 Discussion Group of the Cambridge Sustainability Network — entitled "The Value of Ecosystem Resilience to Insurers" — Ian Kirk, Chief Executive of the South African based Santam Group, has made the following argument:[1)]

> 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 behavior. On a micro level, it will eventually impact certain decisions that we make in terms of underwriting and risk exposure.

These "system dynamics" can be subtle, complex, and counter-intuitive [28]. We have argued elsewhere [9,14] that enhancing water security through desalination may in time expose more people in rapidly growing coastal cities to the oncoming insecurities of sea-level rise — an unintended consequence of technological innovation. Social learning is always in play as well. Hurricane-superstorm Sandy, which made landfall along the New Jersey and New York city coasts in October/November 2012, is more and more frequently being referred to as the "new normal", such that one wonders what then might amount to the inevitable "new abnormal".

But there are known risks other than inundation. And addressing nexus security in respect of these too may have

1) available online at http://www.climatewise.org.uk/issue-two/ (accessed November 11, 2012)

unintended consequences. Enhancing security through principle (D3), i.e., the de-centralization of infrastructure and service provision, may induce a counter-productive loss of security. Bringing an output-return option (for wastewater assimilation) ever closer in space to an input-supply option (for potable water), which is the essence of de-centralization (and the opposite of what has historically secured public health in the city), could risk the insecurity of enhanced pathogen propagation, especially in the event of failure in the system. There is an obvious question:

> Is one big, very infrequent failure in a centralized system of sewerage and wastewater treatment plant better/worse than *n* small, frequent failures (where *n* may be quite large) in a system of many decentralized wastewater treatment plants?

There is some irony, therefore, in the observations of both Olsson [65] and Truffer et al [58] — on the role of the information technology (IT) sector — in contemplating how to respond to such a question. Indeed, their observations have a bearing on fairness, on the moral position of taking care of one's own wastes, and even on matters of civil liberty [66]. Here is the nub of the issue. As responsibility for treating household sewage is progressively devolved down to individual, *private* households, overseeing the maintenance of *public* health increasingly generates a market need and niche for "remote professional service supervision" [58,65], presumably because some individuals cannot be trusted to take care of their own wastes on a 24-7 basis (see also [14]). Progressive de-centralization of the physical, civil engineering infrastructure of the city, it is suggested, should go hand-in-hand with the creation of a progressively centralized and automated (virtual, IT) control-engineering infrastructure.

Tenuous empirical evidence suggests that (in very simple terms) the following are the "observed" (i.e., conjectured) probabilities of disease/infection propagation due to failures in a wastewater treatment system (based on [67]):

The probability of a {small number of infected people, given a centralized (large) wastewater system} is greater than the probability of a {small number of infected people, given a decentralized (small) wastewater system}

yet

The probability of a {large number of infected people, given a decentralized (small) wastewater system} is greater than the probability of a {large number of infected people, given a centralized (large) wastewater system}

How shall we incorporate such considerations into any analysis of whether nexus security is likely to be enhanced by retrofitting buildings for semi-autonomy with respect to wastewater handling (as indicated above), *without* compromising the hard-won security of public health in the city, itself the very basis of livable and sustainable cities in the first place?

5 Cities, their hinterlands, and nexus security

Taking stock of our qualitative assessments of contemporary examples of innovations that have a bearing on nexus security from the perspective of the city, we should ask now: what, if anything, does enhanced nexus security in the city, and the city's demands on supplies from elsewhere — perhaps from well outside the city — imply for security overall, and in particular, with respect to the city and its rural-agricultural hinterland and the city in the context of globalization? Our assessments in this paper have been conducted from the perspectives of the human environment (Section 3) and built environment (Sections 4), both essentially from *within* the city. Yet these are just two of the three compositional elements of a coupled human-built-natural system, where the natural environment self-evidently lies largely outside the city, typically in a watershed. In the framework of a Multi-sectoral Systems Analysis (MSA) [11,47], for instance, our computational studies of urban metabolism have naturally and necessarily included the broader domain of the coupled city-watershed system, e.g. the Atlanta-Chattahoochee case study noted above. In fact, this MSA includes an account of the metabolism of the forestry sector, since it is such an important feature of land cover in the Upper Chattahoochee watershed surrounding Atlanta.

The following provisional observations are offered in response to our question. Cities, we surmise, are likely to become more resource efficient and more self-sufficient, i.e., less dependent on the outside world, if albeit marginally so (on a per capita basis for urban dwellers). On the first account, cities ought to be able to succeed in becoming more efficient in their metabolism of resources, through drawing in proportionately less from outside and recycling more within the city. Taken together, this would constitute a reduction in per capita demand on the rest of the world's resources. On the second account, cities may achieve greater self-sufficiency in three ways: through recycling, including the mechanism of urban farming; through better harvesting across the urban landscape of the incidental (external) resource/supply inputs of wind, precipitation and solar radiation; and through the creation of "storage", i.e., the capacity to have access to resources when otherwise access might be denied, e.g., storage of electricity-providing capacity in the absence of a connection to the electricity grid. Wood sheds and coal cellars, which once provided energy security, have disappeared from the cities of the Global North. Today we look toward storage in the form of batteries. With such strategic shifts over the decades and centuries in predominant fuel forms, the long view of history must also be introduced into gauging progression toward (or away from) overall security. This view should accompany the wider overarching perspective of the city and its watershed-hinterland as a coupled human-built-natural system.

The concept of a city's "hinterland" dates back to the early 1800s [68]:

> [It] was coined to describe [those] surrounding rural territories shaped by the urban demand for food, energy and materials and by the services offered in return by the city.

The evolving nature of the driver of globalization has in recent decades come to challenge the applicability of this self-evident city-hinterland nexus [68]:

> [T]here has been an increasing trend toward considering cities as the nodes of a global network of trade exchanges.

From the perspective of nexus security — as improved simply along the dimension (D1), a diversity of supply options — one might propose that benefitting from all three elements of city self-sufficiency, city-hinterland connectivity, and city-global connectivity, ought to be a good thing, in principle (at least for the city). Except that moving upwards along one dimension of security may entail progressing downwards along another. A conspicuous example here is the increasing C-energy footprint of the transport required to facilitate increasingly remote connectivity and the increasing exposure of city metabolism to the reliability and security of that transport system. In particular, from their analysis of cities of the Global North, specifically with respect to the revival (or not) of the city-hinterland symbiosis, Billen et al suggest [68]: that access of the city to water was and is a local matter; food security seems more a function of both hinterland and global connectivity; while energy supply rests today on connections extending into places far distant from the city. In the case of Paris, for example, the "average supply distance" for energy was 200 km in 1800 (for wood as the predominant fuel), 270 km in 1870 (with access to more remote coal basins), and 3850 km in 2006 [69].

The relationship between the city and the rest of the world is neither constant nor entirely somehow "self-organized". Policy interventions, and their equivocal economics [5], matter. And to Marsden and Sonnino [70] they matter for reasons of health and wellbeing and should preferably imply a deliberate revival of the city-hinterland relationship:

> National and sectoral policies ... are becoming less relevant in dealing with [the 'double burden' of obesity and hunger] — which, to a significant extent, have been caused by global policies that have placed too much emphasis on the production of (rather than access to) food ...
>
> In this context, a growing number of cities around the world are devising their own place-based solutions to the current security and sustainability crisis, largely (although not exclusively) through urban food strategies that aim to forge new alliances between food consumers and producers and between urban centers and their surrounding hinterlands.

Historically, these authors tell us [70], letters between Marx and Engels in the 19th century revealed the former's concern for ecological disruption (as we might now call it), especially through the depletion of soil fertility brought about by the intensification of agriculture in the countryside, itself driven by the ever larger urban settlements — themselves the result of the rise of capitalism. Significantly, the ensuing separation of functions, between city and countryside, has been referred to as the "metabolic rift" ([70], citing others).

If the city-hinterland relationship were to be revived, thereby bringing greater attention to the role of natural systems in the hinterland (as Krchnak et al propose [55]), nexus security might then be more clearly discerned as a function of coupled human-built-natural systems. If this were so, the following closing remark should be made. Holling [16,29] derived his understanding of the all-important property of ecological resilience from observing the behavior of natural environments. Thompson [28] has mapped this insight, on a one-to-one basis, across to the behavior of the human environment. A similar description of ecological resilience in the built environment has yet to be fully articulated. If and when it is, ecological resilience in the behavior of each of the three environments, we assert, should be mutually reinforcing and benefit tangibly the resilience, and hence security, of the coupled whole. And this would be to serve in large part what is meant by city-watershed or city-hinterland symbiosis.

6 Conclusions

The assessment of nexus security provided in this paper has been carried out within the wider setting of our ongoing studies of governance and technological innovation in the transformation of cities, such that they may become forces for good in the environment [14,19,43]. In particular, the present assessment builds on the work of Beck and Villarroel Walker [7], in its review of nexus security as an extension of water security.

Eight principles (four each for diversity of access and for resilience) have been applied in order to structure thinking about eight case studies of urban buildings and infrastructure, which, in their various ways, illustrate progress away from insecurity and toward security. These principles succeed, we conclude, in codifying and understanding past case histories in how nexus security might be enhanced. They point toward how policy interventions and strategies of re-engineering city infrastructure might be framed for the future, if improved security, resilience, diversity of access and sustainability are to be achieved more broadly.

These are early days in the development, review and application of such principles, however. We are very mindful of the elusiveness of achieving operational definitions in these matters and the risks of what we have elsewhere labeled “definition slip”, that is [7]: calling for a new word, here “security”, “resilience” or “antifragility”, out of frustration or *ennui* in defining — operationally — what some might now consider the old word of “sustainability”.

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