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Opinion paper – Panta Rhei

Challenges in operationalizing the water–energy–food nexus

J. Liu[1], H. Yang[2,3], C. Cudennec[4], A.K. Gain[5], H. Hoff[6,7], R. Lawford[8], J. Qi[9], L. de Strasser[10], P.T. Yillia[11,12], C. Zheng[1]
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[1] School of Environmental Science and Engineering, South University of Science and Technology of China, Shenzhen 518055, China

[2] Swiss Federal Institute for Aquatic Science and Technology (Eawag), Duebendorf, Switzerland

[3] Department of Environmental Sciences, University of Basel, Basel, Switzerland

[4] Agrocampus Ouest, INRA, UMR SAS, Rennes, France

[5] GFZ German Research Centre for Geosciences, Potsdam, Germany

[6] Potsdam Institute for Climate Impact Research, Potsdam, Germany

[7] Stockholm Environment Institute, Stockholm, Sweden

[8] Morgan State University, Baltimore, MD 21251, USA

[9] Center for Global Change & Earth Observations, Michigan State University, East Lansing, MI 48823, USA

[10] Fondazione Eni Enrico Mattei, Milan, Italy

[11] Sustainable Energy for All (SE4All), Vienna, Austria

[12] International Institute for Applied Systems Analysis, Laxenburg, Austria

Abstract

Concerns about the water–energy–food (WEF) nexus have motivated many discussions regarding new approaches for managing water, energy and food resources. Despite the progress in recent years, there remain many challenges in scientific research on the WEF nexus, while implementation as a management tool is just beginning. The scientific challenges are primarily related to data, information and knowledge gaps in our understanding of the WEF inter-linkages. Our ability to untangle the WEF nexus is also limited by the lack of systematic tools that could address all the trade-offs involved in the nexus. Future research needs to strengthen the pool of information. It is also important to develop integrated software platforms and tools for systematic analysis of the WEF nexus. The experience made in integrated water resources management in the hydrological community, especially in the frame of *Panta Rhei*, is particularly well suited to take a lead in these advances.

KEYWORDS trade-offs; synergies; IWRM; Panta Rhei; sustainable development goals

1 What is the water–energy–food nexus and why is it important?

The water–energy–food (WEF) nexus constitutes a framework for analysing the dynamic interactions between water, energy and food systems and developing strategies for sustainable development (see Fig. 1). Although progress has been made, particularly in studying water–energy and water–food relations, the WEF framework is just beginning to be explored scientifically. This framework is being developed with a sense of urgency due to the concerns about looming difficulties in feeding the world's growing population with the increasing constraints on the availability of the requisite energy, water and land resources. According to the United Nation's (UN) estimate, the population of the Earth will surpass 10 billion by 2100 (UN-DESA 2011). The Food and Agriculture Organization (FAO) (Flammini et al. 2014) projects that 60% more food, 80% more energy will be required by 2050 to meet global demand; an increase in total global water withdrawals by 50% in developing countries and 18% in developed countries by 2025 is projected. This situation is aggravated by a number of factors, for example, the increasing number of people adding meat to their diets, which is energy- and water-intensive. The inter-linkages between water, energy and food are affecting the development of each of these sectors. The World Economic Forum (2015) report ranked the WEF nexus as one of the biggest risks to world economic stability. While the links between these sectors are understood in a qualitative sense, describing these linkages in quantitative terms is largely lacking.

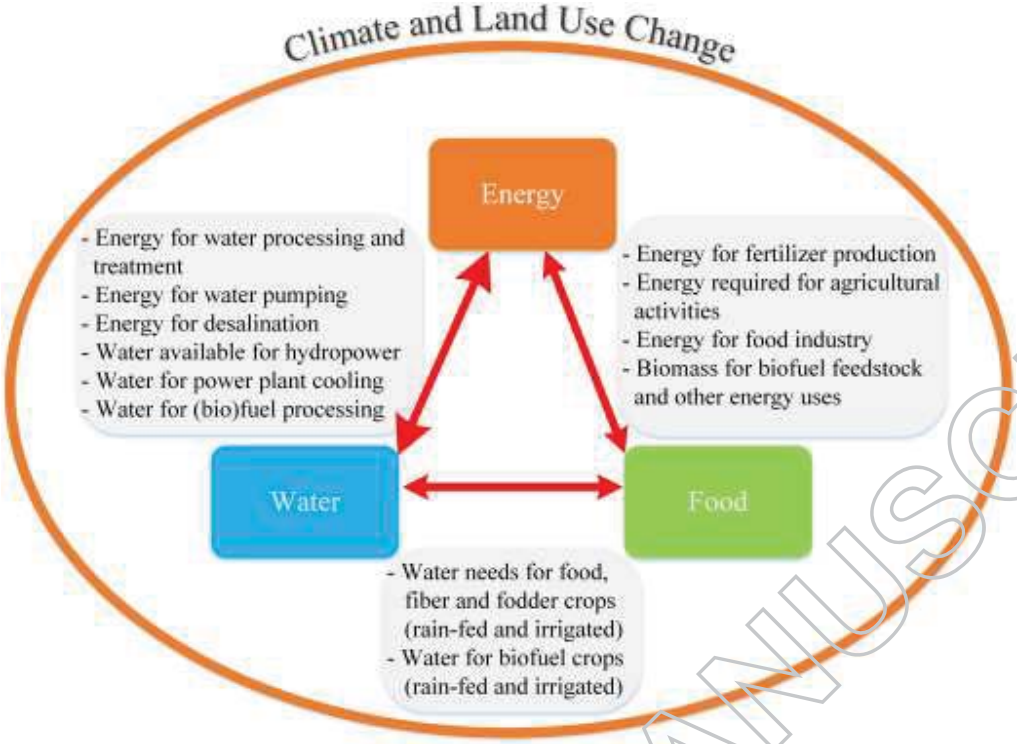

Figure 1. Illustration of the WEF inter-linkages. The items listed are examples that are not meant to be all inclusive.

Since 2008, concerns about the WEF nexus have motivated many discussions regarding new approaches for managing water, energy and food/land resources (Hoff 2011, WWAP, 2015, 2016, Giupponi and Gain 2017). The nexus framework has been gaining acceptance since it was first publically debated during the Bonn 2011 Nexus Conference *The Water, Energy and Food Security Nexus: Solutions for the Green Economy.* In 2014, the FAO used the nexus as an organizational concept to coordinate the complex and interrelated nature of the global resource system that affects agriculture (FAO 2014). A number of national and international organizations are now acting on this concept. At the international level, Future Earth launched a two-year WEF Nexus Cluster project to consider the role of integrated information systems on environmental and anthropogenic forces and improved governance and to assess how these approaches could advance the delivery of a WEF nexus approach. Future Earth has also advanced its Knowledge Action Network (KAN) dealing with food, energy and water in response to this need (Future Earth 2014). The sustainable development goals (SDGs), approved by the UN in September 2015, gave further impetus to a nexus approach across water (Goal 6), energy (Goal 7) and food (Goal 2), which, respectively, contain targets of food security for all, clean water for all, and energy for all; and because inter-linkages are crucial (UN-Water 2016). A well-coordinated nexus approach could be the first step in realizing these goals (Obersteiner *et al.* 2016).

The issues related to the WEF nexus are strongly coherent with the scientific agenda shaped in the frame of *Panta Rhei*, the decadal programme of the International Association of Hydrological Sciences (IAHS) (Montanari *et al.* 2013, McMillan *et al.* 2016, Ceola *et al.* 2016, Kreibich *et al.* 2017). Not only

does the nexus exemplify linkages of socio-hydrology and hydrological changes with energy and food systems, it is also key for water, energy and food security (UN-Water 2013, 2016, van Emmerik *et al.* 2014, Young *et al.* 2015) in the Anthropocene (Steffen *et al.* 2011, Savenije *et al.* 2014, Bai *et al.* 2016, Brondizio *et al.* 2016). Integrated water resources management (IWRM) approaches are integral parts of the WEF nexus. To this end, *Panta Rhei*, which emphasizes the two-way coupling between humans and nature (socio-hydrology) within a more comprehensive framework (Montanari *et al.* 2013), can play a critical role in the innovative development of system tools and information pools for analysing the inter-linkages, co-evolutions, syntheses and trade-offs involved in the WEF nexus (Koutsoyiannis *et al.* 2016, WWAP 2016, Srinivasan *et al.* 2017); and for conceptualizing relationships with external drivers which are themselves changing, eventually under acceleration (Bai *et al.* 2016; Brondizio *et al.* 2016).

2 What is new about the WEF nexus

It is often mentioned that the WEF nexus is not really a new concept (e.g. Benson *et al.* 2015, von Braun and Mirzabaev 2016, Wichelns 2017). That is correct to some extent, as some nexus approaches have been used to study and explore various sectoral inter-linkages. The importance of systemic approaches in the management and governance of natural resources and food systems has been recognized before the rise of the term "nexus" in science and policy making, for instance, IWRM (GWP 2000), landscape approaches (Sayer et al. 2006), and ecosystem-based approaches (CBD 2000), among others. With increasing demands for services and growing desires for higher living standards, the need for more conscious stewardship of the vital resources (i.e. water, energy, food) required to achieve those services and desires has become both more obvious and urgent.

Is the attention to the nexus approach therefore justified? Yes it is. The nexus approach is multi-centric (offering a "level playing field") compared to IWRM and other integrated approaches that mostly originate from one particular sector, inviting others in (e.g. Bazilian *et al.* 2011). Also, the attention currently being paid to the nexus helps generate the required momentum and political will for action, which has been lacking in previous approaches (Biswas 2008, Ringler *et al.* 2013). It may be true that everything is somehow linked to everything else; however, the WEF nexus can add value by stressing the most critical inter-linkages and by developing a new approach around it (Allan *et al.* 2015, Foran 2015). It should be noted that, while in this paper we refer to the water, energy and food *security* nexus, the concept of *resource* nexus can also be found in the literature – water, energy, land and minerals.

In recent years, there has been a rapid increase in studies on WEF nexus issues, as suggested by a literature search of Scopus (published articles and books) from 2010 to mid-September 2016 (by 6 September 2016). Among a total of 231 publications, 98 and 75 were published in 2015 and 2016, respectively. The reported nexus work includes contributions from academic institutions, government organizations, nongovernmental organizations, and business.

3 Research challenges

The WEF nexus presents opportunities for policy makers, business leaders, investors, non-governmental organizations, and the public at large to address three mutually-dependent global security concerns (e.g. access to water, sustainable energy and food security). However, several challenges remain for the corresponding research required for sound operationalization of the nexus. These are largely reflected by considerable data and knowledge gaps and lack of systematic analytical tools to apply nexus thinking effectively.

Developing research methodologies that evaluate synergies and trade-offs in a holistic way, and making decision support tools available to address them are important to avoid conflicts, minimize risk on investment and maximize economic returns (Howells et al. 2013). Both synergies and trade-offs concern not only monetary values involved in the nexus but also non-monetary values which are often difficult to measure in market values, such as water, environment and pollution. Traditional research approaches rarely address questions arising from the interfaces between dimensions even though decisions taken in one nexus dimension can fundamentally affect the choices available in other dimensions. For comprehensive assessment of synergies and trade-offs among water, energy and food sectors, integrated models are needed to investigate the strength of the interdependency between various nexus dimensions and other related themes such as economic growth, poverty, biodiversity, sustainable development, climate change and global security. The currently applied tools are still largely limited to individual sectors and hence not fit for untangling these complex inter-linkages, especially beyond the local scale.

It is rare that nexus boundaries align with traditional management units or administrative boundaries—for instance, river basins, urban areas, or even geopolitical divisions (Perrone *et al*. 2011). This alignment of boundaries and management units poses additional difficulties to access and synthesize information concerning the intersection between nexus dimensions. In fact, the boundary of each dimension: water, energy and food, has different spheres, which makes it quite challenging to characterize and manage interactions beyond the spheres or control and influence of any given nexus dimension (see Fig. 2). Yet knowledge of how the spheres of control, influence and uncertainty operate and impact each nexus dimension is critical for managing nexus interactions (Yillia 2016). Research is needed to elucidate the nature of nexus interactions in all three spheres for any given nexus dimension. In particular, innovative methodologies and decision support tools need to be developed to address interdependencies. This is especially needed in the sphere of uncertainty where interactions and interdependencies can be many but synergies and trade-offs are less clearly defined and corresponding impacts are more difficult to interpret and manage.

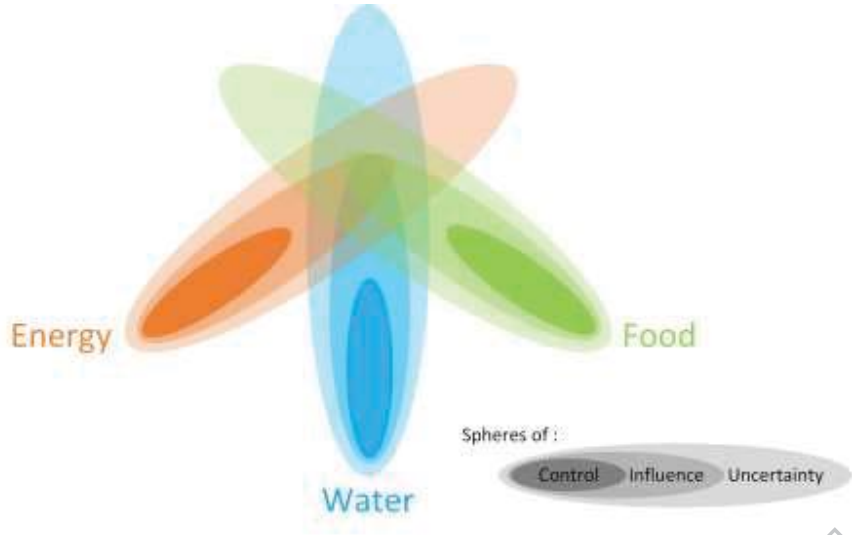

Figure 2. Interactions between the spheres of control, influence and uncertainty in the WEF Nexus

Unifying accounting procedures for various nexus dimensions is another challenge in the WEF nexus. The heterogeneous in data, methods, quality and standards on different nexus dimensions are all constraints for computing the WEF nexus in a systematic and unified framework. For example, accounting for water use in the electricity sector is in principle more straightforward than accounting for energy use in the water sector or accounting for both water and energy use in the agriculture sector. Concerning energy for water, it is difficult to calculate energy end use for water in the domestic sector due to the varied users and uses of water (Yillia 2016). Furthermore, certain nexus dimensions (e.g., the key role of ecosystem services) are still difficult to assess and quantify. As the argument to include natural infrastructure in development planning grows and strengthens, research is required to elucidate and, in particular, quantify in economic terms nature's provisioning and regulating services such as flood and disease control or social services such as spiritual, recreational and cultural benefits, and supporting services, such as nutrient cycling.

Until very recent years, research on the water–energy–food relationships on a large scale often encountered difficulties in obtaining funding. Funding has been often biased towards in-depth knowledge in mono-disciplinary research areas. The lack of sufficient funding has caused a constraint in large steps forward in the knowledge, modeling and implementation of the WEF nexus. The good thing is that since the last few years, there has been an opportunity of enhancing funding on the WEF nexus in different countries. For example, the US National Science Foundation (NSF) initiated the WEF research program in 2015 (https://www.nsf.gov/pubs/2015/nsf15040/nsf15040.jsp). In the same year, the National Natural Science Foundation of China (NSFC) released a joint call for proposal on environmental sustainability together with the NSF, in which the WEF nexus is a priority research area (https://www.nsf.gov/pubs/2015/nsf15091/nsf15091.jsp). Support has also come from international programmes, such as the Belmont Forum, Future Earth and the Sustainable Water Future (http://www.futureearth.org/future-earth-water–energy–food-nexus).

4 Future research of the WEF nexus and contributions of hydrology: addressing synergies, co-benefits and trade-offs

The value of the WEF nexus is the recognition of the coupled nature of these three sectors and the specific focus on critical inter-linkages (e.g. Hoff 2011, Ringler *et al.* 2013, Allan *et al.* 2015). Promoting synergies and reducing trade-offs (concerning both the monetary and non-monetary losses and gains) among these three sectors is a critical aspect of sustainability science (Biggs *et al.* 2015, Halbe *et al.* 2015) and should be aligned with sustainable development goals. Natural resources such as water, energy and land are finite and human needs for them should be placed in the context of limitations of these resources.

Human needs for water, energy and food synergies are geographically, culturally and economically diverse (Mirzabaev *et al.* 2015, Cremades *et al.* 2016). In some communities, nations, or regions, growing more food is essential for survival, a basic human need, but in other regions energy to power machines and automobiles is an important developmental concern. Thus, synergistic use of water, energy and food should be defined in a context-specific way for different regions and their different development priorities (de Strasser *et al*. 2016). Recognizing such diversity enables a better understanding of the WEF nexus and attainable synergies to meet the needs of all.

Synergies across water, energy and food sectors should be achieved to benefit all, for example, through integrated governance (policy coherence) and through nexus tools (multi-functional systems). From the hydrological point of view, an example can be the use of hydraulic infrastructures such as hydropower dams to control flood, and at the same time improve water availability for irrigated agriculture, electricity generation and other uses (e.g. Liu *et al.* 2013, Pech 2013, Daher and Mohtar 2015, Mayor *et al.* 2015). This creates a plausible synergy among water, energy and food sectors, therefore enabling a co-benefit scenario for the communities of the energy sector, farmers, and land use planners near or far from these hydraulic infrastructures. However, when considering other ecosystem services that may be negatively affected, such as downstream fishery industries, additional trade-offs occur. This reveals another critical issue in the analysis and operationalization of the nexus: the system boundaries, geographical extent and spatial scale at which the nexus considered (e.g. Conway *et al.* 2015, Hesengerth *et al.* 2015, Kibaroglu and Gursoy 2015).

A key to the WEF approach is to identify the points at which the resource systems interact and to establish appropriate data exchanges between the modules (e.g. water requirements in the land-use and energy systems; energy needs for water supply and land use; and land requirements for energy and water infrastructure). The output from one module forms the input for the other two. This type of the multi-model framework is the most common way in dealing with complex and multiple systems. It is in essence a loose coupling in which the factors in one system is exogenous to the other systems considered. Given its relative simplicity and transparency, this kind of model framework is expected to be more widely applied in the WEF nexus analysis.

Despite the advantages of the loose coupling of models, this approach has the limitation in considering feedbacks among the individual systems of the WEF nexus. Therefore, tight coupling of models from different sectors, in which the factors from one system are endogenous to other systems, should be developed to quantitatively account for the feedback effects across the systems. In the WEF nexus, this approach could be used to quantify how changes of elements in one system, e.g. the hydrological system, influence the elements in the other systems, and to identify the feedback effects of the changes in the latter systems on the elements in the hydrological system. It is clear that this type of model integration is much more complex than the loose coupling. The complexity of such an integrated model framework may make its development and application more difficult.

As mentioned earlier, there are many models dealing with issues relating to water, energy and food systems, respectively. The integration of models for the analysis of the WEF nexus cannot be confined to specific models or ways of integration. The selection of individual models and the development of analytical frameworks are condition- and scale-dependent. The data required can also vary depending on the issues tackled. There is no one WEF framework that can fit all circumstances. This calls for multi-disciplinary and trans-disciplinary approaches in the WEF nexus studies and in assessing synergies and trade-offs involved (Howells et al. 2013).

Apart from the need to develop integrated modeling approaches as elaborated above, data availability is another aspect that requires much efforts from all the three sectors. Currently, e.g., the data for energy use in the water sector are largely lacking (Perrone et al. 2011, Yillia 2016). Also, many services provided by the three sectors are difficult to measure and put a price on (Yillia 2016). There is a need to improve coordination between researchers in the respective fields, natural resources managers, stakeholders and consumers to generate the data required for quantitatively assessing the synergies and trade-offs involved in the WEF nexus.

5 Summary

The WEF nexus has received much attention since 2011, while the World Economic Forum has identified it as a major source of uncertainty for the global economy. There has been extensive work on the WEF nexus in recent years and the research funding has been gradually increasing. Despite the significant progress visible in the literature, there remain many challenges in scientific research on the nexus, and even more so in its implementation. The scientific challenges are primarily related to gaps in integrated data, information and knowledge related to the most critical inter-linkages and their dynamics. In addition, our ability to untangle the WEF nexus and make the approach operational is also limited by the lack of systematic tools that could address all the synergies and trade-offs involved in the nexus. Future research on the WEF nexus needs to strengthen the pool of information based on physical and social measurements (i.e. data and metrics) and interpret them jointly among all the three sectors. To achieve these goals, it is important to develop observation types and essential variables, datasets, software platforms and tools (e.g. for modeling and analysis on different spatio-temporal scales). In our opinion, it is important for the WEF nexus approaches to identify and model feedbacks between hydrological,

energy and food systems, and correspond stakeholders and societies at large. The experience and knowledge learned and tools and approaches developed from IWRM in the water management communities can be very helpful in developing an integrated framework for tackling the WEF nexus. The contribution of the hydrological community to this course is essential, especially in the framework of *Panta Rhei*, where 'everything flows'.

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