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Perspectives, challenges and directions for future research into the water-energy-food (WEF) nexus

SUŠNIK J.[1,*], STADDON C.[2]

[1]Land and Water Management Department, IHE Delft Institute for Water Education, Delft, The Netherlands

[2]Department of Geography and Environmental Management, University of the West of England, Bristol BS16 1QY, UK

*Corresponding author. Email: j.susnik@un-ihe.org

Abstract In 2018, Albrecht et al. published a review of water-energy-food (WEF) nexus literature, coming to five main criticisms in nexus research. The five central conclusions of that review together with a consideration of on-going projects and recent nexus research insights form the basis for this critical review. The current state of nexus research, and in particular modelling research, is examined and updated to reflect recent advances and correct misperceptions, and put them in the context of larger epistemological issues. The main conclusions are:

1) The considerable and growing diversity in nexus studies precludes a one-size-fits-all approach. Indeed, it has never been an objective to develop a 'grand unified nexus theory or model';
2) A lack of 'fundamental equations' between many nexus parameters hinders full quantification of nexus linkages, though data-driven, stochastic and agent-based approaches offer avenues for development;
3) The use of qualitative and social science methods in nexus studies is rapidly gaining traction, especially when blended with quantitative modelling outcomes;
4) Progress has been made in attempting to break disciplinary siloes, especially when considering integrated assessment models and system dynamics models.

Keywords: nexus challenges; nexus critique; nexus perspectives; water-energy-food nexus

1. Introduction

Over the last decade, the nexus of water, energy, and food (linked to land resources), has been recognised as forming a complex, 'hyperconnected' system essential for global and human development (WEF, 2015). Due to system complexity across scales, impacts and feedbacks are difficult to quantify, and unexpected outcomes can be generated. The nexus is both driven and constrained by climate change, population growth, and lifestyle alterations. System response can influence the driving factors. This is set against a background of planetary limits (cf., Rockström et al., 2009; Steffan et al., 2015). We argue that the WEF nexus is made distinctive by its tight focus on critical and intense "hyperconnections" that bind water, energy and food into a critical 'system of systems'.

Academic interest in the nexus (Hoff, 2011) has rapidly increased over the last decade (e.g., Endo et al., 2015; Albrecht et al., 2018; Bleischwitz et al., 2018; Dermody et al., 2018), with the aim of better understanding and quantifying trade-offs and synergies. Much research aims to feed into high-level policy that is developed with a systems thinking approach (Capra and Luisi, 2014; Scott et al., 2016).

Recent proliferation of work has increased general nexus awareness, knowledge and understanding, and is increasingly focusing on policy relevance (Munaretto et al., 2017, 2018). Despite the progress, scientific and knowledge gaps remain, and there are areas where improvements could be made to achieve greater consistency and 'convergence' between nexus studies. Wider, generally applicable conclusions are difficult to come by. This has, perhaps inevitably, led to criticism regarding the usefulness of the nexus approach (Albrecht et al., 2018), and it is suggested that the epistemological transformation realising the potential of nexus thinking is still to come.

The diversity of aims and objectives, foci, spatial and temporal scales, and modelling tools have contributed to an arguably fragmented nexus landscape. Albrecht et al., (2018) found that although many advances have been made, there are a number of criticisms that can be levelled at the nexus approach:

1. "The use of specific and reproducible methods for nexus assessment is uncommon";
2. "Nexus methods frequently fall short of capturing interactions among water, energy, and food—the very linkages they conceptually purport to address";
3. "Assessments strongly favor [sic] quantitative approaches";
4. "The use of social science methods is limited";
5. "Many nexus methods are confined to disciplinary silos".

These criticisms are re-examined and updated in the light of recent work. The aim of this paper is to show where the main criticisms found in Albrecht et al. (2018) have started to be addressed, and/or can be explained by viewing nexus research objectives from a different perspective. Suggested pathways for new nexus research initiatives are articulated. We posit that challenges outlined here will apply to programmatic efforts around the world.

2. Perspectives on the nexus

Is a 'unified' nexus theory or model possible?

Albrecht et al. (2018) concluded that the majority of articles "utilize the nexus as a conceptual framework or offer descriptive accounts of water, energy, and food systems" and lack coherence. While this observation is valid, there are practical reasons behind the observation. One reason precluding application of a common approach across scales, sites and domains is due to the vast diversity of issues, challenges, scales, sectors and timelines being addressed. Thus, it is not surprising that self-identified WEF nexus research has tended to focus on different parts of nexus systems. The WEF nexus has been 'shrunk' to focus on very specific interactions (Yang and Chen, 2016; Valek et al., 2017) and 'expanded' to include an ever-greater variety of sectors and scales (e.g., human development and resource access: Sušnik and van der Zaag, 2017; energy, mineral resources, and society: Schlör et al., 2018).

Such diversity is a strength and a weakness. On the one hand, if an attempt to 'unify' nexus research was at the fore, such diversity would be self-limiting. On the other, the lack of a strict definition, and therefore the ability to apply approaches targeted to the specific and well-understood challenge at hand, arguably allows for true 'thinking outside the box. There has never, to the best of our knowledge, been an attempt to comprehensively unify the science or create an 'all-encompassing' nexus model.

Commonality to achieve reproducible tools amongst modelling methods or approaches is unlikely to be resolved. There is no overarching framework or approach that can adequately satisfy the different needs and requirements of every study. Some common approaches used for nexus assessments do exist, offering an opportunity for some sort of commonality. Such approaches include: system dynamics modelling (SDM; Meadows et al., 1972; Simonovic, 2002; Sušnik, 2015, 2018); (multi-region) input-output modelling (MRIO; Chen, et al., 2018; Wang et al., 2018); agent-based modelling (ABM; An, 2012); and integrated assessment modelling (IAMs; Huppmann et al., 2019). Transparency in modelling methods, data, assumptions and uncertainties must be improved, and can be achieved by better documentation of models, approaches, and tools.

Exploring interactions is the key to nexus research, but is potentially an insurmountable object

Many nexus studies often fail to live up to ambitions of comprehensive integrated and dynamic assessment of the nexus, and it is important to understand why this is the case. For example, many (MR)IO and LCA studies use static look-up tables which often fail to reflect the dynamic nature of nexus interlinkages. Many IAMs do attempt to dynamically account for physically or statistically-based relationships between nexus sectors. Specifically defined, dynamic relationships that can also have a stochastic component are defined in SDM approaches.

Many interactions have never been thoroughly studied. For example, in Earth Science disciplines, many physical connections have clear empirical, physical, chemical and/or biological foundations, with fundamental equations connecting processes. In the WEF nexus, only in some cases can such clear relationships be defined. Even here, the operationalisation of these relationships may still be contested. Many relationships vary greatly, depending on time, location and scale, and the values can change over time at the same location. Generally applicable linking relationships or interactions may not be definable. Specific relations for a given case can be more reliably assessed (e.g., Hussein et al., 2017) with lower uncertainty. Nonetheless, some WEF connections are not understood or quantified at the general level, such as the impact of land use changes or cropping pattern changes on water quality, energy requirements, or climate impacts. The impact on ecosystems is particularly lacking in nexus assessments (Hülsmann et al., 2019).

Representation of fully coherent and dynamic relationships between the entire WEF nexus sectors is poorly covered in a uniform and consistent manner, especially at larger scales. Uncertainty may be considerable and is often not quantified or acknowledged. More complex and multidimensional interactions within the wider WEF nexus tend to be missing, with most approaches limited to two-sector interactions.

The growing integration of social science and qualitative approaches into nexus research

Albrecht et al. (2018) highlight the challenges of integrating social science and natural science perspectives on WEF nexus relationships. Many studies favour quantitative approaches. This is a result of attempts to assess the behaviour and future directions of nexus systems (e.g., Huppmann et al., 2019; Bakhshianlamouki et al., 2020). However, there has been an increase in the number of studies applying qualitative approaches to understanding the WEF nexus. Indeed, much criticism has followed from contrary observation that too many nexus studies use qualitative or 'conceptual' approaches (cf., Endo et al., 2015). Conceptual or qualitative models are illustrative, aiming to give a qualitative understanding of nexus interactions and of overall system structure. Such studies elucidate nexus issues and behaviour for 'siloed' practitioners or for policy makers not familiar with technical modelling approaches (cf., Purwanto et al., 2019).

Counter to this is the observation that in many studies, quantitative methods are employed to quantify the nexus and to assess the impact and uncertainty of an action across the nexus. At the same time, many of these studies demonstrate that causal or qualitative mapping is used at an earlier stage in the process to understand the overall system structure, helping to design quantitative models which are the most obvious outputs in many publications (e.g., Simonovic, 2002; Bakhshianlamouki et al., 2020). Both qualitative and quantitative approaches are increasingly blended in nexus studies, if not within the final outputs or publications. It can be argued that a blended approach is essential for robust modelling.

While quantitative approaches may be more common, and are essential to understanding how WEF systems respond, such quantitative models must be backed up by sound conceptual or causal models that describe the system structure. Including stakeholders helps ground outputs in reality, making results more relevant for policy makers, something that is increasingly required.

Towards 'nexus' thinking and modelling

Historically, many models have been developed with specific 'thematic' aims. Such models cover a vast diversity of scientific disciplines. Such models were developed to study specific issues, requiring them to be focussed and allowing them to capture the details of specific systems. This approach has resulted in considerable scientific advance. Various approaches have been adopted in an attempt to overcome the risk in siloed approaches. Two notable examples are the development of IAMs, and the re-emergence of SDM. Both are very different in their approaches. IAMs, largely stemming from the climate and energy sciences, attempt to integrate nexus sectors, sometimes from different models, to provide system wide assessment of impacts. IAMs have grown considerably in complexity, but attract criticism for being 'subjective' and having created their own 'reality' which has been accused of being misleading and none as yet cover all WEF sectors comprehensively or coherently.

The second approach, SDM, has a different philosophy. Originally developed for studying industrial processes, SDM has been applied widely in many disciplines. Using the notions of stocks, flows, converters and connecters, SDM is used to build representations of complex systems from the bottom up, but without this system being prescribed a-priori. This means that any system could in principle be modelled within this framework. Due to the inherent suppleness in combining disciplines, SDM can break silos, leading to a greater awareness of systems thinking. One downside is that due to the differences in scope, scales and sectors, developing a generally applicable SDM to serve all purposes is unlikely to be achieved. In recent years, more attention has been placed on either the integration of existing models, or building new models and/or using established approaches in new ways to more holistically model the nexus.

3. Directions for nexus research

The critique of the state of the art in nexus modelling methods and approaches presented by Albrecht et al., (2018) is useful, with a number of valid observations and suggestions that can help further develop nexus research.

- Diversity in nexus studies necessarily precludes a one-size-fits-all approach. It has never been an objective of WEF nexus researchers to develop a 'grand unified theory or model'. A single common approach/tool for all nexus studies is unlikely to be realised.
- Some nexus interactions are well captured in nexus studies, although perhaps not to the extent and depth desired. Data, uncertainty, linking equations, model/system structure, assumptions and limitations are often not fully explained. A lack of 'fundamental equations' between nexus parameters hinders progress in this respect.
- The integration of ecosystems and ecosystem services is glaringly lacking. Having a universally agreed-upon 'currency' with which to assess ecosystems, climate change, and environmental impact could go some way to boosting such integration.
- The integration of qualitative/social science methods is rapidly gaining traction in nexus research. Policy coherence analysis and fuzzy cognitive mapping techniques are adding 'quantitative' robustness to social science approaches. Conceptual system maps are increasingly incorporated into modelling studies.
- Greater stakeholder engagement is needed. Increasing and improving stakeholder and policy involvement will help address both of these concerns.
- Great progress has been made in attempting to break disciplinary silos. IAMs, in particular, attempt to (soft) link thematic models. Likewise, the application of SDM is proving valuable in its ability to develop models from the ground up, not being constrained by nexus sectors, data requirements or modelling objectives.

Following from these, some proposals for future nexus research are made:

- Ecosystem services must be better incorporated into WEF nexus assessments.
- More needs to be done to integrate social science methodologies in nexus studies.
- Qualitative system mapping should become an essential aspect to all modelling studies.
- Stakeholders must be included at the project/study design phase, and continually involved.
- Less emphasis should be placed on developing new concepts, with effort instead going to implementing real-world relevant nexus studies with policy guidance.

This paper summarises the work in Sušnik and Staddon (Submitted; Under Review).

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