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REVIEW ARTICLE

On water security, sustainability, and the water-food-energy-climate nexus

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Abstract The role of water security in sustainable development and in the nexus of water, food, energy and climate interactions is examined from the starting point of the definition of water security offered by Grey and Sadoff. Much about the notion of security has to do with the presumption of scarcity in the resources required to meet human needs. The treatment of scarcity in mainstream economics is in turn examined, therefore, in relation to how each of us as individuals reconciles means with ends, a procedure at the core of the idea of sustainable development. According to the Grey-Sadoff definition, attaining water security amounts to achieving basic, single-sector water development as a precursor of more general, self-sustaining, multi-sectoral development. This is consistent with the way in which water is treated as "first among equals", i.e. privileged, in thinking about what is key in achieving security around the nexus of water, food, energy and climate. Cities, of course, are locations where demands for these multiple resource-energy flows are increasingly being generated. The paper discusses two important facets of security, i.e., diversity of access to resources and services (such as sanitation) and resilience in the behavior of coupled human-built-natural systems. Eight quasi-operational principles, by which to gauge nexus security with respect to city buildings and infrastructure, are developed.

Keywords cities as forces for good, diversity, energy and nutrient recovery, green economy, infrastructure failure, resilience

1 Introduction

We seem to be suffering from some form of "definition slip" regarding the principles for stewardship of the man-environment relationship: from sustainability, to resilience, to security, to smartness, and so on. Judging by the time (and immense frustration) it can take to come up with a definition of any one of these terms, this is unsurprising. The very first words of the introduction to the recently published Sustainability Concepts Paper are these [1] (www.cfgnet.org):

> "Without an operational definition of sustainability with which to work, we shall not make any progress in this project."

These words were spoken in 2007, as a comment to the author of that paper. Exactly the same could be said of water security today. Of the two primary elements of Cook and Bakker's critique of approaches to water security, one is "Operationalising water security: narrowing a broad framing" [2].

If it is just too difficult to hammer out an "operational" version of, say, the principles of sustainability, in order to gain some practical traction with them, perhaps we could allow slippage toward resilience as a more tractable concept and principle for fashioning policy and guiding practical management. One senses, however, that this is something of an illusion, as Liao has recently remarked [3]:

> With growing popularity, the term resilience is increasingly used vaguely such that it is becoming like the word sustainability, i.e., having a diluted and unclear meaning.

In the meantime, urgent issues "on the ground" *are* being addressed and resolved, even if imperfectly, according to the various principles we are still trying to define. Not surprisingly, all of these principles have something to contribute to practical problem solving; and, not to be overlooked, practice re-shapes concepts, every bit as much [1].

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Given the experience of composing the Sustainability Concepts Paper — which took nine years to complete, yet offers no better, *succinct* definition of sustainability than a paraphrasing of the original Brundtland definition [4] — we hesitate to propose some novel definition of water security. It is, of course, the brevity of any such definition that is the essential challenge, not the vastness, complexity and subtlety of all the concepts below, and upon which that one-sentence definition rests as just the pinnacle.

Rather, we shall begin by adopting the prior definition of water security proposed by Grey and Sadoff [5]. As we interpret this definition, it is directed at "water development" (and poverty reduction) as the precursor of subsequent broader (multi-sectoral) economic development. Accordingly, Section 2 brings an economics discourse to bear on this subject and, more specifically, on the notion of scarcity that is deeply embedded within mainstream economics and the concept of security. This, in turn, obliges us to examine how human aspirations (ends) are reconciled with access to supplies of environmental resources, i.e., the means to meet those ends. This examination itself brings our discussion down to the details of human motivation and the expression of personal needs (and wants), i.e. demands. Besides this closer scrutiny from the perspective of economics — or economic feasibility, as one might express this in the terms of sustainability [1] or the Triple Bottom Line [6] — Section 2 examines the working definition of security from the companion perspectives of social legitimacy and environmental benignity. Our enquiry is motivated by these questions: how effective is water security likely to be as an exhortation to action, in particular, if and where that of sustainability might hitherto have failed; and will the concept of security suffer from the limitation of being exceedingly difficult to define in an operational sense, as we have already seen above [2] with sustainability [1] and resilience [3]?

In Section 3, attention is transferred from security in merely the water sector to security in the water-food-energy-climate security nexus. The naturalness of the logic in this transfer is aptly expressed in the title of a 2011 World Economic Forum (WEF) book: *Water Security*: *the Water-Food-Energy-Climate Nexus* [7]. Once one has adopted such a multi-sectoral stance, it is difficult thereafter to confine thinking and analysis to just a single sector, such as water [8]. And whereas Section 2 (on water security) is tacitly concerned with the supply of resources (water), Section 3 focuses instead on the demands for those resources, hence their flows around the globe. In particular, Section 3 treats the demands for environmental resource flows from the less customary perspective of city metabolism, not least because cities are increasingly the predominant origin (or motor) of those demands. Cities are self-evidently points (or nodes) of the most intense intersections among flows of water, food and energy.

Having thus broadened the purview, Section 4 shifts focus once again: to a less macroscopic and more detailed level of analysis in order to establish some applicable criteria derived from the ideas of "diversity of access" and "resilience", as entailed in the working definition of water security. This is achieved on the basis of systems thinking, or "nexus thinking", as it has been called elsewhere [9]. Although resilience is now a familiar phrase in everyday discussions, the concept, we argue, is not always defined or discussed in its most comprehensive sense. Section 5, therefore, is devoted to a somewhat deeper exploration of its origins in the work of Holling [10] and his subsequent observations on the relationship between resilience and sustainable development [11]. He gives us an unusual insight into the nature of sustainable development, which, again, is a perspective that is not often aired in discussions of sustainability in the water sector.

Water security and nexus security are emerging concepts, as both Cook and Bakker [2] and Hoff [9] freely acknowledge. We should fully expect what we understand by them and their further elaboration to change over time, just as has been the case for the concepts of sustainability (as, for example, in [1]). By the end of this paper, our goal is to have secured the conceptual foundations of the notion of security to an extent sufficient to assess subsequently its application in practice [12].

2 Water security and sustainable development

Intuitive definitions are always helpful: as the briefest of exhortations, as it were, or calls to action. The very essence of the ubiquitous Brundtland definition of sustainable development can be expressed in but a single sentence [4]. Yet such brevity, just like that of the essence of Leopold's land ethic some four decades earlier [13], is no barrier on the motivation and inspiration to act effectively in the world [1].

Looking back from Cook and Bakker's "comprehensive review of the concept of water security" [2], there is much to recommend the definition provided by Grey and Sadoff as the starting point for this discussion [5]:

> [Water security is] the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economics.

Among other resources, such as food and energy, i.e., the means to meet our ends (needs, wants, or luxuries), water, it *may* be argued, is unique. One can have "too much" of it, as in floods. Insecurity with respect to water can be a matter of two-sided exposure, that is, both too little and too much. According to Grey and Sadoff [5]:

> [Water] is an input to almost all *production*, in agriculture, industry, energy, transport, by healthy people in healthy ecosystems.
>
> [The] destructive aspect of water, as a consequence of its extraordinary power, mobility, indispensability and unpredictability, is arguably unique.

The words "production" and "risk" in the Grey-Sadoff definition of water security reflect the two sides of water: too little on the productive side, as (in their words) "a source of production, health, growth and cooperation"; and too much on the destructive side, as "a source of destruction, poverty and dispute". Significantly, acknowledgment of the Triple Bottom Line of sustainability and sustainable development [1,6] is apparent on both sides of security so defined: for *profit*, in production and economics; for the *people*, in their safety, health, and livelihoods; and for the *planet*, its ecosystems and environments.

In what follows, we shall circulate around the working definition of water security according to this same sequence of attributes, expressed in the complementary triplet of: economic feasibility (sub-sections 2.1 and 2.2), social legitimacy (sub-sections 2.2 and 2.3), and finally, environmental benignity (sub-section 2.4). An examination from each perspective is needed to evaluate the scope and completeness of the definition.

As far as we can tell, the Grey-Sadoff definition has been motivated by the need for less developed countries to have their socio-economic status raised above some critical threshold, after which their further (economic) growth should be self-sustaining. Their arguments culminate in this phrasing [5]:

> [E]nhanced by local and indigenous knowledge and consultation, there is great potential, and an imperative, for developing countries seeking to achieve water security, poverty reduction and growth to "push down" the stylized Kuznets curve, by greatly lowering environmental and social impacts.

In other words, environmental and social impacts rise to a peak and then fall, as incomes move from being low to high (the general Kuznets curve). But for developing countries, in particular, these impacts should be reduced (over all time) relative to what might otherwise have been given *no* water development, hence water *in*security. The implication is that basic (mono-sectoral) water development brings basic water security, providing the platform on which to build subsequent multi-sectoral, sustainable development [5]:

> For those countries that have not achieved water security, this objective lies at the heart of their struggle for sustainable development, growth and poverty reduction.

In line with what we shall come to appreciate as the utterly dominant view, the primary drag on economic development is taken to be scarcity [5]:

> As water becomes increasingly scarce relative to demand there are emerging fears of inter-jurisdictional waters becoming a serious cause of conflict and constraining growth.

2.1 Scarcity and economic thought

Indeed, scarcity is sufficiently taken for granted in modern, mainstream economics — as a natural fact of life or a naturally occurring phenomenon — for Fine to feel obliged to confess this [14]:

> [D]espite having spent a working life in criticism of the orthodoxy [in economics], I can only be struck by the extent to which the notion of scarcity has attracted so little attention, in my contributions too, while being generally accepted as being indispensable to the mainstream.

It is well worth tracing the history and origins of contemporary, mainstream economics, as this will have much to do with the way in which we can view things such as *basic* human *needs* and (perhaps) distinguish them from wants and desires (as other ends). We shall also need to come to an understanding of how mainstream economics is but one of five ways of managing means and ends — with respect to how (natural) resources, as the means, are brought into alignment with human aspirations, i.e., with our ends (our collectively expressed needs, wants, desires, luxuries, and so on).

In the beginning, as related by Samuel and Robert [15], Aristotle distinguished between "use value", which he associated with the acquisition of resources for satisfying natural needs, and "exchange value", which was regarded as being associated with retail trade and wealth-accumulation. Adam Smith, as the father of classical economics (in the 18th Century), is said to have achieved the following [15]:

> Smith centers the study of political economy on exchange value. In doing so, he overturns the traditional understanding of 'economics' in two ways: he excises use-value from its purview and also legitimizes vanity and greed.

The modern notion of scarcity was subsequently embedded in the foundations of today's orthodox economics during the "marginalist revolution" of the 1870s [14]:

> Crucial is the idea of economic rationality in the form of optimizing individuals. This is true of supply (the theory of the profit-maximizing firm) and of demand (the theory of the utility-maximizing consumer).

Entailed in this revolution was the idea that [15]:

> Utility is assumed to increase the more one possesses, so that three chairs and three tables offer greater utility than two of each.

"More is more", proclaims one of Thompson's [16] theatrical characters in his discussion of scarcity, alongside the alternative discussions of Fine [14] and Samuel and Robert [15]. Or, to put this another way (for example [17], in [18]):

> [I]n the neoclassical world ... the non-satiety requirement ... assumes that people will always prefer a large basket of goods to a small one.

Thus, in the 1930s, Lionel Robbins was able to express what is now generally agreed to be the essential definition of neo-classical economics, which still prevails (as quoted by Mehta [19]):

> Economics is the science which studies human behavior as a relationship between given ends and scarce means which have alternative uses.

And this is indeed the abiding and contemporary definition, for here is Fine [14] quoting Stiglitz [20]:

> Economics is the study of scarcity, how resources are allocated among competing uses.

Samuel and Robert consider utility to have been the essence of economics for the past several decades [15]:

> What is decisively new in neoclassical economics is that 'utility' becomes a placeholder for a mathematical construct.
>
> [W]hen, for example, Jevons asserts 'value depends entirely upon utility', he reinterprets everyday experience and language to suit a mathematical function. It is well known that the invention of 'diminishing marginal utility' constitutes the real and lasting novelty of neoclassical economics, obtained by fitting economic thought to the structure of differential calculus.

Looking back on what he has said as a critic of neoclassical economics, Fine arrives at the following end-point [14]:

> So why do economists, and critics, make such a hullabaloo over scarcity if it only pertains to a limited extent, in special cases, within their own analyses? The answer is not because of the analytical role of scarcity itself but the dogmatic attachment of economists to the technical apparatus that is used to define it in those special cases. That technical apparatus comprises ... the use of production and utility functions and so on, as if economic (and social) activity were the outcomes of automatons.

2.2 Means and ends

Scarcity is based on the idea that resources (means) are limited, whereas wants and desires (ends) are not (see e.g. [14]). Playing on words, and slightly perverting the title of the 1970s text *The Limits to Growth* [21], Mehta has called her book: *The Limits to Scarcity*: *Contesting the Politics of Allocation* [18], to which the works of Fine, Samuel and Robert, Thompson, and Rayner are all contributions.

For Mehta, scarcity is not the same as the numerical limits to biophysical resources on spaceship Earth, i.e., the limits (finiteness) of water, food, and energy. As she says [19]:

> The scarcity postulate (in other words, that needs, wants and desires are unlimited and the means to achieve these are scarce and limited) that underpins modern economics need not be universal. Needs, wants and desires do not have to be endless and unlimited.
>
> More often than not, the problem lies in how we see scarcity and the ways in which it is socially generated.
>
> [S]carcity rarely takes place due to the natural order of things. Instead, it is usually the result of exclusion and unequal gender, social and power relations that legitimize skewed access to and control over finite and limited resources. As such, scarcity is a relational concept ...

Cook and Bakker, in their work on water security [2], would seem to agree, albeit in less strident terms:

> Framings of water security are thus dependent upon one's perspective, as reflected in the diversity of framings put forth in the academic and policy literature.

> We argue that an integrative approach to water security brings issues of good governance to the fore ...

What is "acceptable" in the Grey and Sadoff definition of water security [5] — twice, on the two sides of the exposure to insecurity — will doubtless have to be found through the "governance" of Cook and Bakker [2] and the case-specific "contested politics" of Mehta [18], hence reconciling the "given ends" and "scarce means" of the Robbins definition of neoclassical economics.

It falls to Thompson to provide us with a complete map of this "essentially contested terrain"[16]:

> 'Making ends meet' is ordinary language for economizing, and the ends in question are needs and resources. But needs and resources are not just given; to some considerable extent, we make the ends themselves before we make them meet. Cultural theory [22] is built upon this 'social malleability'; it gives formal expression to the everyday observations that some people are more needy than others, and that some are more resourceful than others. Its basic hypothesis is that whether a person is able to manage his needs and his control over resources depends on the way in which he is caught up in the process of social life. ... There are ... four logical possibilities:
>
> 1) You can manage neither your needs [ends, herein] nor your resources [means, herein]
> 2) You can manage your needs but not your resources
> 3) You can manage your resources but not your needs
> 4) You can manage your needs and your resources.

As it happens, one of the two ways of acting in the world under Possibility 4, whereby ends (needs) and means (resources) are managed ever upwards (as high as possible), is the one strategy countenanced by neoclassical economics. It is enshrined in its non-satiety requirement [16] and in the device of the singular rationality of "rational economic man", i.e., Fine's "automaton" [14]. It is the strategy of the market, defined by its opposition to its counterpart, the strategy of government intervention (i.e., acting according to Possibility 3 above), for when the market strategy fails. But these two universally well-recognized strategies of markets and regulation leave unrevealed (and unexploited) three additional, quite different strategies for "making ends meet".

In fact, to be fair and even-handed with respect to the notion of scarcity, Thompson concludes [16]:

> [I]t is not scarcity per se we need to worry about; it is when scarcity-based arguments and policy decisions go uncontested ... that the little red warning lights should start blinking.

The rationality of the market is not necessarily wrong. However, it is not the *only* rationale for understanding the world and acting in it. It is interesting to note that Cultural Theory [22] is increasingly being referred to as a theory of *plural rationalities*, which surely it is. For Thompson, sustainability itself is an essentially contested concept [23]. The plurality of moral positions entailed in various worldviews on the man-environment relationship, such as fairness, for instance, is a crucial determinant of material-resource flows [24].

In *The Limits to Scarcity* [18], Gyawali and Dixit proceed to show us how Thompson's framework of Cultural Theory can be employed to form a 4-fold typology of private goods, public goods, common pool goods and club goods, through which to understand the dynamics of demand creation and the politics of scarcity in the economic development of Nepal [25]. We too are using Cultural Theory; in our case as a means to explore and shape appropriate styles of governance for enabling cities to become forces for good in their environment [12,26]). In particular, Ney's work on governance [27] for resolving messy policy problems and handling conflict is central (see [1]).

We have thus prized apart the scarcity-security bond and, by association, the scarcity-poverty bond. Scarcity-security *is* a strong bond. But scarcity is not the only factor determining security. We should heed Thompson's analogy of the "little red warning lights" [16].

2.3 Needs, wants, luxuries and demands

To summarize, and to reflect for a moment (lest we forget this), managing needs (ends) relative to resources (means) is the essence of our existence and hence man's interaction with the environment. It is a matter that lies at the heart of the Brundtland expression of sustainable development, as it indeed says, "development that *meets the needs* of the present without compromising the ability of future generations to *meet their own needs*" ([4]; emphasis added). In fact, to reflect further, we should ask: what today might be the relevance of Aristotle's original distinction between use-value, associated with the appropriation of resources for satisfying natural needs, and exchange-value, associated with buying goods for the purpose of re-selling them at a profit? Does this use-value, having been excised by Adam Smith from neoclassical economics (according to Samuel and Robert [15]), still hold some contemporary relevance?

To paraphrase briefly the main message of Rayner's preface [17] to Mehta's book on scarcity, both the argument of *The Limits to Growth* [21] — a form of ecological economics according to Rayner — and the application of the technical apparatus of neoclassical economics [14] end up being "anti-poor". Addressing the needs of the poor, according to Rayner, will require a fundamental shift: away from policy driven by the notion of scarcity to policy shaped by issues of resource allocation, access and entitlement, which has long been the argument of Amartya Sen (see [14]). Although a student of Sen, Fine would however not be entirely in agreement with Rayner on this. Nevertheless, such a shift from scarcity treated as inevitable and absolute will oblige us to focus keenly on judgments on the appropriateness of personal needs and wants.

In this respect, two of the earliest definitions of water security are elaborated below, as quoted by Cook and Bakker [2]. Both echo Sen's concern with "access" and both are "person-centric". The first offered this definition [28]:

> [W]ater security at any level from the household to the global means that every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life, while ensuring that the natural environment is protected and enhanced.

The second, attributed to Rijsberman, was expressed as follows [29]:

> [S]ufficiency of water supply for humans is the primary gauge of water security. For an individual, water security exists when she has access to sufficient safe and affordable water to satisfy her needs for drinking, washing, and livelihood.

Both seem to be biased toward what Aristotle valued as a use, or a "natural need". Between the two, however, one senses the second has pulled slightly back from the "needs" and "wants" of the first (where they are elided as almost indistinguishable) to confine the aspirations of water security to more basic "needs" alone. And if so, this would in turn appear to be redolent of the way in which Grey and Sadoff [5] refer to achieving a *basic* platform of water security (and on more than one occasion). "Water development", in other words, precedes more general (economic) development. Grey and Sadoff's definition of water security, however, through its inclusion of the destructive nature of too much water, dilutes the concentrated emphasis on sufficiency-just-beyond-*scarcity* in the two earlier definitions.

However, both the Global Water Partnership (GWP) and Rijsberman definitions hint at the kind of hierarchy of needs and wants embraced by Maslow in his theory of human motivation [30]: basic physiologic needs, e.g., to survive, to drink, to eat and to keep warm, must be satisfied before the individual can move on to the higher psychological needs of esteem and self-actualization. But this is not so, claim Rayner [17] and, in more detail, Douglas *et al*. [31]. Neither was this the case in a study of whether ecological sanitation systems should be introduced into a community within peri-urban Accra, Ghana ([32]; see also [1]). As Rayner [17] puts it, drawing upon the "radical critique of the idea of needs and wants" of Douglas *et al* [31]:

> [C]onsumption is not the expression of well-ordered preferences driven by the need to satisfy physical urges or vaguer internal demands, but to negotiate social relations.

Consumption of resources in meeting some end, we conclude, is not inward-looking and person-centric, but outward-looking, toward the person-society relationship. To reiterate, "security is a relational concept", as Mehta has put it (above) [19].

"Caught up in the process of social life" is how Thompson [16] might express this — caught up in the jostling, contested interplay among the proponents of his (five) strategies for making ends meet, for reconciling ends with the means, for managing needs and resources, and not necessarily picking off a need to be satisfied before enjoying the consumption of a luxury. Indeed, one might conceivably mobilize resources (water) to meet the highest of Maslow's motivations, of self-actualization, before meeting any of the lower, more basic needs (as observed also by Rayner [17]). The possibility exists for: "Acting very locally [with water], to engender thinking globally [hence self-actualization]" [1], as the complement of "Thinking globally, acting locally", and alternating with it, sequentially over time.

In short, the Grey-Sadoff definition of water security embraces more of Aristotle's use-value, not just his notion of exchange-value, which is the entirety of consideration in modern, neo-classical economics (in the view of Samuel and Robert [15], that is). The problem with the Grey-Sadoff definition — perhaps just as they intended — resides in the word "acceptable", used twice, with respect to there being either too little or too much water. This obviously raises the following questions: acceptable to whom; according to which of the plural strategies of making ends meet; and arrived at through what socially legitimate process of constructive dispute, disagreement, conflict and debate [33]? How indeed, now in the light of these reflections on the economic and social dimensions of the Grey-Sadoff definition, might policies for action be expressly shaped by it [34]?

2.4 Variability and resilience

There is, of course, the third dimension of the "environment" in our working definition of security.

Much of Grey and Sadoff's [5] discussion is in fact about the environment or, to be more precise, the ways in which the variety of (natural) hydrological conditions determine the corresponding variety of trajectories of social and economic development in countries. Their variety is threefold: "harnessed hydrology"; "hampered by hydrology"; and "hostage to hydrology". The most difficult variety of hydrology under which to survive and prosper, say Grey and Sadoff [5], is that with a combined inter-annual and intra-annual variability. Furthermore, climate change, they observe, can only exacerbate this predicament. It is a difficulty (for them) at the heart of the challenge of achieving basic water security. The keys to surviving, then attaining prosperity (again, as they argue), will be achieving a society, economy, and infrastructure that is *diversified* and *resilient* in the face of shocks, i.e., the abnormalities of too little and too much, on either side of the security and comfort of the norm.

Precisely what might constitute such diversity and resilience, and how they might be brought about, is not discussed in detail in Grey and Sadoff [5]. Setting out along this path will accordingly be the subject of Sections 4 and 5 below. Before embarking on that path, however, we must first leave behind our focus on water security in order to adopt a broader view on resource flows as a consequence of man's interactions with the environment. For one thing, our examination of the working definition of Grey and Sadoff [5] has actually brought us up to such a broader view — of a society, economy, and infrastructure that are *diversified* and *resilient* in the face of shocks. For another, given the prevalence of mainstream economic-scarcity thinking hitherto, Mehta herself was dealing with scarcity in the three resource categories of water, food and energy, which (together with climate) constitute the nexus of which we now speak. Water seems to be privileged in this nexus as *primus inter pares* (first among equals).

3 The nexus

To the best of our knowledge, nexus thinking appears to have been arrived at more through prior water thinking than, say, food thinking or energy thinking:

> Water security is the gossamer that links together the web of food, energy, climate, economic growth, and human security challenges that the world economy faces over the next two decades.

So opens the introduction to the recently published book from the World Economic Forum (WEF) *Water Security: the Water-Food-Energy-Climate Nexus* [7].

In a background paper prepared for the November 2011 Bonn Conference on *The Water, Energy and Food Security Nexus* ("Solutions for the Green Economy"), Hoff declares, "Water plays a central role in the nexus" [9]. To confirm and consolidate this visually, "Available Water Resources" forms the *central* node of an accompanying diagram with four nodes. The other three — "Water Supply Security", "Food Security", and "Energy Security" — are triangulated around the central node as a periphery. That periphery is designed so as to suppress any sense that any one of these three nodes might merit more emphasis than the remaining pair [9]. Yet there is a kind of double counting, of course, since "water" is uniquely present in two out of the four nodes. Here too, as in the WEF book, water has been privileged; and, therefore, as in [5], the inference is that water development precedes general economic development.

This concerted effort — for example, in the introduction of the Stockholm International Water Week and Water Prize (in 1990), and the World Water Forum (inaugurated in 1997) — has indeed been a success. It is commonplace today to read and hear of a "global water crisis" [35–37]. A poll of business leaders and economists at the 2012 Davos meeting of WEF rated water insecurity among the five topmost threats to the global economy. In response, utility Veolia Water Americas has launched a website labeled growingblue.com. In an essay[1)] entitled "Blue is the New Green", CEO Laurent Auguste argues that Growing Blue is the new green approach to economic growth. Water development is hence the gateway to more general development [5].

Water *is*, it seems, *primus inter pares* within the water-food-energy-climate nexus.

With due respect to all, however, none of us is entirely above trying to grab the headlines of scientific and public attention. Non-water specialists pursue their own focal interests. For some, the 21st century will be a "Nitrogen Economy" [38,39]. What would that be? Growing Yellow? For others it will be the century in which "Peak Phosphorus" [40,41], or "Peak Food" [42], will render "Peak Oil" a mere bump in the global economic super-highway. Growing Red, perhaps? And this is without even thinking of a suitable color for growing toward our low-carbon futures. What is telling here, of course, is the fact that these calls for greater attention to the otherwise under-appreciated global nitrogen (N) and phosphorus (P) cycles — so vital for food security — resort to drawing parallels with the (self-evidently) much better appreciated energy sector, its security, and its companion global carbon (C) cycle.

There are risks in placing too great an emphasis on one

1) available online at http://www.growingblue.com (accessed October 12, 2012)

sector above all others, as *the* “first among equals”, including in the matter of security. Identifying water security as *primus inter pares* inevitably focuses attention on where, globally, man’s appropriation of water is greatest, i.e., in the agricultural sector and thus in the service of food security. The risk is that of unduly skewing thinking and analysis *a priori* toward this sector, the supply side of the security challenge/nexus, and resource shortages and scarcities (as we have seen above in Section 2; [18]). Yet the demand side of the challenge/nexus [43] is increasingly associated with one of the greatest global drivers of the present century: our rapidly and massively urbanizing world. What then, we ask, might the overall security challenge (and our response to it) look like from this different, but complementary, perspective?

3.1 Cities: as the origin of demand

For their part, cities are increasingly perceived as the engines of the global economy [44,45]. They are where the water, food and energy sectors interact with the very highest density of intersections and inextricable interdependencies. Cities are nodes of concentrated, intensively manipulated, and deeply intertwined global flows of resources — red, yellow, green, blue — all required to sustain the social, economic and industrial metabolism of the city (for example, [1,46–49]). Flows of water *and* energy *and* carbon (C), nitrogen (N), *and* phosphorus (P) are all vital. Growing Rainbow, we might now say, should be the uplifting economic complement of the somewhat threatening notion of a security nexus. No matter how hugely difficult the consideration, analysis, or realization of Growing Rainbow may prove to be, it is (in truth) no more nor less holistic in its breadth and scope than any companion analyses of nexus security — or of sustainable cities, or cities as forces for good in the environment [1].

And yet, growing blue and becoming water-secure *may* be the fastest and most expeditious path toward growing rainbow — as implied, in the words of Grey and Sadoff, by “water development” and “self-sustaining (sustainable) economic development” [5]. In this sense water might be granted special status. If so, such a privileged status for the water sector places an even higher premium on its wise stewardship.

Whereas the assessments of the security nexus given in [7] and [9] are tilted toward being water-centric, *ergo* somewhat pre-occupied with scarcities, shortages and the agricultural sector — and hence strongly supply-side oriented — ours (following the analysis of Section 2) is essentially city-centric and somewhat citizen-centric or person-centric, *ergo* demand-side oriented. To re-balance our thinking about security, i.e., to lift some of the predominant prior emphasis off resource supplies and place it on the resource demands of the city, we must consider two facets of the behavior of a city with respect to the nexus:

1) *Metabolism*, i.e., the flows of resources — energy and materials (carbon (C), nitrogen (N), phosphorus (P), and water) — entering the city from the rest of the global economy and subsequently circulating around and through its economic, social and industrial life before returning to the city’s environment (and the global economy). For this, attention is focused on biogeochemical processing and transformations of materials-energy [50,51].

2) *Pulse-rate*, i.e., an equally natural (bio-mimetic) way of conceiving of the city’s behavior, but in terms of its variations over time, and in a rather special way redolent of the analysis of electrical engineering systems, in particular through use of the concept of frequency spectrum. For this, attention is focused on variations over time understood as composed of a host of constituent sinusoidal components, with periodicities encompassing those of seconds, minutes, hours, days, weeks, months, years, decades, centuries, millennia, and so on [1,52].

Both are key to the way in which we shall examine nexus security and its growth or decline (both herein and elsewhere [12]). Together they also provide a basis for thinking about resilience, insofar as this relates to security, which is therefore the subject of Section 5 below.

4 Systems thinking, cities and security

Abstract language is occasionally needed in some cases of systems thinking. Consider the *system* of the city, abstracted from its physical surroundings, which can be labeled (abstractly) the city’s *environment* (or hinterland). Flows of material-energy into the city we will call *input supplies* and those out of the city *output returns*. Corresponding flows of material-energy within the city system, i.e., its *state* variables, and the mechanics of their transformation in the social, industrial and economic life of the city, i.e., the *structure* of the city’s metabolism, are the means whereby the input, pre-consumption supplies are transcribed into the output, post-consumption returns.

In less abstract terms, inputs are typically described as water, food, energy, transport and so on, while outputs are what we know as wastewater, water pollutants, greenhouse gas (GHG) emissions, solid waste and so forth (not to mention economic goods and services). Yet these familiar words from our everyday experience have allowed something of a “disconnect” to become established, and to persist to the detriment of our appreciation of the role of the city’s metabolism in the wider, global scheme of things (especially global material-energy cycles). For instance, water enters the city, but wastewater leaves it; or food enters, but solid waste and wastewater exit. Thus at a more basic level, and at the level required for our subsequent conceptual discussion, it is more helpful to observe instead that nitrogen (N), for example, enters the city *inter alia* in food and in fuels and exits in wastewater, solid waste and GHG emissions. Carbon (C) and phosphorus (P) have similar trajectories, just as it is illuminating to conceive of flows of Li (lithium) and rare earth elements as linked to strategies for low carbon futures [53]. Although such terms may arguably be overly abstract — at least for a lay audience — they bring necessary consistency to our discussion. There is no need to be pedantic about this, however. It makes eminent good sense to track the flows of water through the city, not those of hydrogen and oxygen.

All of these material-energy flows (inputs, states and outputs) exhibit variations with time, as does — we may note — the entire structure of the city's metabolism; that is to say, the structure evolves. We propose to discuss the nature of this dynamic behavior in terms of the city's pulse-rate, hence the frequencies and the spectrum of frequencies associated with all variations over time.

Variations across space are also self-evidently significant, although our discussion will be largely confined to thinking of variation either in terms of scale, as in a city, ward/district, neighborhood, household or individual; or in terms of de-centralization/centralization — in effect, disaggregating the system of the city into its sub-systems and conversely approximating analysis of the collective, multiple sub-systems through that of a single, aggregated system.

Our purpose now is to use the foundational concepts of metabolism and pulse-rate to characterize nexus security from the perspective of the city. As a point of departure, contemporary definitions of security for the individually considered sectors are recorded as follows (from [9]):

> Water Security: access to safe drinking water and sanitation; access to water for other human and ecosystem uses.
>
> Energy Security: access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses; uninterrupted physical availability of energy at a price which is affordable, while respecting environmental concerns.
>
> Food Security: availability and access to sufficient, safe and nutritious food to meet the dietary needs and food preferences for an active and healthy life.

We note the appearance of the word "sanitation" in Hoff's definition of water security [9].

4.1 Diversification and metabolism

For the individual agent or agency within the city — a person, household, business, utility or indeed the city itself — nexus security has about it an intuitive sense of *access to a diversity of options* for a given input supply, such as water (as in [5]), food, energy, or transport, *and* a diversity of options for a given output return, such as sanitation.

We may seek the security of having multiple options for the visceral benefit of ensuring survival through the maintenance of functions and services vital to the existence of the agent (important concerns of both Aristotle and Maslow [30], as we have seen). Beyond that, with a growing aspiration toward enhanced financial security and wellbeing, more than one option (the essence of diversity) can mean that costs and tariffs for each of these (now) multiple options might vary differently with time. Without such diversity, no economic difference could exist to be gainfully exploited by occasionally switching from one to another more affordable option.

Options may be physically diversified, and technically re-phrased in our abstract terms, in four ways (according to four principles):

(D1) Simply installing some kind of infrastructure to permit access to, for instance, more than one source of potable water from the system's environment (see the definitions of the GWP [28] and Rijsberman [29] quoted above), i.e., from *outside* the city (the system). To this can be added the following three additional options, as options residing *within* the system.

(D2) Reduced consumption of material-energy in the city by one agent that seeks to manage its needs (ends) *downwards* — two of Thompson's Possibilities above [16] (Possibilities 2 or 4) — in pursuit of frugality and eco-efficiency, for example, which may permit greater access to that resource by another, assuming both agents perceive security in such sharing.

(D3) Options may be multiplied through a principle of centralization-*cum*-decentralization, e.g., the provision of an on-site, household wastewater treatment unit that retains access to the centralized, municipal sewerage infrastructure, or even, in addition, to a neighborhood treatment option.

(D4) Diversity of options, moreover, can come from applying the principle of resource recovery and recycle — which could be called eco-effectiveness [54,55] — as in the production of soil conditioners, fertilizers and fuels from urban wastewater and solid waste. Significantly, this is a principle whereby output-return options may be converted into input-supply options.

Options may also be multiplied through changes in an agent's social status (as opposed to physical location and circumstances) with respect to: financial access to an option previously too expensive, as signaled above and by the presence of the word "affordable" in the GWP [28] and Rijsberman [29] definitions of water security; or legal access to something previously barred through some socially-constructed rule (echoing [25]).

Last, for the individual or family household, security associated with access to options for the diverse output returns of metabolism can be a function of two additional considerations: first, perceptions of immediate personal harm likely to be brought about by the various returns, such as GHG emissions, sewage and water pollutants, and food/solid waste; and, second, by the natural mobility and dispersion of the harmful substances in the different physical environments (air, water and soil). Each of us might ask: is this harmful to me; how safely and securely can it be removed from my personal space; and how readily might it come back to harm me, should I access the given option for an output return, i.e., for assimilating the substance back into the environment?

4.2 Pulse-rate: prelude to resilience

Now consider the pulse-rate of the city. Our everyday language describes the nature of the city's life, the nature of its variations over time. Think of the popular phrase, "Thank God It's Friday!". Businesses trumpet the fact that they operate on a 24-7 basis. The cycles of city life are focused on just two frequencies, turning once every 24 h and once every 7 days. We even seek to render the metabolism of the city free from any periodic fluctuation: the constancy, in other words, of "the city never sleeps". The supply of water, food, transport and power, as well as the generation of household and industrial wastewater and wastes, all beat to the 24-7 rhythm. It is as though the immensely rich variety of fluctuations in the natural environment — the *full* spectrum of these variations from seconds, days, intra-annual, inter-annual and inter-generational, to millennia and beyond — are to be subjugated (through our infrastructure) to furnishing human comfort within the narrow 24-7 bandwidth of life in the city.

There is something altogether rather predictable, rather deterministic, about this collective facet of "normal" city life, i.e., the normal city metabolism.

Sporadically (that is, aperiodically) and essentially unexpectedly, these various strands of urban infrastructure fail — perhaps 'safely', as opposed to the illusory safety of never failing (of being fail-safe) — and thereby disrupt the dynamic equilibrium of the 24-7. This surely is stochastic behavior, composed of high frequencies, with fast cyclical fluctuations, predominantly on the order of hours, minutes and seconds, above the 24-7 bandwidth, and having – just as surely – consequences for the notion of security. It is a form of abnormal behavior — the shocks to which Grey and Sadoff refer [5].

The causes of the abrupt, sudden failure may originate in the natural environment (a storm event), the built environment (material failure due to corrosion), or the human environment, such as inadvertent mismanagement of infrastructure, e.g., as a consequence of an inadequate understanding of the structure of the system's (the city's) behavior. Abrupt failure may be a function of much more slowly acting variables with lower frequencies, e.g., the steady, relentless wearing of the materials and surfaces in a pump, which eventually and suddenly fails. For present purposes, however, we shall not be as much concerned about what the causes of failure might be, nor how to arrange for its pre-emptive detection (through routine maintenance, forward planning, or disaster planning), as about the sudden loss of services and functions, i.e., the sudden reduction in security.

The drama and shock of such a loss of security through failure are magnified by the sudden absence of the intensity of normal life in the city, itself heightened simply by the concentration of people there. After the loss of life and limb, perhaps most shocking can be the insecurity of lost access to sanitation, i.e., a loss of access to an output-return option. Insecurity may be exacerbated precisely because this particular return option is normally taken entirely for granted, at least by those of us with access to the paradigm of water-based sanitation in the Global North.

Reporting on the impact of the 2012 Hurricane 'super-storm' Sandy on the city of New York and its surroundings, the BBC News website observed (on 1 November, 2012):

> The storm made landfall on Monday night (29/30 October) in New Jersey, where some 20,000 people remain trapped in their homes by sewage-contaminated floodwater.

It may not be the case that an individual agent in such circumstances is without any output-return option for disposing of excrement (or other forms of "waste" and harmful substances), but rather that the number of *readily accessible* options is suddenly one less than it was before the failure. Indeed, we must now be more specific about the nature of a "harmful substance", for yet another kind of material (not previously discussed) is being propagated through the metabolism of the city, namely the (generic) pathogen, or disease vector.

Surviving a storm is one facet of achieving security under abnormal (non-24-7) circumstances. It is about surviving a *surfeit*, technically in terms of input supplies of water flows that are excessive or of energy flows bringing about a heat wave, with its self-evident allusion to an event with sinusoidal variation. This is the shock of the "too much", which was of such considerable concern to Grey and Sadoff [5]. The converse is surviving shortages, typified most obviously by drought.

To summarize, we have argued that the pulse-rate of normality in the metabolism of the city is dominated by the 24-7 band of the spectrum. Abnormality and any insecurity associated with it are characterized by events and occurrences whose constituent frequencies typically (but not exclusively) reside on either side of that band, whether a rapid water surfeit or a slow extended shortage. This dichotomy, although crude, is our specific point of departure into the subject of resilience. Unsurprisingly, like nexus security (or sustainability), understanding the significance of resilience depends upon features of both pulse-rate and metabolism.

5 Resilience

Eminent ecologist C.S. Holling has argued persuasively that we have engineered most of our urban infrastructure, technologies and industrial production systems so as to enslave their functioning to achieve what he calls "engineering resilience" [11]. For as long as the system is not subject to significant disturbance, it can be managed to maintain function in some desired domain, usually constant or narrowly circumscribed, because that — like the 24-7 pulse bandwidth — often seems to be much more to our liking. In the face of substantial disturbance, however, engineering resilience can be revealed as brittle in quality (Holling would argue). The performance of the system may be knocked out of its comfortable equilibrium and descend into an altogether quite different pattern of function that is not at all to our liking.

"Ecological resilience", on the contrary, would enable the maintenance of essential (if not desired), functions even under such circumstances. This second, complementary form of resilience in the behavior of a system over time is a product of the interplay among relatively slowly changing (low-frequency) and relatively swiftly changing (high-frequency) components of behavior [11]. It has great appeal with respect to the sustainability of cities, as discussed more fully in the Sustainability Concepts Paper of Beck [1].

In particular, and likewise inspired by the work of Holling, Moddemeyer has offered the following definition of resilience in an article entitled "Understanding the Nature of Change: Building Resilience Into Urban Life" [56]:

> Resilience is defined by the Resilience Alliance 'as the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain the same function, structure and feedbacks — and therefore the same identity.'

He does not refer to this expressly as the definition of ecological resilience, *contra* engineering resilience, but we shall take it here as broadly intended as the former. We should note in passing that the Resilience Alliance also has its origins in Holling's seminal work, which includes [10].

There is, in fact, a clear "frequentist"[1)] outlook in Holling's reasoning. For him, it has been the semi-arid grasslands of east and south Africa that best reveal this role of the spectrum of perturbations in understanding the impact of man on the environment [11]:

> Under natural conditions ... the grasslands were periodically pulsed by episodes of intense grazing by various species of large herbivores. Directly as a result, a dynamic balance was maintained between two groups of grasses.

But then such ecological resilience was lost with the rise of man and the modern way of arranging things — in terms of variations with time — to his liking [11]:

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

The constancy man so often seeks — as in the city never sleeps — induces loss of ecological resilience.

Yet there are also variations to be considered across space, not solely those over time. Ecological resilience has companion interpretations with respect to cross-scale interactions [57]:

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

What principles for re-designing the dynamic performance of a city's water (or food or energy) infrastructure could we derive from these, merely by substituting the word "species" by "unit process technology" or "building", and then (conceptually) increasing the number of levels in a hierarchy through nested sub-systems of de-centralization at different scales?

For Holling, sustainable development itself — to which both nexus security and resilience contribute — is founded upon similar insights on redundancy and (in)efficiency of function, specifically in endotherms

1) Expressed in quotation marks to distinguish from its use in statistics. Again, frequency in terms of sinusoidal oscillations is intended here; and again, this "frequentist" interpretation of resilience — with respect to the city system — has been elaborated in greater detail elsewhere [1].

(warm-blooded animals) whose "average temperature is perilously close to lethal" [11]:

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

This brief insight into the resilience of a system, here an endotherm, clearly deals with the metabolism of a system. It also entails a diversity of options *within* the system, a principle of functioning that is at the core of nexus security. It is an unusual insight into the notion of sustainable development, unlike that discussed in [5]. It challenges us to conceive of the behavior of the city in unusual ways. One cannot help but wonder, however, just how secure any agent might feel, were s/he or it operating "at the edge of instability".

To summarize, for the purpose of reflecting on the implications of these concepts of resilience for nexus security (and water security), four determinants of ecological resilience can be extracted from these various insights:

(R1) Increasing diversity of species (up to a point), or of agents and agencies within a city (as embraced under (D2), (D3), and (D4) above), as a complement of the diversity of input-supply and output-return options outside it (covered by (D1) above). Grey and Sadoff, we may note, write of shifting the "structure of the economy toward a more diversified, water-resilient structure" [5].

(R2) Exploiting cross-scale interactions, in the sense of space, the levels, and number of levels in a hierarchy, i.e., centralized (one level) and/or de-centralized (two or more levels), which has a bearing on the diversity of options specifically under category (D3) above.

(R3) Tolerating soft redundancy and (in)efficiency of function within a system, i.e., a diversity of within-system mechanisms or phenomena (such as biogeochemical, metabolic transformations).

(R4) Being (much) more mindful of cross-spectrum interactions, i.e., interactions between slowly- and quickly-varying phenomena, or between bundles of predominantly low- and high-frequency fluctuations. Distinctively significant for Grey and Sadoff were variability and resilience, especially in the face of the transient (high-frequency) shocks of too much water [5].

Moddemeyer touches upon both (R1) through (R4), and (D1) through (D4), when he says [56]:

> Applying resilience thinking encourages us to act now to create and encourage a *portfolio of options at different scales* that are designed to be more resilient to change. [emphasis added]

How these two candidate sets of principles for gauging diversification and resilience should be wielded in practice in order to evaluate degrees of nexus security is the subject of [12].

6 Conclusions

Both security and the nexus of water, food, energy and climate are emerging domains of concern and inquiry [2,7,9]. One should not expect at this point a definitive expression of what they amount to and how, when merged, nexus security should be enhanced. The economics behind policies for improving water security is far from clear-cut [34]. The fact that the nexus *is* an issue today — also reflected in the US National Science Foundation having introduced a program of research on "Coupled Natural Human Systems" (just a decade or so ago) — is a measure of how far a century of ever-increasing specialization of inquiry had previously taken us. This is simply evidence of systems thinking re-asserting itself (as supremely exemplified by [58]).

The current perception of water security is that water is a privileged resource/sector; and that basic, single-sector, water-related socio-economic development is a necessary precursor of multi-sectoral, self-sustaining development [5,7]. Such a portrayal of water security might now go uncontested. The same cannot be said, of course, of what constitutes "basic", or what constitutes meeting the need of one individual before the want of another, or what constitutes access to "acceptable" quantities of water or an "acceptable" risk of temporary insecurity, for instance [17–19].

Based on the present analysis, the notions of both water security and nexus security seem more narrowly circumscribed than that of sustainability, at least in comparison with the Sustainability Concepts Paper of Beck [1]. One is tempted to say that nothing could be more broad and rambling than the concept of sustainability. More to the point, and more specifically, elaboration of the set of eight working principles through which to assess nexus security — according to four facets each of resilience in the behavior of a system and of diversity of access to a resource or service — came far more readily than the corresponding expression of the 15 line items (or dimensions) by which to gauge sustainability thinking [1] (see, in their most succinct form, the "***1***–15 Sustainability Report Card"; http://cfgnet.org/archives/1022). Such speed, or relative ease, in arriving at an "operational definition" of nexus security may indicate nothing more than the result of prior efforts invested in arriving at the 15 line items for sustainability.

Seeking some preliminary proof of the utility of our diversity-resilience interpretation of security is a matter we report on in [12].

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