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Water-energy-food nexus: concepts, questions and methodologies

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Abstract

The water-energy-food nexus has gained increasing attention in the research communities as the security of water, energy and food becomes a very high concern due to future uncertainties. Studies pertaining to calculations of flows and dependencies between different resources, assessments of technology and policy applications, and quantifications of system performance have been conducted to understand their interlinkages and develop management options. This paper provides a state-of-the-art review on the concepts, research questions and methodologies in the field of water-energy-food. First, two types of nexus definition are compared and discussed to understand the nature of nexus research issues. Then, nexus research questions are summarized into three themes: internal relationship analysis, external impact analysis, and nexus system evaluation. Eight nexus modelling approaches are discussed in terms of their advantages, disadvantages and applications, and guidance is provided on the selection of an appropriate modelling approach. Finally, future research challenges are identified, including system boundary, data uncertainty and modelling, underlying mechanism of nexus issues and system performance evaluation. This review helps bring research efforts together to address the challenging questions in the nexus research and develop sustainable and resilient water, energy and food systems.

Highlights:

1. Two definitions of nexus exist but they can be unified under integrated system assessment

2. Nexus research is classified into three questions: internal relationship, external analysis, system evaluation

3. Nexus modelling should consider research questions, system scales and data availability

4. Future research challenges are identified to develop sustainable and resilient nexus systems

Keywords: water-energy-food nexus; definitions; research questions; uncertainty; system evaluation

1 Introduction

The global demand for water, energy and food is driven by rapid population increase, urbanization, and climate change and it is estimated to increase by over 50% by 2050, compared with the 2015 level (Ferroukhi et al., 2015).This will pose a huge pressure on existing water, energy and food systems, which have already been constrained due to the competing needs for limited resources in many parts of the world. More importantly, water, energy and food are interlinked, for example, extreme droughts caused by climate changes can lead to significant food and energy security problems due to intensified water supply stress. Under such circumstances, the concept of water-energy-food nexus was conceived to study and manage the global resource systems (e.g., water, energy and food) comprehensively (Smajgl et al., 2015; Rasul, 2016; Yillia, 2016).

The concept of the 'nexus' has gained increasing attention in the research and policy making communities (Garcia and You, 2016; Weitz et al., 2017). Such systematic thinking is valuable, as ignorance of the interlinkages among these three sectors may result in unforeseeable, adverse consequences. Biofuel is one of the vivid examples. The rapid bioenergy development, which was initially advocated to mitigate climate change by shifting away from fossil fuels, has the potential to cause biodiversity loss (Meehan et al., 2010) and food crisis by land use changes, as biomass crops may compete with food for water and land. Similar cases can also be found in technology applications where the adoption of water-conserving irrigation and desalination technologies may create pressures in energy sector through intensive energy consumptions.

Significant efforts have been made to explore the water-energy-food nexus from various aspects, including calculation of resource flows and their dependencies, assessment of technology and policy applications, and quantification of system performance. What's more, several literature reviews have been published to illustrate the concepts of water-energy-food nexus (Biggs et al., 2015; de Grenade et al., 2016; Wichelns, 2017; Cai et al., 2018), simulation tools (Kaddoura and El Khatib, 2017; Dai et al., 2018), and nexus governance (Weitz et al., 2017) or implementation (Vakilifard et al., 2018). This helped to improve people's perceptions about the water-energy-food nexus. However, none of the reviews provides a critical analysis of nexus concepts, research questions, and their implications on the selection of modelling approaches (Chang et al., 2016). Hence, in this paper, we provide a critical review on the water-energy-food nexus from three aspects, including the nexus concepts, research questions and methodologies, and identify the directions and challenges for future research. This will help bring research efforts together to address the challenging questions in the nexus and develop the consensus on building sustainable and resilient water, food and energy systems.

2. Research methodology of literature review

With an aim to illustrate the concepts and applications of the water-energy-food nexus, a database consisted of published articles all over the world from the Web of Science and Google Scholar was established. Keywords such as "water-energy nexus" , "water-food nexus", "water-energy-food nexus", "climate change & food-energy-water nexus", "bioenergy & water", "water-energy nexus & modelling", were chosen as search terms. Special attention had also been paid on the policy related research to identify applications of nexus in natural resources management. To cover a wide range of relevant research, we supplemented papers pertaining to environment, resource recovery, water footprints, energy production, and food consumption patterns. After that, we exclude irrelevant papers by reading their abstracts and conclusions. The final sample consisted of 161 documents, ranging from 2002 to 2018.

To extract the main focuses in the field of water-energy-food nexus, the selected papers were read multiple times. Then the major findings of each paper were noted, together with their research scale, adopted methods, illustration of nexus concepts and limitations. After that, we held several group meetings to discuss the assessments of each article as well as the classification method of the selected papers to reach a consensus on the subsequent analysis. Finally, the selected papers were classified according to their definitions of nexus, research questions, scales and adopted methods. Challenges for future research were also identified by summarizing limitations of the selected papers. Those aspects will be presented in the following sections with more in-depth analysis.

3 Definitions of nexus

The popularity of the nexus could be dated back to the World Economic Forum in 2008, where the global challenges related to economic development were recognized from the water–energy–food nexus perspective. However, no consensus on the nexus definitions has been agreed upon (Smajgl et al., 2015; Keskinen et al., 2016; Endo et al., 2017), with varying interpretations in different sectors, in different contexts and by different researchers (Keskinen et al., 2016). In general, there are two categories of definitions as below.

In the first category, the nexus is interpreted as the interactions among different subsystems (or sectors) within the nexus system (Sanders and Webber, 2012). For example, the water-energy nexus can be presented as the interdependencies between energy and water, as they are coupled in their supply, processing, distribution and use (Liu et al., 2016). Likewise, when the system boundary is further extended to a water-energy-food system, the nexus can be defined as the interlink between water, energy and food (Gulati et al., 2013; Lawford et al., 2013). Thus, water is needed during the production processes of both energy and food. Energy is required for water abstraction, distribution and treatment. In contrast, food can also be used to generate energy in the form of biofuels. Recently, Cai et al. (2018) has further illuminated the interactions between water, energy and food from three respects, including the interconnected processes (e.g. physical and chemical), the input-output relations during resource production, as well as the interactions dominated by institutions, markets, and infrastructure. In a word, this category focuses on the representation of interactions between different sectors, aiming at grasping the overall characteristics of the complex system by its components' interlinkages. As the security issues of these three sectors become severe, the term emphasizes that failures in one sector may exert pressures on the other two sectors, requiring a holistic management among these sectors.

In the second category, which is more prevalent, the nexus is presented as an analysis approach to quantify the links between the nexus nodes (i.e., water, energy and food). There are many interpretations about this emerging approach. For example, the Food and Agriculture Organization of the United Nations highlighted that the functions of the nexus approach was to systematically analyze the coupled human-nature system, and to produce an integrated management of natural resources across different sectors and scales by building synergies and managing trade-offs (FAO, 2014). While C. A. Scott et al. (2014) held the view that the essence of nexus was to produce a resource recovery, with the byproduct of resource use efficiency improvements. Smajgl et al. (2015) deepened the understanding of this approach to a continuously evolving system, arguing that the interactions among nexus nodes ought to be dynamically addressed. Meanwhile, Keskinen et al. (2016) contended that the content of the nexus is so rich that it could not be interpreted from a single perspective. Therefore, they preferred to define it from three aspects, including an analytical method, governance tool and an emerging discipline, which complemented one another.

Despite the differences between two definitions above, we can conclude that the nexus is put forward to call for an integrated management of the three sectors by cross-sector coordination in order to reduce unexpected sectoral trade-offs and promote the sustainable development of each sector. In this regard, it differs from conventional decision-making practices that are previously considered within separate disciplines (Liu et al., 2015).

4 Research questions

The nexus encompasses a broad range of issues and therefore studies on this topic vary considerably in terms of their focuses. There are many ways to classify current nexus research questions. For example, as for the number of nodes, current studies could be divided into three categories, namely, two-node nexus research (e.g., energy-irrigation (Mukherji, 2007; Shah et al., 2007), energy-water (Marsh and Sharma, 2007; Hussey and Pittock, 2010; Gheewala et al., 2011; Lu and Thisse, 2011; Stillwell et al., 2011; Li et al., 2012), food-energy (Walsh et al., 2018), water-land (Chen et al., 2018)), three-node nexus studies (e.g., water-energy-food (Smidt et al., 2016), energy-food-water (Howarth and Monasterolo, 2016), water-energy-climate (Mu and Khan, 2009), land use-climate change-energy (Dale et al., 2011), environment-water-climate (Groenfeldt, 2010)), and four-node nexus studies (e.g., water-food-energy-climate (Waughray, 2011; Beck and Walker, 2013), climate-land-energy-water (Hermann et al., 2012)). If we focus on the framework arrangement of nodes within the nexus, the current research can be divided into two categories: with a center (Hoff, 2011; Ringler et al., 2013; Rasul, 2014) and no center (Bizikova et al., 2013; Benson et al., 2015). Their differences lie in how important each of nexus sectors is compared with others. In other words, frameworks with certain centers usually emphasize the role of the center in the entire nexus system, indicating that changes in the framework center dominate the state of other related sectors through their interlinkages directly.

Treating the coupled system as a circle comprised of several subsystems, we propose to classify the research questions into three categories: internal relationship analysis, external impact analysis, and evaluation of the coupled system. Such classification, which focuses more on the connections between different sectors as well as the descriptions of coupled system performance, is helpful to understand the nexus connotation and extension, as it distinguishes system response to external environment (e.g. climate change and policies) from the inner features of the coupled system. This also provides valuable insights for decision-makers in policy making and assessment.

4.1 Internal relationship analysis

The internal relationship analysis presents inner features of the coupled system by capturing the interactions between different sectors. To make a clear outline of the internal relationship analysis, the interactions between different sectors are distinguished as one-way impact analysis and interactive impact analysis, as shown in Table 1.

Table 1

The internal impact analysis.

	One-way impact analysis	**Interactive impact analysis**
Connections	♦ Unilateral relationship	♦ Mutual relationships ▪ Bilateral relationship ▪ Feedback loops
Advantages	♦ Lower requirements of resources (e.g. data, time, human, financing) ♦ Manifest how changes in one specific sector affect other sectors ♦ Facilitate preliminary assessments of trade-offs ♦ Serve as a starting point towards integrated managements	♦ Provide more comprehensive assessments of nexus systems ♦ Determine the control or dependence role among multiple sectors ♦ Identify the driving factors or processes ♦ Inspire new solutions for nexus issues from holistic perspectives
Disadvantages	♦ Manifest limited capacity in nexus analysis due to inability to reflect feedback and second-round effects	♦ Resource intensive in terms of time, data, human and financing
Characteristics	♦ Simple and targeted	♦ Complex and holistic

The one-way impact analysis, which manifests how changes in one specific sector may affect its associated sectors, has the potential to provide valuable preliminary insights for decision making even without a comprehensive description of the whole nexus system (Ferroukhi et al., 2015), as it accounts for the potential trade-offs between different sectors to some extent. Many studies employ this one-way impact analysis to investigate nexus impacts due to its analytical simplicity and lower requirements of research resources (e.g. data, time, financing, etc.). For example, Babel et al. (2011) found that land use change caused by biofuel production may have an adverse impact on water quality and quantity, noting that physical and environmental aspects ought to be taken into account in bioenergy policy making. Kondolf et al. (2014) investigated the impacts of rapid development of hydropower dams and found that an unprecedented boom of hydropower dams might result in a greater sediment starvation, leading to a profound effect on downstream productivity of the Mekong River (Winemiller, 2017).

Recently, this one-way impact analysis has been widely employed to analyze the impacts of applications of new technologies within a certain sector on others, as the development of new technologies provides new ways to address the scarcity of resources, with significant impacts on current interlinkages between nexus sectors. To capture the impact of shifts toward more energy-intensive water use, Sanders and Webber (2012) made a water-related energy consumption estimation within "energy for water" system boundaries, indicating that the direct water and steam services account for 12.6% of the 2010 annual primary energy consumption in the United States. Likewise, energy consumption in wastewater treatment plants can be reduced under innovative technologies of energy recovery (Stillwell et al., 2010), integrated real time control (Meng et al., 2017), and operational permitting (Meng et al., 2016). In contrast, Denooyer et al. (2016) demonstrated that the cooling technology shift from open-loop to closed-loop can reduce water withdraws but increase water consumption, noting that site-specific factors are critical to the choice of thermoelectric cooling technologies as increase in water consumption may cause unintended consequences downstream.

Although above one-way impact studies facilitate preliminary assessments of nexus impacts and trade-offs, they merely draw a partial picture of nexus systems and manifest limited capacity in nexus analysis owing to their inability to reflect feedback and second-round effects (Ferroukhi et al., 2015). Different from the simple unilateral impact analysis, the interactive impact analysis could describe the characteristics of the nexus more comprehensively. It can reveal the mutual interrelationship between different sectors through bilateral relationships and feedback loops, which helps to determine the control or dependence role among multiple sectors and identify the driving factors and processes in the development of the coupled system. For example, setting in the context of transboundary basins, Keskinen et al. (2016) qualitatively evaluated the bilateral relations between water, energy, and food in major basins of South Asia and Central Asia, noting that energy and food had greater impacts on water resources in Central Asia while the impact of water supply changes on food was more pronounced in South Asia. The results of Siddiqi and Anadon (2011) showed that the dependence of energy sector on water resources was weak, whereas the dependence of water abstraction, desalination, and treatment processes on energy was strong in Middle

East and North Africa.

Besides, numerous studies attempt to present the interactive impacts between different sectors by depicting their feedback loops through interactions, as changes in the feedback strength and rearrangement of couplings may characterize the dynamics of the system (Kumar, 2015). For instance, wastewater reuse for agricultural production inspired new solutions to advancing the food-energy-water nexus in arid-regions by reducing energy consumptions required for fertilizer and increasing agricultural yields in arid-regions with poor soils, as well as improving water quality by nutrient retention in agriculture irrigation (Mortensen et al., 2016). While Zaman et al. (2012) found that application of tractor in agricultural production led to more energy demand in Pakistan which in turn stimulated the increase of its irrigated agricultural land and share of agriculture value in economy from 1975 to 2010.

4.2 External impact analysis

The water-energy-food nexus system is usually set in a certain circumstance. Any external environment changes can complicate the performance of nexus systems by shaping the production and use of water, energy and food through interconnected processes. The categorization structure employed by Butler et al.(2017) for external threats in water systems is extended to water-energy-food nexus systems. Here, external threats refer to the impacts of outside force, entity, or actor (climate change, pollution incidents, population growth, politics, etc.). The underlying motivation of partitioning of external and internal factors (or threats) is to identify key factors that drive nexus system dynamics. It is also helpful to define system boundary and clarify research issues at the initial or modelling stage. What's more, partitioning of the driving factors enables us to conduct a more targeted analysis and provide valuable insights for prioritization of interventions (Butler et al., 2017), although the categorization is subjective to some extent.

The external impact factors can be classified into four categories based on their sources and occurrence time, as shown in Fig. 1. According to their sources, external factors can be classified into two groups, including physical and social causes. Physical factors such as climate change, extreme weather and natural hazards may change the provision of water, energy and food by influencing their supply chains and production processes. Extreme weather such as droughts and floods might have significant negative impacts on agricultural productivity (Challinor et al., 2010; Bandara and Cai, 2014) and energy generation (Famiglietti, 2014) through water availability. It has been proved that both a hotter climate (with more consumptive water use) and a wetter climate (with increasing irrigation areas) could increase the water and energy use for crops in river basins where agricultural production relies on canal water and groundwater pumping for irrigation (Yang et al., 2016). Beyond that, higher potential evaporation caused by climate change may even increase tradeoffs between hydropower generation and irrigation water use due to decreased water availability (Zeng et al., 2017). While social factors such as user behavior and perception may move the focus of resources management from supply side to demand side. For instance, human dietary habits can change energy use and water footprint throughout the food supply chain. Shifts from current food consumption patterns in US to a food mix diet could increase energy use by 38%, and blue-water footprint by 10% (Tom et al., 2016). In addition, policies and technology may impact the nexus systems through interactions between different resources. It has been demonstrated that agricultural policies in China aiming to improve food security and self-sufficiency may lead to a remarkable decline in local groundwater resources (Ghose, 2014). What's worse, agricultural water conservation subsidies and applications of more efficient irrigation technologies may actually aggravate water depletions by reducing valuable return flows and limiting aquifer recharge (Ward and Pulido-Velazquez, 2008).

The external factors can also be divided based on their occurrence time. The occurrence of extreme weather as well as natural hazards may change nexus systems in a relatively short time. It has been demonstrated that the hydropower production in the Iberia was reduced by 40 % due to the 2004/05 drought (García-Herrera et al., 2007). To survive the drought, the countries in Iberian Peninsula switched to massive imports of fossil fuel to produce less water-intensive power (García-Herrera et al., 2007), achieving the decoupling between water and energy sector. Such situation is also suited to policy changes which may affect human behaviors rapidly. A recent study conducted by Housh et al. (2015) demonstrated that implementing the mandate for cellulosic biofuel production (e.g. Miscanthus) on the Mississippi River Basin had the potential to reduce the nitrate-N loads but introduce stress on streamflow and associated ecosystem services by increasing the water consumption through Miscanthus cultivation. However, the period to recognize the impacts of population growth (Mu and Khan, 2009), climate change (Waughray, 2011; Beck and Walker, 2013) and land use (Al-Bakri et al., 2013) on nexus systems is much longer. Comparing the conditions in the year of 2000 to those in 2030 and 2050 respectively, Mu and Khan (2009) indicated that an increasing grain demand caused by population growth may require further intensification of land and water use, and climate change might cause declines of availability in both surface water and groundwater resources. While Berardy and Chester (2017) found that the temperature increase due to climate change over multiple decades is expected to result in more water and energy consumption through increasing irrigation requirements in Arizona where agriculture has a high dependency on energy-intensive water supply.

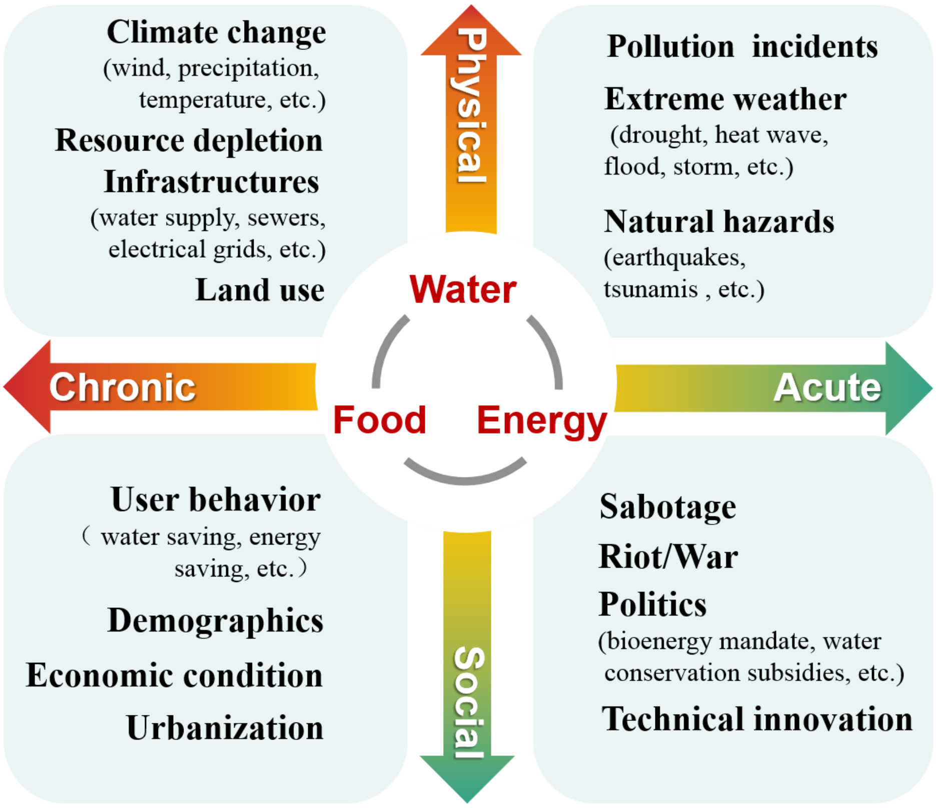

Fig. 1. The classification of external factors.

Besides the above concerns, the term of nexus is also directed to manage the complex nexus system efficiently and sustainably (Anik Bhaduri and Scheumann, 2015). Some researchers have attempted to evaluate the effectiveness of policies from diverse interest groups through a nexus prospective. Establishing an energy-water-land nexus system, Howells et al. (2013) estimated that the benefits of a local biofuel development related policy, which was proposed to guarantee the energy security indoor and to reduce GHG emissions, were precarious due to climate change in Mauritius. Investigating two possible joint operation modes of Rogun Dam and Nurek Dam, Jalilov et al. (2016) suggested that neither the Energy Mode nor the Irrigation Mode could lead to optimal benefits for all the riparian countries from the water-energy-food nexus perspective.

4.3 Evaluation of the coupled system

Except for internal and external impact analyses, assessment of the whole system performance, such as resilience (Hosseini et al., 2016) and sustainability (Nguyen et al., 2014), is another nascent field of current research.

Resilience refers to the ability of a system maintain and recover its essential functions during and after an external shock or disturbance (Hosseini et al., 2016). Evaluation of resilience of the nexus system is important for comprehensive management of complex system and rational exploitation and utilization of resources, as irreversible changes may occur once the external disturbance beyond a certain range. Attempts have been made to evaluate the system performance under changing environment from resilience perspective. For instance, Suweis et al. (2015) found that the resilience of a coupled population-food system was losing due to the increasing dependency of food security on global trade. The negative impacts of policy changes on system resilience have also been identified. It was demonstrated that water conservation (e.g. improvements in irrigation efficiency) subsidies could result in an increasing water use through irrigation expansion. What's worse, such policy change may even aggravate water scarcity, deteriorate water quality, and impair river basin resilience through loss of flexibility and redundancy (C. A. Scott et al., 2014). Beyond that, the term of resilience is also useful to validate the coping strategies in response to climate disruption within nexus systems. The study conducted by Scanlon et al. (2013) suggested that applications of natural gas in power generation were feasible to cope with water-energy nexus issues along with droughts as they consumed less water in electricity generation compared to traditional coal or nuclear power plants, which contributed to the resilience enhancement of power plant during droughts.

Besides resilience, system sustainability, which represents system's ability to continue its functionality with limited resources indefinitely, is also important for coupled systems, as ignorance of it may result in shortsighted policies which may work initially but fail in the long run. Establishing a biofuel production system consisting of three subsystems (e.g. water supply, biomass production and biofuel), Nguyen et al. (2014) demonstrated that raising the dependencies of water supply on biomass production may decrease the system sustainability, implying that the quality of the coupled system may degrade as time went on. However, due to the vague definition of system sustainability, quantifications of this performance measure are still limited.

5 Modelling approaches

There are various methodologies for the nexus research, however, research priorities, aims, scales and data availability are found critical to decide which approach should be used for the water-energy-food nexus research. Moreover, no single approach is applicable for all situations (Endo et al., 2015; Liu et al., 2017).

As illustrated in Fig. 2, the appropriate methods vary in response to the scale and research priorities of a specific nexus system. Specifically, a higher degree of data aggregation is likely to be required as the system scale moves up. Conversely, more detail of the inner mechanism of the nexus system, both social and physical should be represented, as the system scales down. Accordingly, models, such as the computable general equilibrium model, econometric analysis, and ecological network analysis, play important roles in large scale nexus research as their consideration of man-made links (e.g. global supply chains of food and energy (Lawford et al., 2013)) creates opportunities to investigate the socioeconomic interactions between remote places (Silviu, 2015). However, the investigation and mathematical methods can be applied to illustrate nexus issues at almost all scales due to their strength in overcoming data absence and providing valuable insights during an initial stage. While the agent-based model is much more suitable for revealing the individuals' decision impacts for their consideration of individuals' heterogeneities and life-cycle analysis exert its advantages in assessments of policy and technology shift pertaining to resources consumption and environment. Besides, the integrated index is powerful to include various social and environmental factors in policy planning.

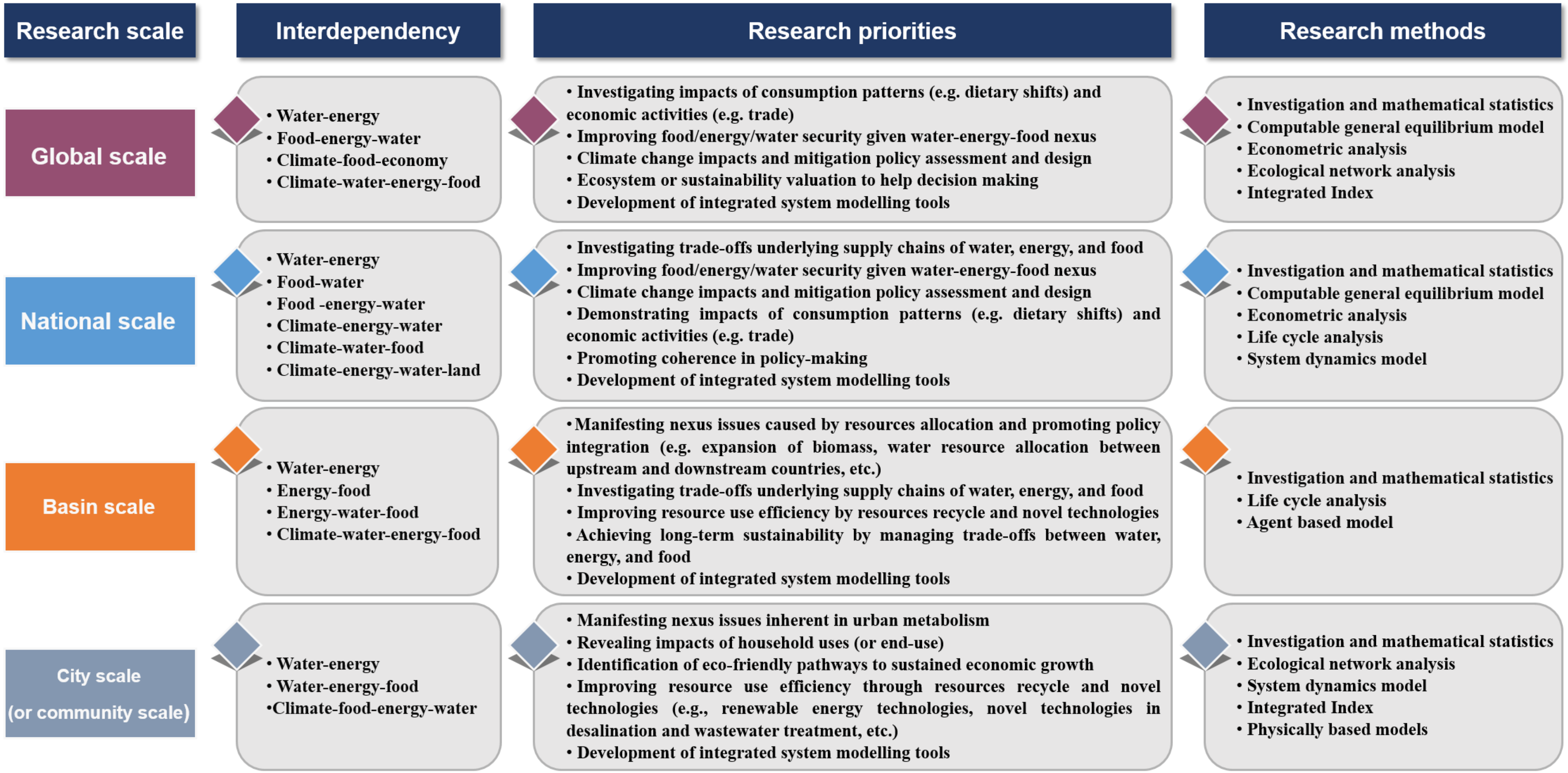

Fig. 2. Summary of nexus research methods and their applications.

Based on the state-of-the-art research methods, the eight key approaches, i.e., investigation and statistical methods, computable general equilibrium model, econometric analysis, ecological network analysis, life cycle analysis, system dynamics model, agent based modelling and integrated index, are discussed briefly in terms of their advantages, disadvantages and applications, with an aim to identify research gaps in current nexus methods.

5.1 Investigations and mathematical statistics

Investigations and mathematical statistics, which illustrate nexus issues through field surveys, expert panel, and collections of public data released by local agencies and governments, and related literatures, are the most widely used methods to explore the interactions between nexus sectors . Tracing related resources consumptions associated with the production process of a certain resources, researchers could make quantitative assessments about the interactions between water, energy, food and other resources through data analysis. Adopting such method, Machell et al. (2014) identified that electric power generation accounted for approximately 15% of total global freshwater water withdrawals and about 70% of global water was consumed by food production. While Ramırez et al. (2006) revealed that strong hygiene regulations may account for one or two-third of the total increase of energy consumption in the meat industry of four European countries as the temperature of water used for cleaning and sterilization increased from 60 °C in 1990 to 82 °C in 2001 for the sake of food safety. Through field surveys, Alimagham et al. (2017) found that conventional scenarios of soybean production are more environment-friendly in comparison with mechanized scenarios because of their lower energy consumption and GHG emissions.

Such methods are also useful to capture pivotal factors (e.g. climate change, land use changes, demographics, basin infrastructure) which dominate the evolution processes of the water-energy-food nexus system. Aggregating the questionnaire responses across all respondents, Lawford et al. (2013) obtained the ranking of the importance of different factors that may influence the Water-Energy-Food Nexus, and provided some recommendations to improve the sustainability of each individual sector based on the ranking. Likewise, Smajgl et al. (2015) succeeded in formulating the dynamic framework of water-energy-food nexus in Mekong basin by identification of interlinked variables between different sectors through the Delphi technique which relied on investigations of a panel of experts.

The studies above demonstrate the fact that there exist complex interlinkages between nexus sectors, and qualitative analyses (e.g., Lawford et al. (2013), Smajgl et al. (2015)) can bring some valuable insights into decision making. Moreover, key variables, which can be potentially estimated for a broad range of impact categories at various scales (global, national and local scales), pave the way for an integrated nexus modelling and assessment (Liu et al., 2016). Yet, statistical approaches cannot provide insights into the internal mechanism of interactions between water, energy and food, resulting in great difficulties in policy making and evaluating.

5.2 **Computable general equilibrium model**

The computable general equilibrium model (CGE) is a kind of economic model, which is widely applied to policy analyses pertaining to economy (Silviu, 2015). The CGE models can evaluate the impacts of policies on the nexus systems through price mechanism by grasping the interlinkages relevant to market behavior and changes (Ge et al., 2014). Considerable progresses have been made in nexus quantifications with various CGE models, including GTAP-W model (Calzadilla et al., 2011), GEM-E3 model (Kancs and Wohlgemuth, 2008; Németh et al., 2011) and IMPACT model (Rosegrant et al., 2002). Using the GTAP-W model, Calzadilla et al. (2011) demonstrated that the effects of trade liberalization on agricultural production and water use are modest. While Wianwiwat and Asafu-Adjaye (2013) identified that promoting bio-liquid policies would increase the price of manufactured food and decrease the food manufacturing in the short term, but their effects would be smaller in the long run, indicating that the adverse impacts of such policies on food security were limited in the long term. Similar research is also conducted by Ge et al. (2014), which shows that even though the expansion of non-grain fuel ethanol raises the food prices by intensifying the competition of land, capital and labor between food and fuel ethanol production, a supply of marginal land to non-grain fuel ethanol can still enhance the food security in China by reducing food imports, providing valuable insights to manage the trade-off between biofuel energy production and food security.

Although the CGE model could provide a comprehensive interpretation about the macro-economy and its interaction with the natural resource system, challenges in the above methods still exist. With a large number of parameters involved, the validity of the model results highly depends on the quality of the data which are used in model calibration. Moreover, the hypothesis about the economy within the model is somewhat identical or simple that it may not in accordance with the realities, leading to a large deviation of the policy evaluation.

5.3 Econometric analysis

Econometric analysis employs statistical methods to provide empirical content to economic relations by analyzing non-experimental economic data (Wooldridge, 2012). The method of multiple regression analysis lays the foundation for econometric analysis. However, econometric analysis is different from general statistical methods introduced in Section 5.1, as it manifests nexus systems through a set of mathematical equations and elucidates nexus issues based on economic theories.

Econometric techniques and procedures have been widely used to infer causality (Huang et al., 2008) and test economic theories (Pao and Tsai, 2011; Allard et al., 2018) in the field of nexus research. For example, the regression results of Zaman et al. (2012) empirically revealed the bi-directional causality between agricultural growth and energy consumption in Pakistan, demonstrating that actions pertaining to promoting energy efficiency and diversifying energy sources will indeed contribute to sustained economic growth in Pakistan where agriculture plays a dominant role in economy. Pao and Tsai (2011) confirmed the Environmental Kuznets Curve hypothesis for the four BRIC countries, noting that the relationship between CO_2 emissions and gross domestic product fits an inverted-U curve.

Beyond the above research, numerous attempts have also been made to examine the validity of existing policies. A recent research, which investigated the impacts of biofuel production on the ecosystem in six regions of the world through panel econometric techniques, confirmed the conclusion that expansion of biofuels was not a good choice to cope with climate change given its negative impacts on biodiversity and water resource at the global scale (Zaman et al., 2016). Similar methods have been utilized to provide recommendations for future policy design. Ozturk (2015) manifested the food-energy-water nexus for the BRICS countries by simultaneously modelling each individual sector that was linked separately to multiple regressors, noting that food security may be challenging for the five countries as the demand and supply gaps of energy and water widened. This indicates that economic-environmental policies are imperative to stimulate sustainable development for the BRICS countries in the long-run, as increasing energy demand for economic growth may lead to environment degradation among the five countries (Ozturk, 2015).

Econometric analysis is more targeted and efficient in policy assessment and design than general statistical methods. However, analogous to CGE models, econometric models heavily rely on data (Semertzidis, 2015), and some underlying assumptions may not be justified (Hamiche et al., 2016). What's worse, misleading conclusions may be drawn due to ignorance of key variables in econometric models and application of small data samples (Pao and Tsai, 2011). To get more reliable results, it is suggested to use large sample sizes, panel data approach (Huang et al., 2008), and multivariate models to conduct econometric analysis (Zachariadis, 2007; Ozturk, 2010). In addition, unrecorded economy should be considered to get closer to real economy when making assumptions in econometric modelling (Ozturk, 2010).

5.4 Ecological network analysis

Ecological network analysis (ENA) evolved from input-output analysis (Chen and Chen, 2015) is currently one of the main methods for evaluating the interactions between economic and natural components. Taking systems as the integration of multiple entities connected by metabolic flows, ENA can offer a unified analysis for both direct and indirect flows embodied in interwoven chains of production and consumption, indicating the potential to investigate the trade-off between multiple elements (Chen and Chen, 2016). It has been used to dissect metabolic flows (e.g. water, energy, carbon emissions) in urban metabolism (Chen and Chen, 2016; Chen and Chen, 2017a) and global trade of energy (Duan and Chen, 2017) and virtual water (Yang et al., 2012). Combined with other metrics such as linkage analysis (Lenzen, 2003; Fang and Chen, 2017), Finn's cycling index (Finn, 1976) and system robustness (Fath, 2015), ENA is capable to detect the role transition of a sector and quantify the system performance (cycling and resilience). For example, using Beijing as an example, Chen and Chen (2016) identified that most urban sectors rely on manufacturing in the energy–water nexus, and the impact of nexus on energy networks (±200%) is larger than water networks (±30%). Furthermore, the average robustness of the energy-water nexus network seemed to be lower compared to natural ecosystems, as it had more intensive material exchanges (Chen and Chen, 2016).

In addition, compartment-oriented ENA metrics such as control allocation and dependence allocation can identify the control or dependence role among multiple sectors (or components) by tracking the metabolic (or material) flows (Chen and Chen, 2015). This analysis is critical for locating the driving factors of changing nexus systems and inspiring new solutions for resources management from both systemic and sectoral levels (Chen and Chen, 2016). For instance, with the aid of control allocation and dependence allocation, Chen and Chen (2017b) revealed that high-pollution industries which were moved outside the urban boundary of Beijing, were expected to have impacts on the local carbon emissions for the constant demand of urban citizens, indicating that carbon-cutting policies might not be effective unless a full optimization of supply chains was given. Duan and Chen (2017) applied a similar approach to investigate the mutual interactions between water and energy inherent in global energy trade and took China as an example to demonstrate the usefulness of such analysis in policy design. Their results showed that although no country was controlled by China via energy trade, the international trade of energy made China’s water security more vulnerable to other countries due to strong water import dependence associated with energy products. This informed the policy makers that strategies pertaining to reduce the proportion of water-intensive products in energy import mix are more beneficial.

Despite the strength of ENA in analysis of complex interactions, ENA is essentially a static method due to its steady-state assumption that the inputs must equal the outputs for each component and the whole network. Hence, the dynamic characteristics of the network system cannot be captured unless a longitudinal study is conducted (Yang et al., 2012). In addition, the implication of ENA in urban planning is still limited due to its sectoral level analysis and the lack of indicators directly related to land-use based urban planning (Chen and Chen, 2015), although ENA can be related to environmentally friendly planning for its consumption-based insights (Chen et al., 2014).

5.5 Life-cycle analysis

Life-cycle analysis (LCA) is one of the most widely used methods for quantifying the environmental impacts of a given product or process throughout its entire life cycle. It can accurately show the quantification of any unit during its life cycle and easily export its calculation processes, with the characteristics of identifying all of the inputs or outputs that may have significant impacts on environment (Nair et al., 2014). Due to above advantages, LCA approach, which could provide a consistent analytical framework and environmental data support for decision-making, has been extensively applied in assessing the environmental impact of nexus sectors across their production and consumption processes, aiming to seek effective ways to cope with current resources shortage and global climate change.

Using the integrated life cycle assessment (LCA) method, Al-Ansari et al. (2015)

made an integrated environmental evaluation of energy, water and food supply chains, and indicated that food system had the most significant impact on global warming. While Feng et al. (2014) proved that wind power production, compared to other electricity generation technologies, would significantly reduce the carbon emissions and water consumption over its whole life cycle. In addition, LCA has also been frequently applied for evaluating the impacts of construction and operation of urban water supply facilities on environment (Lundie et al., 2004; Friedrich et al., 2007; Foley et al., 2010). Foley et al. (2010), for instance, demonstrated that operational energy and greenhouse gas emissions presented a positive relationship with nitrogen removal and a non-significant correlativity with phosphorus removal in wastewater treatment plants. Such method is also useful for policy-making by comparing the impacts resulting from different options. For example, results of Chang et al. (2015) implied that a coal-to-shale gas shift in power generation was a promising way to a lower water intensive electricity in China, as the water consumption of shale gas-fired electricity was less than that of China's present coal-fired electricity given the extraction-to-wire effects.

However, the LCA method still has some drawbacks despite its extensive applications in nexus research. With a high dependency on data, the LCA method is difficult to apply in data-scarce regions (Hamiche et al., 2016). Moreover, due to the subjective decision of the definition about the system boundaries, it is therefore inevitable to leave out some production processes, which often leads to significant truncation errors in the calculations of LCA. Further, the LCA seems to be a static method and may not be directly suitable for dynamic analyses of complex systems (Nair et al., 2014). To some extent, it is difficult to consider social factors within a coupled system based on LCA method with a focus on assessments of environmental impacts (Balkema et al., 2002).

5.6 System dynamics model

System dynamics modelling (SDM), a top-down modelling method based on causal mechanism, follows the assumption that system behaviors are determined by their structures. It allows comprehensive analysis of multi-sectoral systems at both macro and micro levels by establishing causal feedback loops among the elements within a certain system. This makes it well suited for multidisciplinary and multi-actor problems (Stave, 2003). For example, Chhipi-Shrestha et al. (2017) had adopted such method to identify critical factors that constrained the sustainability of the urban water system in Penticton, noting that it was the hot water use that contributed the most to energy use and carbon emissions of the operational phase of the urban water system. Such approach has also been extensively applied in policy evaluation. Establishing main causal-loop diagrams of the climate-energy-water nexus, Newell et al. (2011) found that technology innovation, increase of redundancy in distribution and transmission networks and a dynamic system thinking in policy-making were helpful to improve the resilience of the national electricity market in Australia. While K. El-Gafy (2014) demonstrated that raising the self- sufficiency from wheat in Egypt through wheat trade pattern policies were expected to increase its wheat cultivated area as well as water footprint of wheat production for the interval 2010-2050, compared with the base line scenario in 2010.

Such models contribute a lot to overcoming difficulties that may otherwise impede the development of holistic policies (Newell et al., 2005). The causal feedback loops developed by system dynamics model could assist in the identification of the sources of problem behaviors and the understanding of the feedback structure of the system. Based on the dynamic analysis under different scenarios, the system dynamics model could offer optimal system structures to coordinate the various factors within the system and provide scientific basis for decision-making. However, due to the subjective abstraction and simplification of the nexus system during modelling process, it is necessary to involve relevant stakeholders in the SDM modelling process as much as possible to avoid the inconsistences between reality and the model caused by subjective factors.

5.7 Agent based modelling

Agent based modelling (ABM) is a “bottom-up” approach where every agent is a discrete autonomous entity with distinct goals and actions within a particular social context. By modelling agents individually, the full effects of the diversity that exists among agents in their attributes and the behaviors can be observed at the bottom level (Macal and North, 2010). What’s more, the emergent phenomena at the system level can also be investigated through aggregation of all agents’ behaviors (Du et al., 2017). Thus, agent based modelling breaks through the limitations of single-level and individual-perspective, and provides a more realistic and effective modelling framework for describing and investigating complex systems by offering a way to model social systems that are composed of numerous agents which can interact with and influence each other, learn from their experiences, and adapt their behaviors so they are better suited to their environment.

Recently, Ng et al. (2011) established an agent-based hydrologic-agronomic model to explore the interlinkages between the farmers' planting decisions and their associated effects on stream nitrate load when carbon allowance trading, and markets for crops (including biofuel crop) are considered. Their results proved the usefulness of such models for coupled human-environment nexus within a watershed. Hereafter, Khan et al. (2017) investigated the impacts of agents' water resource management decisions on the water-food-energy-environment nexus system at watershed scale through a more generalized ABM framework by coupling the water system model with SWAT model, noting that the impact of agent preferences on crop production was more significant than that of hydropower generation. However, due to higher requirements of data, challenges of noneconomic behaviors' definitions and computational requirements, application of this method to nexus related issues is currently limited, but promising in further research.

5.8 Integrated Index

The integrated index method usually presents various social and environmental characteristics of systems by multiple indicators. With the aid of these indicators, researchers are able to capture the overall properties of nexus systems regardless their complexity (Endo et al., 2015). What's more, index based methods contribute a lot to comparative assessment and benchmarking (Yigitcanlar et al., 2015) by describing system performance in a uniform and standardized format. For example, Kourtit et al. (2017) derived a holistic picture of sustainability of 39 global cities based on their efficiency performance indicators, indicating that European cities gain higher sustainability efficiency scores in terms of their human environment. Beyond that, this method can also provide valuable information for policy planning by manifesting a comprehensive outline of nexus issues (Flörke et al., 2018; Schlör et al., 2018). Taking urban surface-water deficit as an indicator, Flörke et al. (2018) identified that climate change and population growth could intensify the competition of water between urban and agricultural sectors, noting that improvement in irrigation efficiency became an essential adaptation option to enhance urban water security.

As cities become the center of water-energy-food nexus discussion (Duić et al., 2014; Wang and Chen, 2016; Brandoni and Bošnjaković, 2017; Schlör et al., 2018), efficient managements of nexus systems call for consideration of multidimensional performance (sociology, ecology, economy, etc.). More integrated indicators should be introduced to measure the performance of nexus systems in a holistic way (Yigitcanlar et al., 2015; Schlör et al., 2018). The UN-Habitat City Prosperity Index (CPI) was therefore proposed to identify factors that make urban cities become more prosperous and the areas where policy intervention is needed from five aspects (productivity, infrastructure, quality of life, equity, and environmental sustainability) (UN-Habitat, 2013). After that, attempts have been made to combine CPI with regulations of urban nexus. Yigitcanlar et al. (2015) proposed a multi-scalar approach to assess the environmental sustainability of CPI in urban cities and applied it to the Gold Coast to demonstrate its usefulness. Schlör et al. (2018) established the Nexus City Index (NXI) based on CPI and employed it to quantify the resilience of the food-energy-water nexus in urban cites. Their results suggested that NXI put city resilience on a comparable scale without reducing the complexity of nexus systems and offered opportunities to cope with prosperity gaps in urban planning (Schlör et al., 2018). Despite the above advantages, the application of such indicators in urban planning is still challenging, as it highly depends on systematic database (Schlör et al., 2018). In addition, major difficulties also lie in how to build a rational index system and eliminate the bias resulting from the use of weights among indicators (Yigitcanlar et al., 2015).

6 Directions of future research and prospects

The existing studies offer a promising outlook for water-energy-food nexus from different aspects, which can support in assessing trade-offs, predicting potential (unintended) effects, providing a co-optimization base for different stakeholders who often have conflicting interests and visualizing the impacts for informed decision making (Agboola and Braimoh, 2009; Hurford and Harou, 2014; Santhosh et al., 2014; Liu et al., 2015). However, limitations of current studies still exist. Grouping the above analysis together, future directions of nexus research are identified from four aspects, including the system boundary, data uncertainty and modelling, nexus mechanism and system evaluation, as shown in Fig. 3.

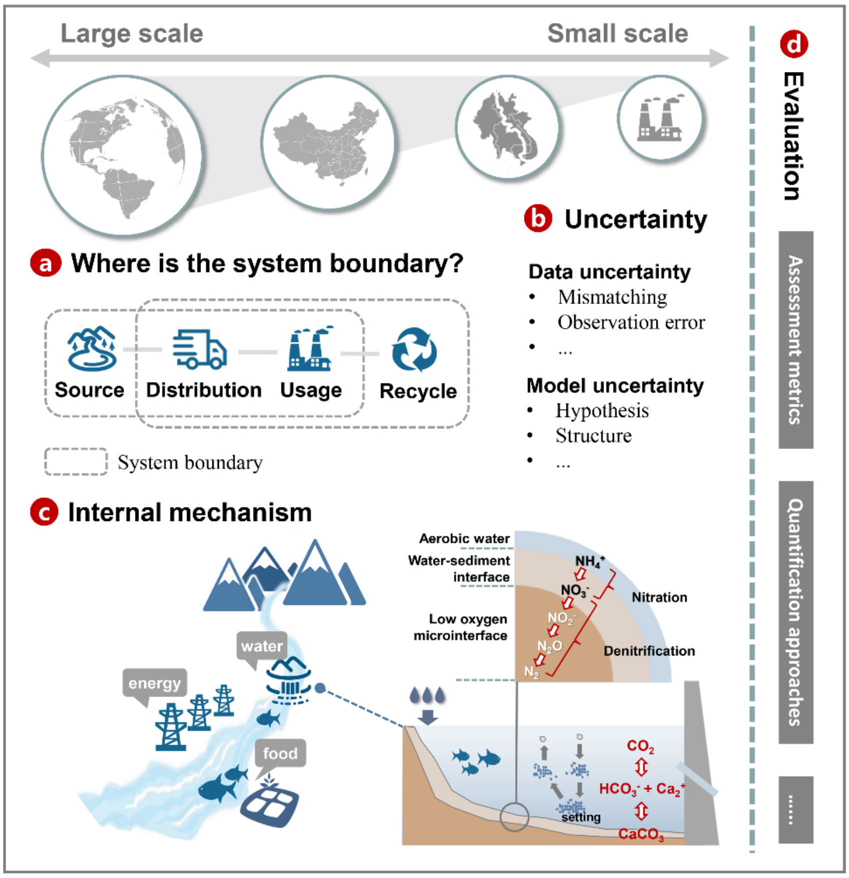

Fig. 3. Summary of future nexus research directions. (a) Definitions of the system boundary; (b) Date uncertainty and modeling; (c) The underlying mechanism referring to the physical, chemical processes associated with resource flows as well as their supply chains. For example, setting the nexus issue within a water-hydropower-agriculture system, the internal mechanism refers to flow states (e.g. velocity, temperature), sediment transport, growth of algae and biochemical reactions (e.g. nitration and denitrification via the water-sediment interface) along with hydropower generation and food production, as well as decision making mechanisms; (d) The evaluation of coupled nexus system, including assessment metrics and quantitative assessment approaches.

6.1 System boundary

It is of great importance to define the system boundary when conducting nexus analysis, as different system boundary definitions result in different results. For example, Liu et al. (2016) concluded that energy embedded in agricultural, municipal and industrial water use (e.g. irrigation, wastewater collection) accounted for 1.0%−1.9% of total primary energy in the United States in 2010, however, considering a wider range of processes where energy is applied to water for other outputs (e.g. steam-driven power generation), the proportion increased to 47% (Sanders and Webber, 2012).

The difficulty of system boundary definition lies in how to choose an appropriate boundary. On one hand, a narrow boundary might leave out some important interlinkages, which means that the description of the nexus system is under-representation. For example, merely focusing on conflicts between hydropower generation and irrigation issues with an ignorance of the interactions between water and inland fisheries in food security may lead to a partial evaluation of water-energy-food security nexus in riparian countries (Cooke et al., 2016). On the other hand, with a large system boundary, more processes are included in the nexus system and thus more data, assumptions and detailed understanding of the processes are required to develop a nexus model (Garcia and You, 2016). For example, for a global water-energy nexus, a large number of end-use processes (e.g., dish cleaning) need to be accounted for, increasing the difficulty of modelling due to varied users (Yillia, 2016) and end-use processes representation (Kyle et al., 2016). Moreover, it is much more difficult to extract and synthesize valuable information from different sectors considering their interactions, as the nexus boundary varies from resource management units to administrative boundaries (Liu et al., 2017). An appropriate selection of system boundary is critical for the nexus and thus required for further research.

Currently, it has been widely accepted that the definition of system boundaries should base on research aims (Avellán et al., 2017; Chen and Chen, 2017a; Albrecht et al., 2018) and data availability (Chen and Chen, 2017a). It is of great importance to note that water-energy-food nexus can go beyond its system boundaries (Avellán et al., 2017; Chen and Chen, 2017a). Taking the urban nexus research in Beijing as an example, Chen and Chen (2017a) suggested that upstream activities (e.g., indirect energy or water use outside Beijing) beyond the system boundaries ought to be considered due to their significant impacts on urban metabolism. In this regard, introducing the Driver-Pressure-State-Impact-Response (DPSIR) framework designed for adaptive management of Social-Ecological Systems (Gari et al., 2015) into modelling might be an effective way to demarcate system boundaries, as the scale of the two DPSIR elements (State Change and Impact) within the system of concern can provide valuable information for the establishment of system boundaries (Atkins et al., 2011). This has been demonstrated by Atkins et al. (2011) which showed that DPSIR was capable to quantify the environmental state changes as well as their impacts on societal benefits resulting from the pressures.

6.2 Data and modelling uncertainty

The themes of the research vary as the research scale changes, as shown in Fig. 2.

In the literature, global scale research focuses more on the impacts of climate changes on agriculture and water availability, as well as the changes in virtual water/ water footprints caused by the global trade (Yang et al., 2012; Duan and Chen, 2017). At the national scale, more attention is paid to resource security relevant issues as well as their associated environment impacts under various policies. While studies pertaining to quantification of the interactions between water, energy and food at household scale are more concerned about behavioral and technological factors (Abdallah and Rosenberg, 2014). Different research problems have different data requirements. The larger the system scale is, the more concerns about social and economic data. However, the data from government reports and published data are of varying quality and availability (Perrone et al., 2011), as they are released by different sectors for various purposes without consistent reporting standards (Ernst and Preston, 2017). The use of these data may cause great uncertainty in the nexus research. Moreover, some data are aggregated at large scale (Perrone et al., 2011), making it unsuitable for small scale research. This is the case in climate-related nexus studies (Waughray, 2011; Beck and Walker, 2013; Berardy and Chester, 2017), where application of climate models and their downscaling (Howells et al., 2013) introduces uncertainty to the final results.

What's more, assumptions and simplifications are frequently introduced in nexus research to deal with data scarcity. For example, Liu et al. (2016) had to assign constant energy intensity values to water-related processes except desalination in temporal variability analysis of water-related energy consumption due to lack of data on those processes. Owing to the lack of empirical data, two extremes of behavior (e.g. cautious and bold) are defined by Ng et al. (2011) to represent the farmers' behaviors in their water-energy nexus system through an ABM framework, which means the simulate results may not adequately represent the reality. Likewise, Jalilov et al. (2016) had to exclude the groundwater use for irrigation and introduce many assumptions on cropped area and crop water use in an agronomic model when conducting the water-energy-food nexus research. Such assumptions or simplifications may help overcome some data scarcity, however, they can also exert an impact on the final results and even misrepresent the interactions among nexus sectors. In addition, models such as CGE, which consist of several sectors including economy, water, crop and energy, may have numerous sources of uncertainty, ranging from model inputs and structures to scenario assumptions.

To address above issues, endeavors should be made to improve data availability for nexus research. On one hand, special efforts should be made in data monitoring and collection, data processing as well as uncertainty analysis. Recently, implications of innovative sensor technologies (Abegaz et al., 2018) (including remote sensing (Scanlon et al., 2017)) have been demonstrated to have remarkable utility in providing new data sources. Besides, advanced data science techniques (e.g., machine learning, correlation analysis, cloud computing (McCabe et al., 2017), Geographic Information Systems (Cai et al., 2018), etc.) as well as high performance computers are expected to speed up data uptake and facilitate analysis of massive datasets. Combination of these techniques indicates a promising future for data uptake and analysis. On the other hand, there is an urgent need to advance data-sharing through development of new data sharing mechanism which can stimulate broad participation and cooperation from different governments, research institutions and communities (Fekete et al., 2015). Connecting existing and new datasets can produce more accessible and useful data to prioritize problems, support nexus modelling and inform decisions (DOE, 2014). In addition, further research on the trade-offs between simplicity and comprehensiveness in the modelling process will provide new insights to develop appropriate models, generating robust results with limited data (Kaddoura and El Khatib, 2017). Beyond that, modelers should make the structure of nexus models more standardized and modularized, offering opportunities to analyze structural uncertainties better by exchange and recombination of model components (DOE, 2014).

6.3 The underlying mechanism of nexus

Future research needs to characterize the interlinkages between nexus sectors, with a focus on understanding of the underlying mechanism of the nexus. One of the most critical knowledge gap is that the majority of current studies focus more on the supply chains and resource use efficiencies of nexus sectors under different scenarios, for example, water use in food production (Siebert et al., 2010; Finley and Seiber, 2014), energy implications in water use (Kahrl and Roland-Holst, 2008). Yet, consideration of physical, biophysical and chemical processes is important for conceptualizing relationships of nexus sectors (de Grenade et al., 2016). Knowledge gaps also exist in interactions between ecological, economic, and social dimensions (Räsänen et al., 2015).

Dynamic quantification methods are required to capture the vital factors affecting the coupled nexus system performance and to reveal the dynamics of natural processes along with social processes that underpin the interactions between nexus sectors. For instance, few studies have been conducted to understand how the development of hydropower will affect soil erosion, sediment transport and nutrient composition (e.g. the nitration and denitrification via the water-sediment interface) within rivers. This is important to identify the systemic risk of runoff utilization, develop adaptive utilization strategies considering the nexus and evaluate the reasonable exploitation scope of hydropower.

Based on above, there is an urgent need to develop nexus-specific models to provide a better representation of nexus systems (Albrecht et al., 2018), as implications of existing models derived from other fields (e.g., LCA from management science and econometric analysis come from economics) may lead to a partial description of feedback and interactions of nexus systems due to these models' specific design purposes (Miralles-Wilhelm, 2016). As nexus elements being considered continue to expand (Dai et al., 2018), a nexus-specific model ought to be flexible enough to support module extensions (Chang et al., 2016), reveal physical and social dynamics, and facilitate analysis across multiple temporal and spatial scales (Albrecht et al., 2018). Given current data availability, such models are also required to have the ability to combine quantitative with qualitative data (Albrecht et al., 2018) to alleviate intensive and extensive data requirements during modelling. In addition, to establish an integrated and flexible model for water-energy-food nexus, multiple stakeholders and decision makers should be engaged into modelling processes to incorporate valuable and timely information from different sectors (e.g., technological descriptions, human activities) and avoid ignorance of vital processes or interactions owing to the site-specific nature of nexus (Keairns et al., 2016; Albrecht et al., 2018), which can be done through better interagency collaborations.

6.4 The evaluation of coupled nexus systems

One motivation of the nexus research is to better manage the water-energy-food system in order to promote sustainable development under changing environments. Assessments of the resilience and sustainability of the coupled systems are therefore important to understand their long-term performance under changing environments. However, in water-energy-food system, resilience and sustainability depend not only on the characteristics of the individual subsystems but also on the interlinkages among different subsystems (Hosseini et al., 2016), as changes in one subsystem may cascade quickly and widely through the couple system, triggering a series of chain reactions. The assessment metrics and approaches designed for individual systems may be no longer applicable to the nexus system as a whole. In addition, due to the loose coupling of nexus sectors in most of current methods (Yillia, 2016), the feedback is usually considered exogenously, resulting in an inadequate representation of the nexus system. All these create great challenges for the evaluation of resilience and sustainability of coupled systems.

Thus, efforts are required to investigate the resilience as well as sustainability of the coupled system, including assessment metrics and quantitative assessment approaches for nexus systems. However, this might be challenging, as multiple dimensions (sociology, ecology, economy, etc.) ought to be included to assess nexus system performance owing to the wide connotation of nexus. Fortunately, emerging concepts like NXI (Schlör et al., 2018), CPI (UN-Habitat, 2013) and entropy theory (Tamvakis and Xenidis, 2013) are expected to rectify this situation, as they exemplify how to combine different aspects of the research system in a holistic way. What' s more, Tamvakis and Xenidis (2013) evidenced that the framework based on entropy theory was useful to quantify system properties due to their strength in capturing underlying interactions (including feedback (Mayer et al., 2014)) among system components (both living and non-living). This study also informed us that transforming system performance into entropy can facilitate a direct and explicit way for assessing the overall system behaviors (e.g., resilience (Tamvakis and Xenidis, 2013), sustainability (Mayer et al., 2014)) through aggregation of behaviors at the component level as a single metric. This can inspire researchers to use innovative ways in development of assessment metrics and methods for nexus systems.

7 Conclusions

This paper provides a critical review on the concepts, research questions and methodologies in the field of water-energy-food nexus. The key findings are summarized below:

1) Two definitions of nexus currently exist in literatures, but they can be unified under integrated system assessment. The first one defines nexus as the interlinkage between different resources, while the other one treats nexus as a novel approach to investigate nexus systems with various meanings in different contexts. The two definitions could be unified through integrated management of the nexus to reduce unexpected impacts and sectoral trade-offs and promote the sustainability and resilience of the entire nexus system.

2) Current research can be classified into three categories: internal relationship

analysis, external impact analysis, and evaluation of the coupled system. Such classification is helpful to catch the hotspots in nexus studies scattered in various disciplines, as it stimulates more focuses on the connections between different sectors as well as the coupled system performance. What's more, partitioning of internal and external factors enables us to clarify site-specific nexus issues, conduct a more targeted analysis, and provide valuable insights for prioritization of interventions.

3) Eight modelling approaches are discussed in terms of their advantages, disadvantages and applications, providing guidance on model selection in the nexus research. It is identified that the connotation of nexus is so rich that no single approach is applicable in all situations however the appropriate method should be selected considering research questions, research aims, scales and data availability of the nexus system changes. For example, the CGE Model is more appropriate to investigate macro-economy and environmental change at regional and global scales due to its consideration of man-made links. While ABM is much more suitable for revealing the individuals' decision impacts for its description of individuals' heterogeneities and decision-making processes.

4) Despite the progress in water-energy-food nexus, limitations of current studies still exist, and four challenges for future research are identified. Analysis indicates that current research does not adequately address problems inherent in system boundary definition as well as the uncertainties associated with data and modelling. What's more, the internal mechanism analysis of nexus issues is somewhat constrained due to partial description of nexus systems. Challenges also exist in the evaluation of system performance, where nexus-specific assessment metrics and quantitative approaches need to be developed.

Therefore, more efforts are required to advance holistic assessments of water-energy-food nexus. Current discussions suggest that implications of DPSIR framework in nexus modelling may be useful for clarifying system boundaries, while improvement in data availability through innovative technologies is promising to address uncertainties associated with data and modelling. Besides, there is an urgent need to develop nexus-specific models to elucidate the underlying mechanism inherent in water-energy-food nexus. Emerging concepts like NXI, CPI and entropy theory are expected to stimulate more holistic assessments of system performance. These efforts may also be helpful in providing concise information to support decision-making in reality. In this regard, this review helps bring research efforts together to address the challenging questions in the nexus research and develop resilient water, energy and food systems.

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