Science of the Total Environment 651 (2019) 309–322

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Developing interpretive structural modeling based on factor analysis for the water-energy-food nexus conundrum

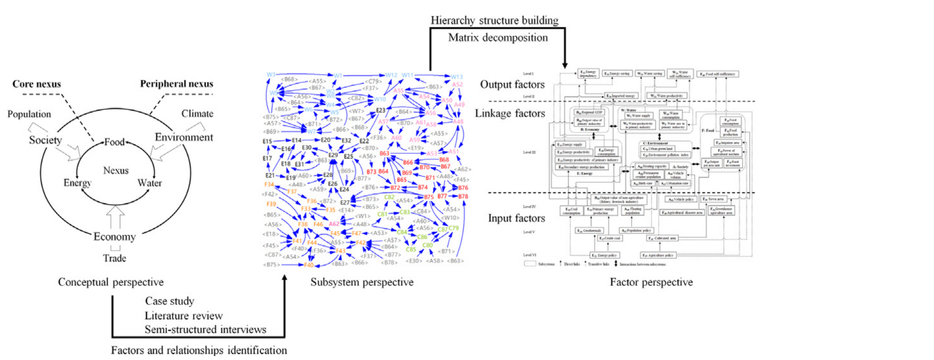
Guijun Li [a], Daohan Huang [a,c], Chengshuang Sun [b], Yulong Li [a,*]

[a] School of Management Science and Engineering, Central University of Finance and Economics, Beijing 100081, China
[b] School of Economics and Management Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, China
[c] Intern (2017–2018), Stockholm Environment Institute U.S. Center, Somerville, MA 02144, United States

HIGHLIGHTS

- Conceptual framework and representative factors of urban WEF nexus are analyzed.
- Factors in Beijing WEF nexus are classified as input, linkage and output factors.
- The hierarchy structure of WEF nexus factors is established with ISM method.
- The energy subsystem is the essential system to govern the WEF nexus in Beijing.
- Integrated policies are critical to sustain the WEF nexus development.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 February 2018
Received in revised form 14 September 2018
Accepted 14 September 2018
Available online 15 September 2018

Editor: Elena PAOLETTI

Keywords:
ISM
Water-energy-food nexus
Hierarchy structure
Sustainable development

ABSTRACT

Factor identification and analysis are effective ways to explain and quantify complex relationships in the water-energy-food nexus (WEF-nexus). It has been acknowledged that factors in the WEF-nexus vary by time, level and location, but the hierarchy between factors has been largely ignored. Taking advantage of the interpretive structural modeling (ISM) method, this paper presents an identification and analysis on the interwoven factors in an urban WEF-nexus in Beijing. As a result, 87 representative factors have been identified and classified, with a hierarchy structure established by ISM. Based on the relative importance of given factors, factor hierarchy structure shows that the energy system in the core nexus is the essential system and is critical to promoting the WEF-nexus in Beijing; factors from peripheral nexuses – such as population and vehicle volume – also have a significant influence on nexus governance. Furthermore, integrated policies from subsystems within the core nexus or between the core and peripheral nexuses are critical to secure WEF in Beijing. Factor analysis suggests that the portrayed nexus structure could provide valuable references for further quantification and decision making.

1. Introduction

Water, energy and food (WEF) resources are slow variables in a regional sustainable development system, and the security of WEF is the critical step in sustaining regional development (Hoff, 2011; Li et al., 2016a). With a series of complex and dynamic interconnections embodying WEF production, consumption and management processes

* Corresponding author at: Room 340, Building 4, School of Management Science and Engineering, Central University of Finance and Economics, Shahe Campus: Shahe Higher Education Park, Changping District, Beijing 102206, China.
E-mail addresses: ligj@cufe.edu.cn (G. Li), hdh612@email.cufe.edu.cn (D. Huang), suncs@bucea.edu.cn (C. Sun), liyulong@cufe.edu.cn (Y. Li).

https://doi.org/10.1016/j.scitotenv.2018.09.188
0048-9697/

(Covarrubias, 2018), any strategies focusing on single resource management would lead to serious unintended consequences (World Economic Forum, 2011). For example, provision of free or subsidized power in agriculture is one of the concerns resulting in groundwater overexploitation (Sharma et al., 2018). Therefore, it is crucial to place WEF equally in one platform – forming a water-energy-food nexus – to get stakeholders involved, and to shift the nexus from concept to practice with decision making from a systems perspective. The first step for a nexus approach is to identify and analyze those numerous interconnections interwoven in the WEF-nexus black box (Keskinen et al., 2015; Hamdy et al., 2014). Therefore, our research studies interactions in the WEF-nexus system and focuses on level partitions between factors intertwining in the nexus system to raise awareness among decision makers and to promote nexus governance.

The water-energy-food nexus (WEF-nexus) was formally set forth in 2011; it focuses on the interdependence between water, energy and food (Hoff, 2011; Li et al., 2016a; Endo et al., 2015). There is a large body of literature on this subject. Some studies define the nexus concept from the perspective of resource security, management and justice (Hoff, 2011; Allouche et al., 2015; FAO, 2014); develop a theoretical basis for nexus analysis such as resources eclecticism (Leck et al., 2015), environmental governance (Weitz et al., 2017) or process modeling (Garcia and You, 2016); and map a conceptual framework to explain the interdependence in an urban or regional background. These studies detail interactions between WEF and social, economic and environmental subsystems (Wong, 2010; Foran, 2015) and identify interrelated factors with embodied behaviors (Hussien et al., 2017), which is critical to understanding and quantifying the nexus system. Other research – using multivariate statistics (Gulati et al., 2013), integrated indices (de Strasser et al., 2016), physical models (Bazilian et al., 2013), system dynamics (Li et al., 2016b; Halbe et al., 2015), or linear programming (Peng et al., 2017) – has attempted to quantify linkages between factors and present system behavior in an uncertain environment. Both streams of literature contribute to the understanding of complex interconnections and also bring a holistic perspective in nexus governance to the forefront, showing three core characteristics of the WEF-nexus: a polycentric network structure, dynamic complexity and place-specificity. Although great advances on a nexus framework and quantification have been made in an urban scale (Covarrubias, 2018; GIZ and ICLEI, 2014), a lack of unified official actions in practice, methodological hurdles in quantification (Chang et al., 2016) and disaggregated data scattered among sectors (Scanlon et al., 2017) are significant weaknesses and obstacles for further nexus research and practices. This highlights the importance of structural modeling in nexus research. With factor identifying and hierarchy structure building, structural modeling is definitely one of the most appropriate approaches to manifest system structure and feedback mechanisms on a theoretical level and implicate the involved structural changes on an alternative policy (McLean and Shepherd, 1976), which has been widely used in studying interdependent elements in a complex system (Turoff et al., 2016).

To identify factors and their interconnections in nexus research, structured or semi-structured interviews have been widely used, together with the Delphi method (Smajgl et al., 2016), case studies (Covarrubias, 2018) and literature reviews (Karabulut et al., 2016). Participatory processes such as brainstorming sessions (Halbe et al., 2015) as well as interviews of relevant stakeholders are effective ways to explore factors and their interconnections in watershed research. But this face-to-face approach is time-consuming and introduces unwanted leadership (Bañuls and Turoff, 2011). The Delphi method was developed to address these drawbacks by controlling feedback and anonymous interactions among experts, but its disadvantage is that it is hard to make complex forecasts with interrelated factors (Bañuls and Turoff, 2011), which is at the core of a nexus. Literature reviews and cases studies depend on adequate literature; the former has expertise on a wide range of relevant elements from a singular perspective and also critical connections between WEF such as energy for water pumping to secure food security, while the latter could distinguish place-specific factors and linkages with case experiences (Sushil, 2012). To largely enable strengths and avoid weaknesses, a combination of semi-structured interviews, case studies and literature reviews are employed in this paper to identify numerous factors and interconnections.

The hierarchy among factors in a nexus system is still ambiguous, but the CLEWS framework and the Nexus Tool 2.0 framework make an initial factor classification, which is based on an input-output perspective. The CLEWS framework (Bazilian et al., 2013) simply classifies the input and output factors or index in a single system to achieve an interface WEF integration by building connections between WEAP, LEAP and AZE modules (Dale et al., 2015). The Nexus Tool 2.0 framework (Daher and Mohtar, 2015), captures factors in WEF production, consumption and transportation processes, and adds place-specific factors besides input and output factors from a holistic perspective. Input-output classification enables WEF integration and efficiency promotion, but it would still be difficult for nexus governance without factor interaction analysis and a level partition between factors. Conceptual framework, causal graphs and process modeling with directed graphs are three popular means to analyze factor interaction. Without specific factors, a conceptual framework is from a holistic perspective at a macro level to illustrate influencing directions and dynamics among subsystems (Hoff, 2011; Conway et al., 2015; Rasul and Sharma, 2016). Although all factors shown are entangled, causal graphs show the interconnection between specific factors within the system boundaries (Halbe et al., 2015), together with causal looping and linkage properties (e.g. positive or negative). Process modeling (Garcia and You, 2016) is effective in factor analysis from a singular perspective, not only presenting the co-evolvement among interdependent subsystems, but also identifying factors and nexus points in processes. Taking advantage of directed graphs with an element set and contextual relationships (Malone, 1975), ISM quantifies interconnections with a matrix through paired comparisons which would reduce 50% to 80% of the linkages to define system structures (Watson, 1978), and specific relationships and the overall structure of the intertwined elements are portrayed in a digraph model (Bañuls and Turoff, 2011).

To address these gaps in the research, we will explain interpretative structural modeling (ISM) and develop an ISM analysis framework taking the WEF-nexus as an example (Section 2). We then identify factors and their interconnections within an urban WEF-nexus system (Section 3). Our empirical analysis focuses on Beijing to examine the ISM analysis framework and urban WEF-nexus conceptual framework. Results and outcomes are presented in Section 4, followed by discussion (Section 5), conclusions and suggestions for future research (Section 6).

2. Interpretative structural modeling (ISM)

ISM is a qualitative analysis tool for studying and analyzing complex relationships between interdependent variables in order to transform entangled systems into visible, well-defined models, with graphical representations (Warfield, 1976; Sushil, 2012). It has been widely used in the areas of energy, construction, innovation and green buildings (Shen et al., 2016a; Wang and Zhang, 2009; Sandbhor and Botre, 2014). With an element set defined from the entangled system, ISM based on practical experience and expert knowledge examines every element pair to identify their directed relationships which would be recorded in an interaction matrix (Watson, 1978). Using the concepts of reachability and transitive inference, ISM modelers could map the hierarchy structure for an entangled system efficiently and effectively through matrix transformation and decomposition (Watson, 1978). Total interpretative structural modeling (TISM) is the recent promotion for tradition ISM with a direct relationship and a transitive relationship contributing to the knowledge base of the interpretive logic of all relationships (Sushil, 2012, 2016, 2017). Therefore, six steps are developed