Trends in the development of water-energy-food nexus methods

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Although a novel way to address complex cross-sectoral interactions, the water-energy-food nexus approach is proving challenging to implement in practice and policy. To improve the utility of the nexus approach, there is a need to evaluate nexus assessment methods. Review and analysis of fifty-four publications revealed that nexus assessment spans diverse disciplines, policy, and practice. However, use of comprehensive, interdisciplinary methods that capture cross-sectoral linkages is uncommon – less than 20% of methods used were designed intently to explain nexus interactions. We highlight key trends in the development of robust nexus methods, including integrated models, transdisciplinarity, mixed methods, and qualitative approaches.

1.0 Introduction

With conventional resource management failing to address interlinked water, energy and food challenges, a nexus perspective is increasingly promoted in both academic and policy circles as a way to enhance water, energy and food security. This systems-based perspective recognizes water, energy and food systems as both interconnected and interdependent (Bazilian et al., 2011; Wolfe et al., 2016; Foran, 2015). Therefore, the components must be considered together. The nexus framework generally proposes examining how, where, and when water, energy, and food systems interact to more effectively and sustainably manage resources (Hellegers et al., 2008; Hoff, 2011; Scott, Kurian & Wescoat, 2015). By focusing on linkages, it aims to maximize synergies (mutually beneficial outcomes) and minimize trade-offs (non-optimal outcomes) among resource sectors (Hoff, 2011; Scott, Kurian & Wescoat, 2015). The underlying assumptions of this framework suggest that a systems approach will strengthen cross-sectoral integration and improve management outcomes to enhance water, energy and food security (Scott, Kurian & Wescoat, 2015).

In 2011 the water-energy-food nexus concept was launched into global development discussions, first at the Bonn 2011 Nexus Conference and then through the Global Risks 2011 report by the World Economic Forum (Ringler et al., 2013). The conceptual models presented in these two papers laid the foundation for ongoing nexus research. Both papers Hoff (2011) and World Economic Forum (2011) discuss the water-energy-food nexus in terms of security, but have different underlying assumptions. Most notably, Hoff (2011) places the availability of water resources in the center of the nexus, emphasizing its importance as both a state and a control variable. In contrast, World Economic Forum (2011) places equal emphasis on each of the water, energy and food systems.

2.0 Evaluating the Water-Energy-Food Nexus

The water-energy-food nexus has played many roles in research. The nexus has been referred to as a perspective (Smajgl, Ward & Pluschka, 2016), framework or approach (Smajgl, Ward & Pluschka, 2016; Mayor et al., 2015), research tool (Keskinen et al. 2015), policy-making instrument (Keskinen et al. 2015), and, less commonly, as a methodology (UNECE, 2013; de Strasser et al., 2016). Similar to other conceptual frameworks that aim to integrate diverse components, the nexus has been criticized for having a vague meaning, uncertain terminology, and a tendency overemphasize one of the three sectors -- water, energy, or food (Smajgl, Ward & Pluschka, 2016). Developing and evaluating methods for the water-energy-food nexus requires a clear understanding of the nexus itself (de Strasser et al., 2016). However, not only is there no universal definition of the nexus (Endo et al., 2015a), but also, there is a limited discussion of nexus definitions in the literature (Benson et al., 2015). The ambiguity is proving to be problematic. Numerous conceptualizations exist, many of which are competing or overlapping (Benson et al., 2015). Without a defined scope, the nexus approach can become unruly and lead to unmanageable problems and poor implementation (Gain, Giupponi & Benson, 2015). To clarify and strengthen the nexus approach, more attention needs to be paid to understanding how to assess nexus interactions at multiple scales (Benson et al., 2015). Focusing on implementation will help establish the water-energy-food nexus as a useful tool and improve its value in resource management. Although use of the nexus concept in research has been growing rapidly, little consideration has been afforded to determining how best to implement and assess it in practice (Endo et al., 2015a).

A systematic review of existing nexus methods, including their strengths, limitations and disciplinary foundations, is needed to improve implementation of the nexus approach and provide for rigorous and replicable nexus assessments (Semertzidis, 2015). Although nexus assessments will be site- and study-specific, and cover a wide range of applications, nexus methods should attempt to transcend single-sector tools and instead, present deeply interdisciplinary and comprehensive approaches designed to address specific nexus challenges. We reviewed over 200 recent publications on the water-energy-food nexus and found 54 articles that explicitly presented methods for water-energy-food nexus assessments. These 54 articles are the focus of this study.

3.0 Methods

To identify water-energy-food nexus methods, we searched the Scopus database using the keywords "water", "energy", "food", and "nexus" in the abstract, title and keywords. We included only publicly-availably, peer-reviewed journal articles, with no restriction on publication date. The Scopus search resulted in 182 items. An additional 24 articles were obtained through review of reference lists of included items, and four policy reports were selected based on the authors' prior knowledge of their relevance. Thus, a total of 210 articles were reviewed.

Articles were categorized as either "conceptual" or "methodological", or excluded. Methodological articles were selected based on the following criteria: (1) substantial engagement with nexus concept in terms of natural resources sustainability; (2) engagement with all three sectors: water, energy and food; and (3) presentation of methods for evaluating the nexus. Articles that met only the first two criteria were categorized as "conceptual" -- commonly, these articles engaged with the nexus as a framework, perspective or concept. Articles were excluded if they did not meet any of the selection criteria, for example, if they used the "nexus" as a buzzword.

Of the 210 articles identified, 81 articles were excluded (39%) based on the criteria above. Ten books, book chapters or policy papers were reserved for review at a later time. More than half of the articles reviewed (119) engaged substantially with the water-energy-food nexus, however, only 54 presented methods for evaluating the nexus. We coded the subset of 54 articles for information related to publication (i.e. journal, year, journal discipline) and nexus methods (i.e. single discipline; interdisciplinary; qualitative, quantitative, or both). The results below describe the 54 articles that present methods for evaluation of the water-energy-food nexus.

4.0 Findings

Our review revealed that the conversation about specific methods to evaluate the water-energy-food nexus is emergent and rapidly growing. Articles reviewed were published through February 2016, however, less than one-quarter (22%) were published prior to 2015[1]. Water-energy-food nexus methods have been published in journals spanning a broad range of disciplines -- nearly thirty different journals are represented. Approximately 36% were published in journals related to the field of water resources, 23% environmental science and policy, 15% energy, 11% engineering and technology, 6% global change, and 4% or less in each of food science, agriculture, and hydrology journals.

More than half (55%) of the articles used primarily quantitative methods to evaluate the water-energy-food nexus. Approximately one-quarter (24%) used quantitative and qualitative methods together, whereas 20% utilized only qualitative methods. We found that slightly less than half (46%) of the articles presenting water-energy-food nexus methods did not show an overt inclination toward water, energy or food as sectors. However, more than a third (38%) of the articles did show some preference for one sector, either in terms of framing their analysis or from where the methods used were derived. Preference was most commonly given to the water sector (22% of all articles), reflecting the genesis of the nexus concept, whereas 9% and 7% emphasized the energy or food sectors, respectively. The remainder of the articles privileged two of the three sectors -- either water-energy or water-food.

Despite the fact that the water-energy-food nexus involves multiple sectors, interestingly only half (56%) of articles proposed using an interdisciplinary approach. However, more than two-thirds of articles (68%) proposed using more than one method although sometimes methods were all derived from the same discipline. The methods used or proposed most often drew from pre-existing disciplinary techniques, that were not designed for nexus evaluation. In nearly half of the studies (46%), while they drew from existing methods, proposed adjusting or recombining these methods to evaluate the nexus. However, many authors (37%) merely applied existing disciplinary methods without significant revision or adjustment for the scope of nexus challenges. Interestingly, only nine studies (17%) presented methods that were specifically tailored to nexus questions.

Methods proposed for evaluating the water-energy-food nexus are derived from various disciplines. Our review revealed that many and diverse methods have been used or proposed for examining the water-energy-food nexus, and many studies proposed combining multiple different methods. A total of 129 different methods were referenced in the papers reviewed. We tabulated and categorized methods based on discipline and/or type of method (Table 1). Methods based in environmental management and economics were most commonly utilized. Thirty-seven studies, or 69% of all 54 studies using methods, used at least one method from the field of environmental management. Twenty-four studies, or 44% of all studies, used at least one economic method. Interestingly, fifteen studies, or 28% of all studies, used at least one qualitative social science method.

[1] Of all 210 water-energy-food nexus articles, 90% were published since 2013, and 50% were published in 2015 alone.

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Table 1: Number of times each method, or type of method, is used or proposed in the sample set. At least 37 of the 54 papers used more than one method.

Environmental Management	**37**
Scenario analysis	12
Footprinting	11
Life cycle assessment	8
Stakeholder engagement	3
Decision support	2
Benefit sharing analysis	1
Economic	**24**
Input/output	9
Cost-benefit analysis	2
Tradeoff analysis	1
Tradeoff frontiers	1
Social accounting matrix	1
Economic modeling (optimization modeling, dynamic panel modeling, root test, process graph framework, GTAP, POLES, E3ME)	6
Value chain analysis	2
Supply chain analysis	1
Sefficiency	1
Qualitative Social Science	**15**
Institutional analysis	3
Questionnaires	3
Historical analysis	2
Political economy	2
Agent based modeling	1
Delphi technique	1
Discourse analysis	1
Ontology engineering	1
Stakeholder analysis	1
Hydrologic	**10**
Hydrologic modeling (e.g. SWAT, Vmod, WaterGAP, floodplain modeling)	6
Water balance modeling (e.g. WEAP)	4
Geospatial	**9**
Spatial analysis	7
Remote sensing	2
Integrated Modeling	**9**
Integrated assessment models	5
Climate, Land, Energy, and Water Systems model	3
Hydro-economic modeling	1
Statistics or Indicators	**6**
Indicators/Metrics	4
Principal component analysis	1
Logit regression statistics	1
Systems Analysis	**5**
Multi-sectoral systems analysis	2
Systems informatics and analytics	1
Sankey diagrams	2
Energy	**4**
Long-range Energy Alternatives Planning system	2
Emergy analysis	1
Other energy models (e.g. OSeMOSYS, DynEMo, MARKAL/TIMES, PRIMES)	1
Food Systems	**4**
Caloric-demand analysis	2
Source-to-service resource modeling	2
Geophysical Models	**3**
Downscaled GCMs	1
General equilibrium model	1
Other geophysical models	1
Development	**2**
UNECE Transboundary River Basin Nexus Assessment	2
Agricultural	**1**
Agro-Ecological Zoning model	1

5.0 Progress Toward Nexus-specific Methods

Although our review revealed 129 different methods have been used toward assessment of the water-energy-food nexus, nearly half (44%) of the studies reviewed apply methods from a single discipline. Because nexus challenges are multi-disciplinary, assessment methods must transcend disciplinary silos and integrate knowledge from multiple areas (Wolfe et al., 2016). However, the use of either quantitative and qualitative methods together or integrated modeling tools are uncommon (24% and 17% of all studies reviewed, respectively). Further, many integrated tools are limited in their scope and ability to consider complex interactions and feedbacks among sectors (de Strasser et al., 2016). Nexus assessment methods need to be holistic, collaborative, robust, truly integrative, able to inform coherent policy, and multi-scalar, in order to contribute to the goals of coherent intersectoral policy and resource efficiency. Below we highlight trends in nexus methods presented in the literature that provide examples of progress toward innovative and robust approaches.

5.1 Integrated Assessment Tools

Integrated assessment tools, such as the Climate, Land, Energy, and Water (CLEW) modeling framework (Bazilian et al., 2011 and Howells et al., 2013) and others (Dahter and Mohtar, 2015; Yang et al., 2016) have been applied for nexus assessment. Although the Climate, Land, Energy and Water (CLEW) modeling framework is not new, nor fully integrated (Bazilian et al., 2011), it offers a comprehensive assessment of water, energy, and food system interactions. Using a module-based approach, this model integrates water, energy, and land models in conjunction with climate change scenarios. Key linkages between water, energy, and land (and/or food) sectors are identified and physical flow and commodity as well as cost accounting information are exchanged at linkages (Howells et al., 2013). Data inputs and outputs are linked between modules in an iterative fashion.

The module-approach allows for a wide range of tools to be incorporated to examine both tradeoffs and synergies within integrated systems. A major challenge of these integrated models is that the time required to construct, calibrate, and validate these models doesn't lend itself to policy timelines. Bazilian et al. (2011) offer six insights to improve the application of the CLEW model for nexus assessment and policy dialogues. These are: (1) develop finer model resolutions to capture smaller spatial scales; (2) reduce data requirements to make the models transferable to regions with limited data; (3) conduct medium term temporal scopes; (4) include multi-resource/multi-interlinkage representation; (5) make software accessible to resource analysts; and (6) use a systems approach to account for upstream or exogenous impacts.

In our study two 'new' integrated modeling tools were presented: WEF Nexus Tool 2.0 (Dahter and Mohtar, 2015) and a hydro-economic water system model (Yang et al., 2016). The WEF Nexus Tool 2.0 first identifies the system of study and then uses national water, energy, and food strategies to examine the impacts of different scenarios. The model, which was created for Qatar, has a publically accessible user interface (available at www.wefnexustool.org) that allows the user to vary (a) type of crops; (b) energy sources; (c) water sources; and countries of import for each crop to examine impacts across the different sectors. The modeling framework presented by

Yang et al. (2016) incorporates physically-based hydrologic modeling, hydro-economic modeling, and ex post scenario analysis to identify potential areas of conflict based on development trajectories. Instead of trying to optimize decision making, their ex post scenario analysis supports policy and planning under a range of possible future scenarios, particularly regarding hydropower dam development and precipitation changes.

5.2 Transdisciplinary Methods

Some authors called for participatory approaches that include a broad range of actors including academia, government, private sector, NGOs, and civil society. Broad participation of this sort can be considered transdisciplinary research, particularly when stakeholders are involved in the process of developing research questions (Endo et al., 2015b). Transdisciplinary approaches to the water-energy-food nexus can help increase collaboration, improve identification of interrelationships between sectors, and promote data sharing.

Wolfe et al. (2016) advocates for transdisciplinary teams that will utilize a systems approach to synthesize knowledge from a variety of stakeholders to address water-energy-food nexus challenges. They propose a “food-energy-water nexus system” platform that consists of system informatics, information analysis methods and tools, and systems analytics designed for decision support. Wolfe et al. (2016) suggests that this information system be designed in coordination with a community of experts and contributors, in order to achieve a tool that is flexible and allows for growth. The authors note the limitations of such an approach, particularly the need for increased data availability and sharing, as well as the challenge of forming and maintaining transdisciplinary work team among scientists, engineers, policymakers, and practitioners.

Endo et al. (2015b) discuss how multiple methods can be utilized together in a transdisciplinary framework in order to achieve integration between sectors. The authors suggest that a transdisciplinary approach can be especially effective for achieving coherence in policy and management between sectors by engaging stakeholders in the design and undertaking of nexus research based on co-production with diverse stakeholders. However, the authors also acknowledge salient barriers to productive transdisciplinary collaboration: (1) the lack of a common language among scientists from different disciplines; and (2) the lack of robust methods to evaluate the process and outcome of such transdisciplinary processes (Endo et al., 2015b).

5.3 Mixed Methods

Only one-quarter of the studies reviewed utilized mixed methods, which herein are understood to be a combination of both quantitative and qualitative methods from any discipline. For example, Sharma et al. (2010) utilize remote sensing, hydrologic modeling, and statistics combined with institutional analysis and questionnaires. By combining quantitative and qualitative methods, research approaches can achieve more breadth and depth (Johnson, Onwuegbuzie & Turner, 2007), thus they can be especially appropriate for the purpose of conducting a holistic assessment of multi-faceted challenges of the water-energy-food nexus. Because mixed methods approaches are often interdisciplinary, they can be more effective at identifying complex interrelationships. Further, mixed methods and interdisciplinary approaches demand collaboration across disciplines.

Endo et al. (2015b) present qualitative and quantitative methods from both interdisciplinary and transdisciplinary approaches that can be used specifically to assess the water-energy-food nexus. They identify qualitative methods, such as questionnaire surveys, ontology engineering, and integrated maps that can be used to describe the water-energy-food nexus, whereas quantitative methods are suggested for examining the nexus, such as physical models, benefit-cost analysis, integrated indices, and optimization management models. Using site-specific integrated methods, comprised of sequential mixed methods, enabled these authors to combine knowledge from multiple disciplines and coordinate among stakeholders at different spatial and temporal scales.

Stucki and Sojamo (2012) combine quantitative indicators and descriptive analysis of political economy to explore the water, energy, and security nexus in Central Asian countries. Further, they analyze definitions of important terminology, such as "water security" and "energy security", in order to identify the elements of the nexus. By taking a mixed methods approach, the authors discover that water and energy insecurity in Central Asian countries is primarily due to governance and politics, rather than resource scarcity.

5.4 Qualitative Social Science Methods

With much of the integrated nexus methods deriving from systems thinking, there has been a growing interest and need to explore the social dimensions of the water-energy-food nexus. In our meta-analysis, 33% of the papers used at least one qualitative social science method as part of their study. We discuss several social science methods that help illustrate the complexity of water, energy and food systems. The qualitative methods discussed below help contextualize historical, institutional, economic or political components of the water-energy-food nexus to inform more holistic thinking.

Using a historical and institutional analysis of water resources management in the transboundary Syr Darya Basin, Soliev, Wegerich & Kazbekov (2015) highlight the complexity of water, energy, and food resources and the institutions that govern them. Their analysis reveals how institutional settings for water management have evolved and how multiple factors (i.e. economic, social, and political) can hinder or enable integration across sectors. Given the complexity of these systems, Soliev, Wegerich & Kazbekov (2015) emphasize the importance of understanding this complexity to develop appropriate policy and management strategies.

Villamayor-Tomas et al. (2015) conducted institutional analysis using the Institutional Analysis and Development framework, coupled with a value chain analysis to examine how institutions help facilitate or limit nexus integration. Primary (i.e. interviews, surveys) and secondary data (literature reviews) were collected and analyzed. A conceptual model, designed by identifying input-output linkages as well as influential actors and institutions, helped evaluate institutional and physical path dependencies (Villamayor-Tomas et al., 2015). Employing a critical lens, Foran (2015) focuses on how asymmetrical power relations shape and reshape production and consumption patterns within the water-energy-food nexus. Foran (2015) discusses how uneven development practices are deeply embedded in social structures and political contexts—or water, energy, and food regimes—and must be understood in this context to address equity concerns.

The complexity of the water-energy-food nexus is also a theme in Smajgl, Ward & Pluschka (2016). Bringing together a panel of six sector specific experts, Smajgl, Ward & Pluschka (2016) employs the Delphi process (see Lindstone and Turoff, 1975) to assess water-energy-food nexus impacts from proposed development initiatives in the Mekong basin. The expert panel for this study concludes that single sector interventions can have rippling effects through water, energy, and food systems. Therefore, accurately identifying the factors that substantially influence water, energy, and food dynamics is a critical first step for nexus research (Smajgl, Ward & Pluschka, 2016).

5.5 Systems Thinking

To help capture the complexity of interrelations and interactions among water, energy, and food systems, systems thinking methods can offer valuable contributions to nexus research. Wolfe et al. (2016) present a cyber-physical framework approach that draws on technical advances to address the "big problems" facing water, energy, and food systems. With systems integration considered the weakest aspect of the water-energy-food nexus (ibid), this framework discusses how a three-part cyber platform that stores and transmits data for decision-makers could help system integration. Broadly, the three components that promote data acquisition and accessibility are: (a) systems informatics; (b) information analysis methods and tools; and (c) systems analytics and decision support. The proposed drivers and users of such a platform are people, or rather, a community of diverse stakeholders that can offer a variety of data and perspectives for data sharing and collaboration. Two decision support tools (accessible via Agroclimate.org and agmip.org) are presented as successful examples of such cyber platforms.

Halbe et al. (2015) highlights how *reflexive governance* can help understand complex systems and help facilitate long-term transitions that support more sustainable outcomes. This framework was developed to understand the increasingly importance of actor networks that influence decision-makers, civil society, and business leaders among others (Halbe et al., 2015). Their research, which is specifically designed for a nexus perspective, includes a strong participatory component to determine and define the problem to address and to create causal loop diagrams. These causal loop diagrams are based in systems thinking and illustrate resource flows and feedback loops. Through a combination of individual and group causal loop diagraming, multiple system designs are created, compared, and then selectively combined. This systems-based participatory mapping exercise can form the base of or offer important insight into quantitative models. An additional interesting contribution from this framework is that it includes a learning assessment. As interventions that promote desired outcomes are explored, the educational needs to reach these desired outcomes are identified to help achieve the end-goal.

6.0 Challenges

Water-energy-food nexus assessments encounter challenges that reflect the "big" problems (Wolfe et al., 2016) inherent to complex interrelationships of the nexus. Because nexus questions involve multiple sectors and disciplines, nexus methods often require large and diverse datasets. The lack of adequate quantities or types of data was noted as a significant limitation by many (Karabulut et al., 2015; Semertzidis, 2015; Endo et al., 2015b; Yang et al., 2016; Hurford and Harou, 2014; Wolfe et al., 2016). Further, the need for quantitative approaches that incorporate methods for dealing with uncertainty, for example Bayesian causal networks, was also noted (Stucki and Sojamo, 2012; Villarroel Walker, Beck & Hall, 2012; Semertzidis, 2015). Nexus challenges are site-specific and depend on scale of analysis, infrastructure, and geopolitical context. Although difficult to compare between sites, local-scale, targeted tools may provide more relevant results (Daher and Mohtar, 2015) and reveal subnational dynamics (Stucki and Sojamo, 2012).

Further, nexus approaches often require interdisciplinary and transdisciplinary approaches. Interdisciplinary research teams must negotiate among diverse ways of producing knowledge, integrating information, and conducting methods (Endo et al., 2015b). Further, facilitating transdisciplinary teams, which can include scientists, policymakers, practitioners, and lay citizens, is difficult due to the lack of a common terminology (Wolfe et al., 2016) and widely varying goals and priorities. Both types of diverse teams are difficult to form, facilitate, and maintain. However, bringing together the ideas and perspectives of actors from multiple sectors and disciplines is key to addressing nexus interrelationships.

7.0 Conclusions

Nexus research is rapidly expanding. More water-energy-food nexus papers were published in the first two months of 2016 than all of 2014. Furthermore, in December 2015 the National Science Foundation announced a new solicitation titled, *Innovations at the Nexus of Food, Energy, and Water Systems (INFEWS) Nexus.* With an anticipated budget of $50,000,000, this call is expected to catalyze a cascade of nexus research.

As water-energy-food nexus scholarship advances, there is a need to further develop consistent and specific tools that can support comprehensive and integrative methods for nexus research and practice. Given the highly site-specific and dynamic nature of the nexus, a completely uniform method is neither preferable, nor realistic (Brandt et al., 2013). By providing a review of the current landscape of nexus methods and identifying trends in the development of new methods, we have highlighted promising future research directions to better capture the complexity of water, energy and food systems.

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