Urban Nexus Science for Future Cities: Focus on the Energy-Water-Food-X Nexus

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Keywords:
Water-energy-food systems; urban nexus science

Abstract:
Purpose of review:
Rapid urban expansion of the world's cities is placing unprecedented demands on the energy, water, food, and other (X) systems (e.g. mobility) that each offer multiple life-supporting services. Coordination that considers inter-sectoral connections among these urban systems and services remains nascent in practice, yet are critical to the future well-being, resource/operational efficiency, and resilience of urban areas. This paper therefore proposes an applied 'urban nexus science' framework to identify integrated and synergistic pathways toward achieving urban sustainability.
Recent findings:
The design, planning and operation of urban W-E-F systems can benefit from integrated analyses to accelerate infrastructure, land use, and hazard mitigation planning and decision-making. New knowledge quantifying the key effects of W-E-F systems designed in isolation versus as increasingly integrated systems, especially when exposed to hazards, health risks or extreme events, are a critical need.
Summary:
Interactive system modeling and participatory technologies are needed to support stakeholder engagement and two-way (and multi-directional) information flow, for exploring outcomes of alternative solutions for integrating W-E-F sectors. To support such important efforts, research is needed to fill critical gaps in data, identify tradeoffs, and develop synergistic solutions that measure sustainability co-benefits based on different levels of urban integration among W-E-F systems and services.

Introduction

The world's population is urbanizing more rapidly than at any time in human history (UNDESA, 2014). Some countries have had 2010-2015 annual increases of 3-5% (a doubling of urban population within only 13 - 25 years) (CIA, 2016). Over half of humanity is now living in urban areas (United Nations 2014), having crossed this threshold in 2008, seven years ahead of the 2015 estimates made in 2001 (CIA, 2001). Currently, estimates project that by 2050, water and food demands will grow by over 50%, while energy demands may double and potentially triple in the case of urban energy demands (National Intelligence Council, 2012; IRENA, 2015; Creutzig et al. 2014). If providing for these new demands are managed in an unsustainable manner, and without considering interconnections, outcomes may be increased instability, conflict, resource scarcity, environmental damage, and climatic change (Bizikova et al. 2013; WEF, 2011).

In response to these challenges and potential opportunities, and building on

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Brugmann et al. 2014, this paper proposes developing an 'urban nexus science' (UNS) roadmap as a means of identifying and exploring synergies, tradeoffs, and co-benefits across WEF systems for building 21st century resilient and sustainable cities. UNS, as a strategic approach towards transformations, aims to explore and develop evidence on the co-benefits of increasingly integrated systems design via interdisciplinary strategies. This paper offers a framework for understanding urban nexus science and its application to WEF, and a summary of the core challenges, data gaps, and potential transformative solutions associated with the WEF nexus.

WEF and Urban Nexus Science

The WEF nexus can be conceptualized as a function of the interaction among the three WEF sectors (Figure 1.1). Integration can be conceived as the areas where each sector overlaps (i.e., areas a, b and c). The degree of overlap is associated with a "triple dividend" that promotes ecosystem protection, economic development, and social equity (Institute of Sustainable Development 2013). A major challenge to achieving resilient and sustainable cities is increasing the areas that overlap (e.g., Figure 1.1a to 1.1c) and identifying most-critical uni-directional, bi-directional and multi-directional dependencies, synergies, and feedback loops between systems.

One example participatory framework for guiding design, planning and operation of urban systems is presented in Figure 1.2. This Figure illustrates how cross-cutting factors that enhance or inhibit integration of WEF security and WEF-related outcomes can be explored. The framework includes five core dimensions: 1) outcomes (equity, growth, and ecosystem health); 2) WEF sectors (water, energy and food security); 3) urban informatics that accelerate planning and decisions on land use, infrastructure, transport, and hazard mitigation; 4) stakeholder engagement and mapping (of cross-scale actors and institutions); and 5) global trends (e.g. urbanization, environmental change, and globalization). The framework depicts a cyclical process that is iterative and nonlinear, involving multiple transitions in technologies, plans, policies, behavioral change, and financing.

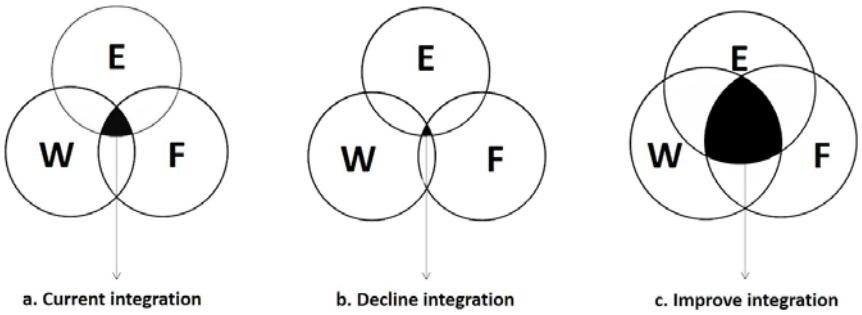

Figure 1.1: Integration of W-E-F Sectors

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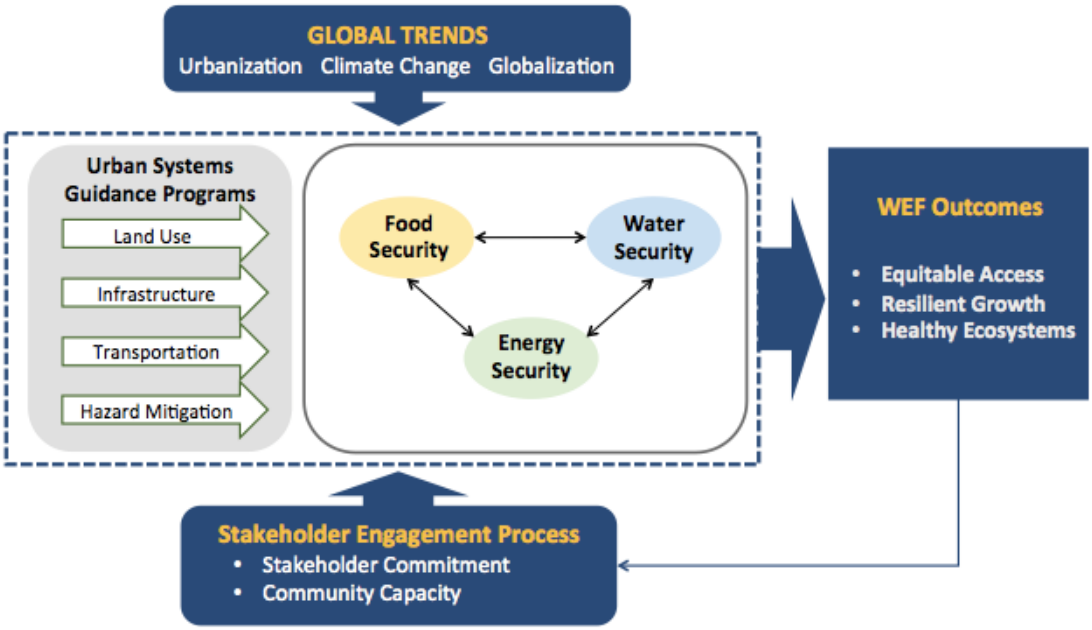

Figure 1.2: Future Cities: W-E-F Conceptual Framework
Source: Adapted from Hoff (2011)

Equity, Growth, and Ecosystem Health Outcomes
Starting with desired WEF-related outcomes, the goal is to achieve upgrades in WEF systems to develop equitable, resilient and healthy cities for people and trans-boundary ecosystems. Ecosystem services that serve populations in cities are benefits received from well-functioning ecosystems that often extend beyond urban boundaries. Such services are key outcomes of WEF security and play a crucial role in the quality, quantity, reliability, affordability, flexibility, and adaptability of the supply and maintenance of water, energy, food, and other systems and services. Economic development can be more sustainable through transitions toward decoupling growth in GDP from environmental impacts, and accelerating greater resource use efficiency. Social equity – including the distributive, procedural, and intergenerational aspects of equity - can be improved by increasing access to and participation in the FEW nexus decisions that increase benefits of healthy environments and economies for all populations.

Water, Energy and Food Sectors
As noted, the degree to which the WEF sectors are integrated at key nodes of stakeholder groups (across a diverse array of actors and institutions), can influence outcomes of priority to urban communities, city-regions, and their supporting ecosystems. Decisions in one sector are increasingly understood as affecting the outcomes of the other sectors, and new research frameworks point to the need for enhancing data systems to quantify these interactions (e.g. Ramaswami et al., 2017) . For example, urban areas are net consumers of food, water and energy, attracting these from the surrounding hinterland and other parts of the planet. Tackling issues

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with one resource is often associated with the supply and demand for others (NIC, 2012). Supply-demand mismatches may also be addressed through increasingly decentralized systems, yet tradeoffs must be considered. For example, a shift to urban agriculture creates opportunities to increase energy efficiency by reducing transport distances of food and pumping of water to cities, increase access to healthy foods in "urban food deserts" in poor neighborhoods where there is little to no fresh produce locally available, and reducing pressures on ecosystems services by recycling water and nutrients from wastewater in urban areas (Walker et al. 2014). However, tradeoffs and barriers exist that need to be identified e.g. the potential for more water- and carbon-emissions intensive agricultural production, capital costs to growers, land pricing, and social acceptability of urban-grown food).

Urban Systems Guidance

Urban system guidance programs are comprised of planning, policies, regulations, capital investment and adaptive management activities that govern the provision of public goods and services of different urban systems. Examples of urban systems guidance programs include programs aimed at managing infrastructure systems for transportation, energy, water, food, hazard mitigation, and urban land use patterns. Coordination of programs and their plans across urban systems is essential to increase efficiency, reduce duplication and avoid conflicts in supporting integration of the WEF sectors (Hopkins 2001, Schwab 2010). However, existing "legacy" guidance systems that affect water, food, and energy production and distribution are frequently "silo'ed," and solutions are considered independently of one another (Brugman 2014).

Stakeholder Engagement

Strategic stakeholder engagement efforts and integrated decision processes provide opportunities for stakeholders to develop shared goals for the future, as well as participate in the creation of polices for achieving these goals. Stakeholders include formal and informal actors in the private and civic sectors as well as governmental units that organize, engage, and act in concert or individually. Engagement can generate understanding and agreement on problems and ways of solving them. Engaged stakeholders are more likely to have a sense of ownership of proposed solutions and foster commitment and willingness work hard for the realization of the proposals (Brody 2003b, Burby 2003, Lyles, Berke and Smith 2014b). A decision making process that fails to include all relevant local organizations, which represent diverse interests, is less likely to facilitate integration across the nexus sectors. The success of engagement in decision-making is predicated on two core activities: 1) developing a diverse coalition of stakeholders committed and willing to act on WEF issues; and 2) providing resources to strengthen public and non-profit organizational staff capacity to support stakeholder engagement efforts (Burby 2003).

Global Trends

Finally, cities must increasingly face global trends that can be viewed as disruptive forces. Rodin (2014) and others (IPCC, 2015) posit that both acute and chronic

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hazards associated with environmental change, rapid urbanization, and globalization pose significant challenges to cities. Hazards and environmental change have emerged as major contributors to the expanding geographic area and increasing frequency and intensity of exposures of people, infrastructures, and ecosystems to risks associated with sea level rise, extreme weather events (e.g. floods, droughts) and the decline in quality and quantity of ecosystem services that provide critical life supporting services to cities. Annual average per capita loss has more than tripled in the US over the past 50 years (Gall, 2011), and annual worldwide losses have quadrupled over the prior three decades to nearly $200 billion (World Bank, 2016).

Rapid urbanization makes cities increasingly vulnerable as municipal governments struggle to keep pace with management of growth pressures. Examples include inadequate land use controls to steer new development away from the expanding hazardous areas, failure to provide and maintain critical and basic infrastructure services to meet rising demands, and insufficient access to health care to respond to multiple urban health risks including disease outbreaks due to climate change and close contact of shifting populations. Globalization also impacts cities via multiple pathways. Examples include worldwide integration of supply chains and urban-regional economies, transport of products to distant rather than local markets, increased use of fossil fuels and greenhouse gas emissions, to large-scale involuntary migrations of displaced people from across geographic borders due to economic dislocation, and lack of housing, water and food.

Key Challenges/Research Questions

- *Knowledge of the interconnected impacts of disruptive global forces is highly uncertain.* The interdependencies of WEF systems and the related institutions managing supply chains for global business and government continuity is poorly understood. A single disruption frequently triggers another, which exacerbates the impacts of the first, so that the original shock may cascade and result in the culmination of multiple extreme events. For example, a major hurricane strikes that causes failure of the transportation system and electricity supply grid that leads to food insecurity and the shutdown of water treatment infrastructure that, in turn, causes a public health problem, and even conflict and unrest.

- *WEF sectors are poorly integrated as urban system guidance programs treat each WEF sector individually.* The reactive and disjointed approach is characterized by decision-making that is often fragmented across policy arenas, internal to a local jurisdiction (e.g., emergency management, transportation, and land use) and across the narrow objectives of individual local agencies, or as bounded by the narrow objectives of federal and state agencies (Berke et al. 2015). In this context, urban and regional policy making and planning efforts need to transition from focusing on individual WEF sectors planned in isolation of each other, to move towards new efficiencies or synergies that increase productivity,

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equitable delivery, affordability, reliability, and overall quality of urban services, as well as the health of ecosystems.

- *Lack of stakeholder awareness of the WEF shortages and commitment to act in response to the risks*. There are several core factors that constrain commitment and willingness to act on WEF issues that are similar to public reaction to climate change and natural hazards (Berke and Lyles 2013, Glass at al 2017). WEF issues tend to vary along the continuum of risk perceptions / thresholds of tolerability due to several factors: 1) rationale for integration of WEF sectors is abstract and poorly understood, despite a well-developed understanding of impacts of better integration; 2) adverse impacts associated with security threats to WEF sectors are perceived as distant in time, which reduces the sense of urgency when other concerns appear more immediate and relevant; 3) integrated management of WEF sectors is constrained due to a weak sense of personal responsibility that is not within the realm of individuals, with other actors and institutions considered responsible for taking action; and 4) efforts to better integrate WEF sectors are inhibited by transaction costs of institutional and finance coordination with rewards and co-benefits not yet well understood.

Data/Knowledge Gaps

- *Lack of multi-dimensional measures that reflect level of integration among the WEF sectors.* One-dimensional measures like household water consumption or energy consumption are easy to measure and the data are readily available. The multidimensional measures need to reflect the interdependencies among the WEF sectors. For example, a rise in household water consumption is directly linked to energy consumption; on production side, water constraints limit energy production and vice versa.

- *A gap in measures that relate the level of integration of the WEF sectors to outcomes deemed important by society.* Examples of measures that link degree of change in integration to outcomes include monetary efficiencies, creation of urban ecosystem services (e.g., green infrastructure that reduces urban heat and energy demands, and sequesters CO2), and percent of low-income population with access to food, potable water, and affordable energy.

- *Integrated modeling systems approaches are needed that can identify the potential trade-offs and synergies among sectors, and identify holistic solutions*. Much has been published on the conceptual framings of WEF nexus; yet, most of the attempts to operationalize the WEF nexus did not go beyond integrating the material flows and accumulations of two of the three sectors with few exceptions (Villarroel Walker et al., 2014). Science-based models need to estimate water, food, nutrients, and energy entering, leaving and cycling within a city as a function of change in water and energy infrastructure technologies, transportation systems, urban land use patterns, and impact of hazard events and climate change. The models should reveal the synergies and tradeoffs

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among options for reducing water use and the recovery of energy and nutrients as a result of potential changes. Models provide a scientific basis for creating scenarios, estimating social, economic and environmental impacts, building consensus and informed deliberation among stakeholders (Newell and Cousins 2014).

- *To overcome potential weak institutional commitment to WEF nexus issues new urban nexus science and related decision support tools are needed to enable local stakeholders to participate in the design of place-based strategies.* The tools should be based on scientific and technical information that is perceived as credible and legitimate. They should be interactive, offer a broad range of impacts and alternative policy solutions, and allow participants explore impacts and options on their own. The decision support tools can facilitate early and ongoing stakeholder participation to increase likelihood of commitment to WEF issues.

Potential Transformative Solutions Needing More Research

A New Urban Nexus Science: Designing for Circular Abundance

A new urban WEF nexus science that builds on the concept of designing for circular abundance, a general framework developed by McDonough and Braungart (2013), involves integration of energy and water efficient businesses, technologies, or other resources that flow from one to another in a synergistic, sustainable manner. The approach often centers on decentralized, closed-loop models of spatial planning and service provision, with outcomes emphasizing environmental sustainability (both in the context of conservation and ecosystem services), economic development and social equity. It would strive to shift from fossil fuels to renewable sources; derive new water and fertilizer from reuse of wastewater, and capturing rainfall, stormwater runoff, and agricultural water. It would produce food with recycled energy and water, and strive for zero waste. Water, energy and food security, affordability and accessibility to disadvantaged groups that often lack equitable access are all aspirations of an urban WEF nexus model, complementing 'circular abundance' (Brears, 2015) and 'circular economy' concepts (McKinsey, 2016).

Integrating Technologies and Infrastructure Systems

Urban WEF Nexus models focusing on different spatial and temporal scales can aim to integrate WEF sectors and co-locate different technologies – such as vertical farming; blue, green and solar roofs; and waste-to-energy technologies -- so as to allow the movement and utilization of resources easily from one production facility to the next. Additional details on each of these three categories are below:

1. Urban agricultural methods that are water efficient like aquaponics, hydroponics (with LED Grow lights), and vertical greenhouses;
2. Water treatment technologies that can produce drinking water, energy generation (methane), and mineral/nutrient recovery; and
3. Innovative energy solutions like utilizing waste from fish farms for energy generation and implementation of solar panels for financially self-sustaining areas.

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Co-locating multiple production processes can have potential to improve the efficiency of each individual process, minimizing the amount of raw resource inputs (such as fuel, water, land) required, and eliminating waste. Creating a system of "circular abundance" requires holistic water-food-energy planning. A well-known and aligning concept to "circular abundance" is "industrial symbiosis", where a small Danish city of Kalundborg (population 16,000 in 2015) is often cited as one model. However, this particular symbiosis evolved in self-organized fashion in a specific – Scandinavian- context (Ehrenfeld and Gertler 1997). In large-scale and often disconnected systems, the technical and social complexity of the challenge generally overwhelms even the most qualified urban sustainability planners and therefore more district-scale, and distributed experimentation approaches are now underway.

Community Capacity Building

Explore new approaches that build community capacity to understand, engage and act on urban problems. For example, urban citizen science involves the collection of valid and reliable data on a range of issues like nutrition and food access, water and air pollution, and small-scale infrastructure (efficiency of stormwater drainage systems) by neighborhood residents. It supports the idea that local people have the power to co-learn with researchers and build capacity of their communities from within. Ultimately citizen science is about respecting the capabilities of local people, developing support that local people can work in collaboration with investigators, and recognizing the rights of local people being studied. Conventional research needs to be adapted to participatory approaches to foster capacity building, and ensure that research addresses locally defined needs and generates solutions that fit local context, as well as improves the quality of data. Finally, the disparities between disadvantaged people and the general population and perceptions of the ability to self-govern are deeply entrenched and cannot be undone through conventional research initiatives. Expectations for making real progress should take a long-term view, requiring fundamental transformations in which researchers and local people are viewed as equal partners in co-developing information and in strengthening local capacity.

Other potential approaches to community capacity building that have been underutilized that involve group model building or facilitated modeling. These capacity building activities are well-established approaches to bring stakeholders together and elicit their mental models using causal mapping (Vennix et al, 1992; van den Belt 2004). The resulting causal loop diagrams then serve as platforms to reach a shared understanding among stakeholders facilitating community capacity along the way.

Conclusions

Cities are experiencing the highest levels of population growth at any time in human history. At the same time, rising threats from multiple global forces (e.g., climate change, economic dislocation, ageing infrastructure) will all shape food, water and energy security for urban populations. Understanding of the sustainability outcomes due to fragmented and piecemeal approaches to guiding urban development and

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management of related W-E-F systems is critical. Examining the disruptions and innovations for future cities at the nexus of life-supporting water-, energy-, food-, and other (e.g. waste, mobility, buildings/housing, communication) (W-E-F+) systems and services can be considered a 21st century grand challenge.

This paper offers a conceptual framework to understand how the core dimensions of urban systems, which includes higher density of populations, infrastructure systems and services, and rapidly evolving design practices for integrating energy, water, and food systems. Thee related planning and decisions , based on democratic engagement efforts, can influence the degree to which W-E-F sectors are integrated and able to generate sustainable outcomes. Consequences and risks shaped by isolated efforts in water, energy and food sectors are explored. A key finding is that knowledge on the interdependencies among urban systems, W-E-F sectors and the impacts of disruptive global forces remain poorly understood in practice, and the understanding of these interactions remain primarily qualitative in nature. However, this paper offers an initial conceptual framework that will need further testing and case studies to explore the extent to which critical gaps in data can be identified for measuring the level of integration among urban guidance programs, and resulting effects on sustainability and resilience of W-E-F systems and services.

System modeling and place-based approaches that bridge quantitative and qualitative analyses, new public-private partnerships, and business models are all needed for examining outcomes and accelerating desirable approaches toward integrating W-E-F sectors that understand tradeoffs and help accelerate consensus based and evidence-based solutions. For example, understanding recovery patterns, system interdependencies (e.g. as resource inputs to or cascading failures from one system to another), and critical consumption and production trends at the nexus of energy, water, food, and other 'X' (x=mobility, housing) services for population in cities, are critical science and society-relevant inquiries to enhance urban development and management strategies (Marcotullio, Sarzynski, Sperling et al. 2016). Interdisciplinary approaches to urban W-E-F nexus science are expected to help develop collaborative efforts across sectors, scales and jurisdictions, enabling new scientific and societal capacities to anticipate changes and effectively respond to emerging risks. Emphasis on enhancing multi-level governance and urban systems guidance programs with cities will be critical, especially in responses to: 1) urbanization, in how it shapes affluence, rapidly rising water-energy-food resource demands, and related emissions, risks and social vulnerabilities; 2) environmental change, specifically in terms of new and not-yet-seen thresholds of stresses and shocks to and from W-E-F sectors; and 3) globalization, by harnessing new levels of W-E-F connectivity, while also using data to reduce inequality and risk.

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