METHODOLOGIES AND PRINCIPLES FOR DEVELOPING NEXUS Definitions and Conceptualizations: LESSONS FROM FEW NEXUS STUDIES

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Highlights

- *Synthesize existing knowledge in defining and conceptualizing FEW Nexus*
- *Provide scientists and practitioners in the FEW domains the tools to define and conceptualize*
- *The study provides narrow-broad definitions, simple-complex conceptualization frameworks for the FEW Nexus*

Abstract. *Food-energy-water (FEW) resources are fundamental to society's functioning and understanding them is crucial for sustainable development and supporting life on earth. This paper presents a review of the current approaches being used in the development of FEW Nexus frameworks with an emphasis on the methods for defining and conceptualizing these frameworks by different types of stakeholders. This framework provides scientists, consultants, and practitioners in the FEW domains the tools, and knowledge, needed to successfully implement the Nexus. The paper also describes knowledge gaps in the FEW Nexus domains.*

The objectives of this paper are to (a) synthesize existing knowledge to support stakeholders in defining and conceptualizing their FEW Nexus, (b) provide a framework to clarify the definitions and conceptualizations of FEW Nexus for a project or an application being developed for a specific stakeholder application, (c) to apply the experience and principles of the FEW Nexus to other Nexus can be developed. Stakeholders in this study include the users of the Nexus, scientists, and range of practitioners including policy makers, private sector and practitioners in the field, and resource managers, among others. The following questions assisted in addressing the objectives: What are some existing definitions and conceptualizations in FEW Nexus? Which elements are currently included in the definitions and conceptualizations? How should FEW Nexus be defined and conceptualized for a project or application? How can existing definitions be adapted, or new ones created, for a project or study? What are the consequences of choosing a particular definition or conceptualization? Based on this experience, the steps needed for developing a FEW Nexus are reviewed and clarified. The study provides narrow and broad definitions and simple and complex conceptualization frameworks of FEW Nexus that stakeholders can use while being aware of the limitations and knowledge gaps.

Keywords. Food-Energy-Water (FEW) Nexus definitions, FEW Nexus conceptualizations, narrow and broad definitions simple and complex conceptualizations.

Introduction

Food-energy-water (FEW) resources are fundamental to society's functioning (Bizikova et al., 2013) as they are the basic elements for human survival, economic growth, and development, and these resources are becoming more exhaustible resources over time (Mitra et al., 2019). Therefore, understanding the FEW Nexus is crucial for sustainable development and supporting life on earth. They touch most, if not all, of the sustainable development goals (SDGs), specifically SDG 2 (food), SDG 6 (water), and SDG 7 (energy) and their interactions (Mitra et al., 2019). These can relate to about 40 water, energy, and food targets within the identified sectoral goals (Weitz, 2014). FEW resources are under significant stress due to current management practices and are experiencing high demands (Bizikova et al., 2013), which are further exacerbated by increasing pressure from increasing population, globalization, rapid economic growth, unsustainable urbanization, increased demand for land (Babaie et al., 2019), climate change, land use and lifestyle changes (Muhammed et al., 2021; Nedd et al., 2021), and more recently due to the COVID-19 pandemic (Ibn-Mohammed et al., 2021). It should be noted that FEW is also referred to as water-energy-food (WEF), energy-water-food (EWF) etc.

Despite global efforts to achieve energy, water, and food security, as of 2011, approximately one billion people are considered undernourished, nearly 0.9 billion do not have sufficient access to safe water, and no less than 1.5 billion people are living outside the modern energy network (Mannan et al., 2018). These numbers are changing (increasing) over time. Another study (Mitra et al., 2019) estimates that, as of 2016, 2.1 billion people lack access to safely managed drinking water, 1.06 billion people lack access to electricity, and about 815 million are undernourished. About 4 million deaths/year are found to be associated with air pollution (using some form of biomass for cooking and heating), contaminated water (through hospital wastewater, agricultural waste or inadequate wastewater treatment), and food deficiencies (such as insufficient food, malnutrition, or obesity) and cannot have a normal active life (Ahmad et al., 2021; Borchers-Arriagada et al., 2020; Chatkin et al., 2021; Keairns et al., 2016; Sarin et al., 2020). The shortfall in FEW resources can cause social and political insecurity, geopolitical conflict, irremediable environmental damage (Bizikova et al., 2013), and even death.

The FEW Nexus is complex and has key characteristics of a “wicked problem.” Most of these characteristics apply to other Nexus applications as well. It has multiple stakeholders and disciplines with various unique and potentially divergent values, views, understanding, and commitments (Mercure et al., 2019). Many aspects of the FEW Nexus are highly variable depending on the adaptations made to the context, geography, and scale at which it is applied (Bell et al., 2016). Therefore, the problems have pervasive uncertainty, often not solvable by traditional approaches because solutions can change the problem's nature (Mercure et al., 2019). For example, during the past 50 years, the cultivated area has increased by only 12%, however, the agricultural production has increased 2.5 to 3 times, through the rapid expansion of the use of irrigation and fertilizers. As a result of the expanded use of irrigation agriculture accounts for 70% of the water withdrawals worldwide, and at the same time has resulted in an accelerated decline in soil quality and biodiversity (Keairns et al., 2016; Lark et al., 2020; Tilman et al., 2001).

The interconnected nature, complexity, and mercurial nature of the FEW Nexus has been identified in a number of studies. Initially, a general framework was developed in 2011-12, then tools began to be developed in 2013-14, and, since 2015, FEW studies have focused on the applications of the FEW Nexus. The literature documenting these studies has increased rapidly during the last decades. Traditionally, FEW Nexus studies have focused on the elucidation of interlinkages between physical resources systems. However, it has been indicated in several studies that future work should incorporate environmental, economic, social, and political disciplines (Lawford et al., 2013; Webber, 2016). A number of studies have investigated dual-sector interactions, for example, food-water and energy-water, and, therefore, while they are not relevant, they are not sufficiently cross-sectoral (Smajgl et al., 2016). The cross-sectoral approaches help coordinate policies among different sectors and reduce unintentional tradeoffs (Albrecht et al., 2018). Similarly, studies employing interdisciplinary and hybrid approaches that integrate qualitative and quantitative methods from various fields can help address the social and physical aspects of water, food, and energy systems (Albrecht et al., 2018). Transdisciplinary approaches, i.e., working collaboratively across traditional lines and with various stakeholders such as industry and government entities, can help to address key challenges in complex FEW Nexus (Bergendahl et al., 2018) and help attain sustainable development goals. Several studies have also highlighted the need to develop decision support tools, modeling approaches, quantification of tradeoffs in the Nexus, improved communication among stakeholders, and implementation of Nexus (Daher et al., 2019; Namany et al., 2019; Shannak et al., 2018). The focus of this paper is to provide a review of the definitions, conceptualizations and frameworks in the FEW Nexus as well as suggestions for adapting them to individual studies and applications. Further, relate them to other Nexus applications as well.

The objectives of this study are (a) synthesize existing knowledge to support stakeholders in defining and conceptualizing their FEW Nexus, (b) provide a framework to adapt the definitions and conceptualizations of FEW Nexus for a project or an application in the real-world, and (c) to apply the experience and principles of the FEW Nexus to other Nexus can be developed. In this study, we define stakeholders as users of the Nexus: Stakeholders in this study include the users of the Nexus, scientists, and range of practitioners including policy makers, planners, producers, developers, field, and resource manager among others.

The following questions can assist in clarifying the objectives for a specific application: What are some existing relevant definitions in FEW Nexus? What factors are currently included in each definition? How should the FEW Nexus be defined for a project or application? What are the consequences of choosing particular components in the definition? What are some appropriate existing conceptualizations and frameworks for the FEW Nexus? How should the FEW Nexus be conceptualized based on the properties of a project? Can existing conceptualizations and frameworks be used or adapted or do new ones need to be developed? How can existing conceptualizations and frameworks be adapted or new ones created for specific project or study? All these questions are addressed in detail in this paper.

Key Research Questions

What Are Some Existing FEW Nexus Definitions and Descriptions?

In this section, the several definitions and descriptions available in the literature are listed (Fig. 1). The term FEW Nexus has no globally agreed definition (Dombrowsky and Hensengerth, 2018). The way in which they are defined and portrayed is evolving (Keairns et al., 2016) because of their rich diversity, complexity, and mercurial nature as well as the range of applications of FEW Nexus to addressing real-world problems. Therefore, in many cases stakeholders (scientists and practitioners) interested in working in this area can start by choosing definitions suitable for their study. In other cases where a FEW Nexus application is implemented (for example by a government agency) it may be a matter of adapting the definition as is or modifying it. To facilitate this, we provide how FEW Nexus is defined by various groups in the recent peer-reviewed literature in terms of connections, consequences, elements, categories, perspectives, and approaches. These definitions are summarized in Fig. 1 and the elements of these definitions are summarized in Fig. 2. In addition, we can assess the stakeholder needs and evaluate the types of definitions best suited to their needs. Leck et al. (2015) have defined a Nexus as one or more connections linking two or more things. The things can be disparate ideas, processes, or objects (Leese and Meisch, 2015). In the case of the FEW Nexus the needs focus on linking the food, energy and water sectors. This leads to the use of a definition that relies on different elements to describe the connections linking these domains. Howarth and Monasterolo (2016) used eleven elements to define the FEW Nexus. The FEW Nexus encompasses natural resources that are essential to communities in every part of the world. Food is needed in sufficient quantity for health and well-being of human populations. Water is also needed to meet domestic needs for clean drinking water and to facilitate waste disposal. In the last century in particular with the expanded use of irrigation it has become an essential input for food production. Enabling the green revolution in India and rapid increases in food productivity in other areas. According to the UN Food and Agriculture Organization (FAO), over 70% of the freshwater withdrawals are used for irrigation and food production. Energy also plays a role in food production using irrigation water. FAO also estimates that 30% of the annual global energy produced is used in various ways within the food sector (farming, transportation, food processing). Linkages between water and energy have been recognized for many years: water reservoirs have been built to support hydropower plants, water is used for processing oil products and minerals into useable products, and using water for fracking has become a common extraction procedure in the oil and gas industry. The potential for conversions between water and food production through new technologies, and between food and energy through the production and use of biofuels have been developed. To explore these options, it is important to have a framework for analysis and exploring the options; hence the idea of a FEW Nexus has become very popular. The design of these frameworks can be tailored to the problem or application being addressed. However, an underlying set of principles is needed to endure consistency. The principles that have emerged for the FEW Nexus are summarized here at a general level, which makes it possible to extend the Nexus approach more widely to different domains that influence one other.

1. In addressing FEW Nexus definitions some combination of the following system elements needs to be addressed, either singularly or all together. According to Howward and Monasterole (2016) the eleven elements needed to address the FEW Nexus include Uncertainty, connectivity, risk, impacts, nonlinearity, feedbacks, robustness and flexibility, emergence, hierarchical organization, independent system, and dependency.
2. Descriptions of the FEW Nexus are often based on the specification of the consequences. These descriptions or framing of the Nexus are based on economical, societal, and environmental consequences (Keairns et al., 2016). Security framing tends to focus more on supply chain concerns (economical and societal consequences) and less explicitly on impacts on biodiversity and land-use changes. On the other hand, footprint framing focuses on environmental impacts where economical and societal consequences are less explicit (Deepa et al., 2021; Deepa et al., 2022).
3. Descriptions also need to include the mercurial nature of the FEW Nexus. According to (Zhang et al., 2018), these descriptions fall into one of three categories. Category 1 incorporates the mercurial nature of the Nexus. The Nexus is treated as a novel approach to investigate Nexus systems with various responses in different contexts. A Category 2 Nexus focuses on the interlinkage (interactions) among different subsystems (or sectors) and between different resources. This is similar to the general definition. In Category 3, a Nexus is treated as a hybrid integrated system assessment. This involves integrated management of the three sectors by cross-sector coordination in order to reduce unexpected sectoral trade-offs and to promote the sustainable development of each sector.
4. Descriptions also reflect perspectives. The first three perspectives shown in Figure 1 are from Keskinen et al. (2016) and the fourth is from Ghodsvali et al. (2019). Two additional perspectives have been added to reflect those who use the Nexus concept for practical applications. To some extent, the perspective reflects the way in which the stakeholders plan to use the Nexus. The first perspective in Figure 1 is based on the use of the Nexus as an analytical approach or tool. Here, a Nexus-based analysis is a systematic process that explicitly includes consideration of water, energy, food, and other linked sectors in either quantitative or qualitative terms with a view to better understand their relationships and hence provide more integrated information for planning and decision-making in these sectors. Perspective 2 is based on the governance framework. This perspective explicitly focuses on linkages between water, energy, food, and linked sectors as well as their related actors (e.g., representatives from the water and/or environment ministry from each of the four member countries are in the Mekong River Commission Council) to enhance cross-sectoral collaboration and policy coherence, and ultimately promote sustainability, win-win solutions, and resource use efficiency. Perspective 3 is from a boundary concept perspective. Here, the Nexus is an emerging discourse that emphasizes trade-offs and synergies across water-energy-food connections and encourages actors to cross their sectoral and disciplinary boundaries (i.e., acting as a boundary concept). Perspective 4 is from a transdisciplinary perspective with three main elements: key drivers, characteristics of the systems to be integrated, and thresholds to actions. In some cases, new Nexus developments include more than one (or all) of these perspectives.
5. Definitions are based on approaches Again, the approach is influenced by the stakeholders and the motivation for advancing the Nexus. The first approach in Figure 1 is analytical consisting of a quantitative definition that advocates for definitions-based modeling interactions among the FEW sectors and provides a basis for improving communication and data exchange among the three sectors. The second approach is sectoral. It views the Nexus as a programmatic characterization useful for addressing cross-sector issues. This more subjective (qualitative) definition provides an integrative view of each sector (F-E-W) and resources (water, energy, and food) at all levels. This approach characterizes the interconnectivity among the three sectors and requires unified definitions of terms that apply across the FEW Nexus. The third approach is a system-of-systems approach. This more practical definition considers many "Nexi" (people, cultures, and socio-ecological systems) and interactions that differ geographically and spatially. In this definition, the interactions (bottom-up and top-down information flows and collaborations) are integrated and the potential for undesirable trade-offs is minimized. While this broadens the scope of the discussion, it can make the discourse more complex and follow-on actions less defined and harder to implement.

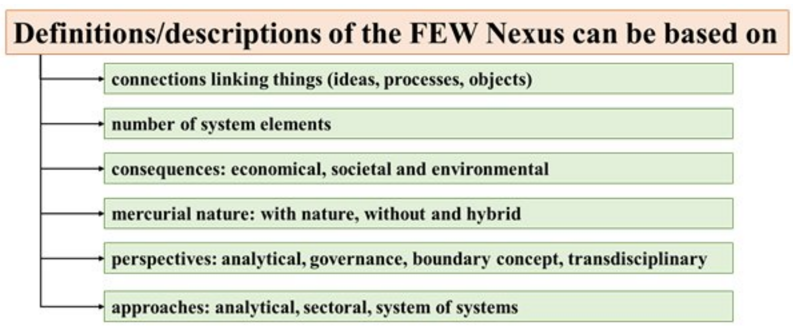


Fig. 1. Synthesis of definitions and descriptions from the literature review.

Analysis of FEW Nexus Definitions and Descriptions

The analysis of existing FEW Nexus definitions and descriptions addresses the question: "what are the elements included in the FEW Nexus definition? It can be observed that the general definition of FEW Nexus namely: one or more connections linking two or more things is common and underlying among all the definitions for any Nexus. The definitions vary because there are several ways of making connections between things including connections between ideas or processes or objects. The definitions can have various properties, perspectives, consequences as well as the approaches. As noted earlier, the connections between things may describe properties such uncertainty, risk, impact, feedbacks, nature of relationships, etc. The nature of relationships can describe existing or emergent relationships which may be known or unknown or partially known. The nature of relationships may be described mathematically as linear, nonlinear, probabilistic or some combination. The connections can utilize analytical, sectoral, system of systems approaches to define the FEW Nexus. The connections can take into account the large variability in FEW Nexus fully, partially or not at all in terms of the context, geography, and scale at which it is applied. The FEW Nexus definitions can include perspectives such as analytical, boundary concept, disciplinary, governance etc. The definition could take the sectoral or system of systems or hybrid approaches. The definitions can include one or more of the following consequences: economic, social, and environmental. These are synthesized as bullets in Fig. 3. The nature of connections is also dynamic and they change as the interdependencies change and the specific locale where these components exist also shift. Due to transferability and trade some components may be important for different locales as in the case for trade of commodities with significant virtual water transfers.

FEW Nexus Definition Developed in this Study: Narrow to Broad

The way a study or a project defines and describes the FEW Nexus is important because it affects how conceptualizations and frameworks are chosen and finally how they are analyzed. Therefore, addressing the question: "how can the FEW Nexus be defined for a specific project?" becomes important. The FEW Nexus definition developed in this study addresses this question and provides the stakeholders an opportunity to develop their definitions. The developed definition can be a narrow definition, a broad one or something in between. To define the FEW Nexus, the stakeholder needs to understand whether they are defining the FEW Nexus as the totality of the food, energy and water sectors or if they are truly looking at the Nexus where the three sectors overlap reflecting areas of common interests among the three sectors. Then accordingly, the stakeholder or his/her consultant needs to go over the analysis of the current definition for the Nexus provided in Fig. 2 and choose the following from each of the 3 steps:

1. **The way to describe things.** The things can be described in terms of the ideas, processes, or objects. Specifying the type of ideas, processes and objects and choices add constraints to the scope of the definition and can improve its clarity

2. **The way the connections between things are described**. They can be based on properties, perspectives, consequences, and approaches.

3**. Specifying the chosen properties, perspectives, consequences, and approaches**. They can be chosen from the list provided in the Fig. 2 or additional ones can be added. Adding details improves the definition's clarity.

A stakeholder could develop a narrow definition/description of a FEW Nexus by choosing one element from each step. For example, processes could be chosen in step 1, approach chosen in step 2 and a single sectoral approach could be chosen from the list of approaches in step 3. This results in a narrow definition of FEW Nexus descriptions. This FEW Nexus would be the connection between processes described by sectoral approach.

The stakeholders can also develop a broad definition/description of a FEW Nexus by choosing several or entire list in each step. For example, the definition can be based on choosing all the three things (ideas, processes, and objects) in step 1. Similarly, all in step 2 namely: properties, perspectives, consequences, and approaches could be chosen. Finally in step 3, all the 10 properties, 4 perspectives, hybrid approach and all 3 types of consequences could be chosen. The definition of the FEW Nexus is broadened when these multiple components are considered. The broad definition of the FEW Nexus can be: The FEW Nexus can be defined as the connection between processes, ideas and objects described by 10 properties, 4 perspectives, 3 consequences (Fig. 2). The definitions can also fall between narrow and broad depending on the items chosen in the three steps (Fig. 3).

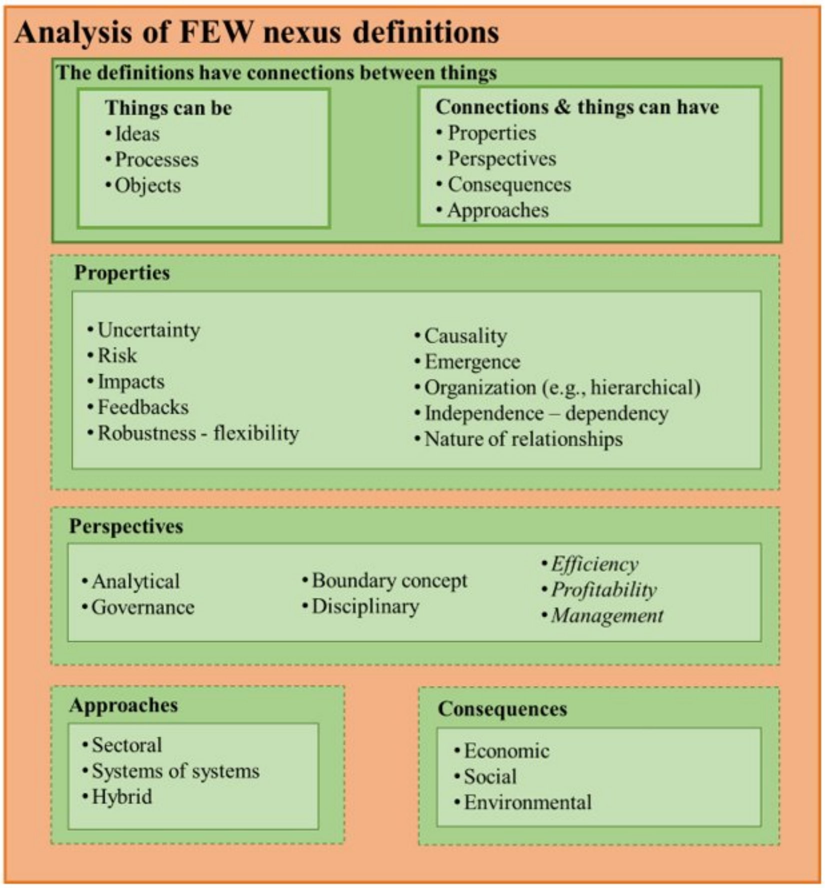
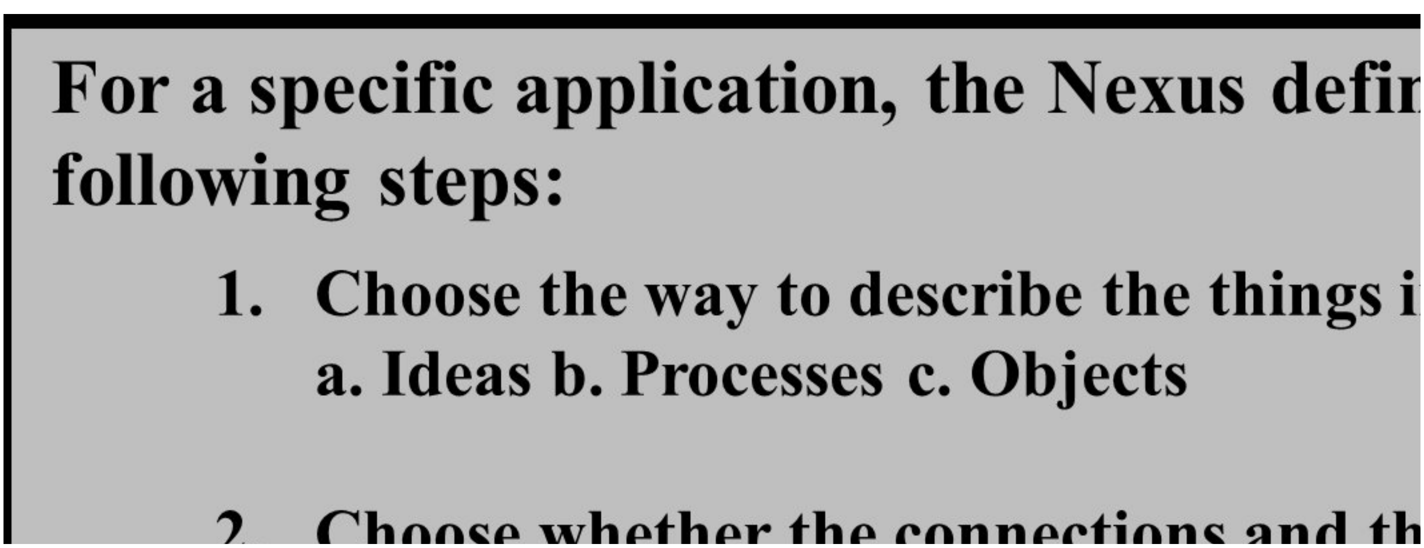


Fig. 2. What elements are currently included in FEW Nexus definitions? This table shows an analysis of existing FEW Nexus definitions and descriptions as well as new ones included in this study (Italics) to address the question.



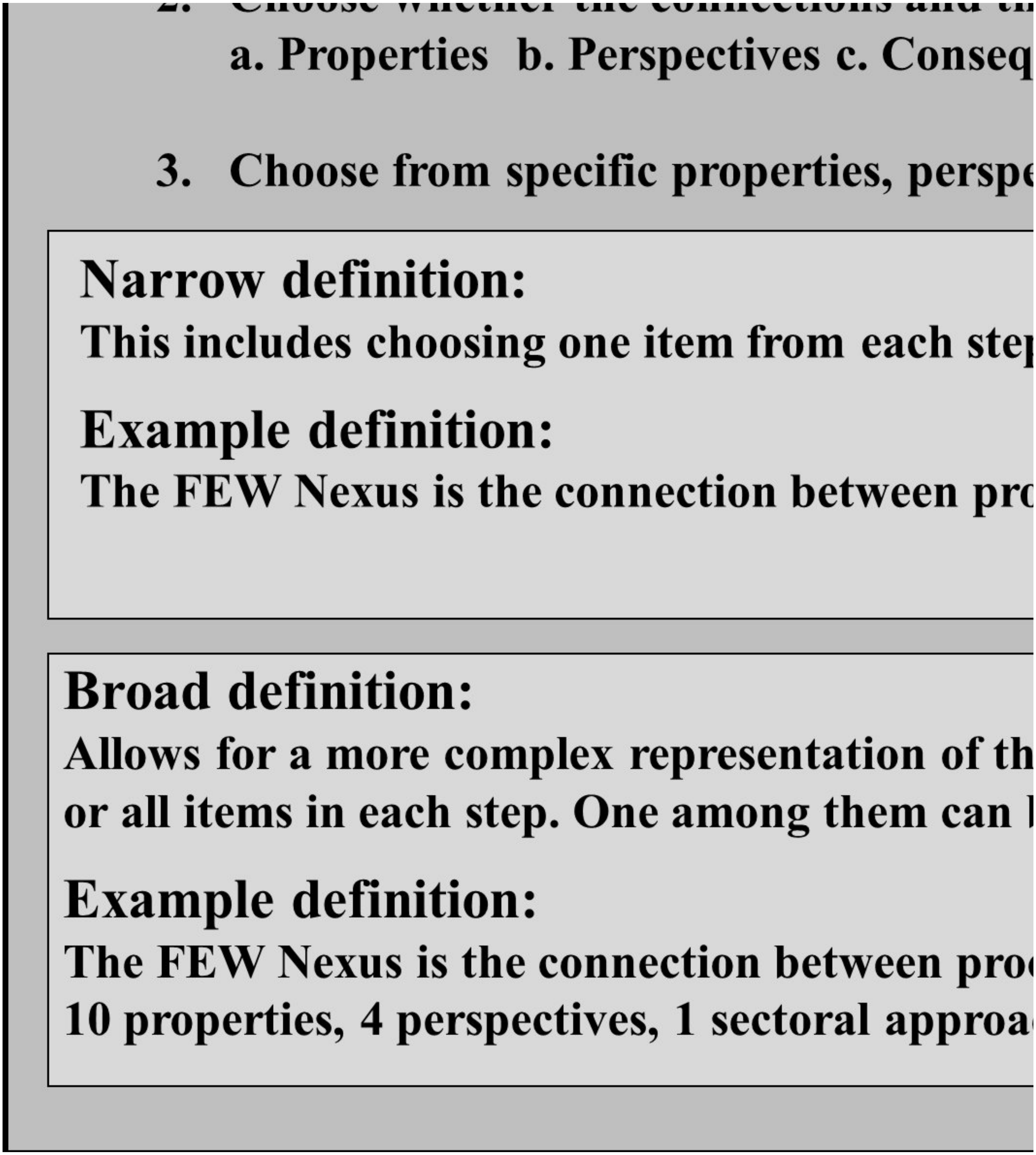


Fig. 3. Steps for Creating definitions and descriptions for a FEW Nexus. This can be adapted to other Nexus definitions as well.

The table below (Table 1) provides a guideline that different stakeholders could use in developing their definition of FEW Nexus. It should be noted that these guidelines are not exclusive to the FEWS Nexus but can be applied to any set of disciplines or sectors that interact with each other.

Table 1: Potential guidelines for definition: List of elements that stakeholders are likely to include in their definition

Stakeholder	Things			Connections between things			
	Ideas	Processes	Objects	Properties	Perspectives	Approaches	Consequences
Researchers/ scientists	X	X	X	One of more properties	Analytical, Boundary concept Disciplinary	Hybrid	Economic, environmental
Producers	X		X	Impacts, robustness,	Effectiveness and	Practical,	Economic

				risk and uncertainty	profitability	sectoral	Environmental
Municipal: planners and managers		X		Organization, risk, feedback, robustness, nature of relationships	Analytics Management Governance	System of systems, conceptual	Economic, social, environmental
Urban development	X	X		Nature of relationships	Analytical Governance, management	System of Systems,	Social, economic
Agriculture, food, and energy industries		X	X	Organization, impacts, independence, nature of relationships	Efficiency and Profitability	Sectoral Hybrid	Economic Environmental
Government policy and administration	X		X	Organization, Impacts risk	Governance Efficiency and profitability	Economic, social, environmental, practical,	Social, economic

Consequences of Choosing a Particular Definition

While choosing a particular definition by selecting the elements in the three steps, stakeholders need to be aware of what they are choosing and what they are leaving out. If a stakeholder chooses to define the FEW Nexus as the overlap of the food, energy, and water sectors and common interests among these three sectors, they need to be aware that the totality of the food, energy, and water sectors is not being considered. This big picture also provides the stakeholders the flexibility of adding or removing elements to the definitions later. The narrow definition simplifies the description of the FEW Nexus, while the broad definition adds to its complexity. A narrow definition can simplify the FEW Nexus and can be used for smaller projects or projects with limited resources. However, it can also result in missing some of the details. On the other hand, a broad definition can be used for larger projects or projects with sufficient resources. For example, the narrow definition "The FEW Nexus is the connection between processes described by the sectoral approach" is missing several properties, consequences, etc.

Applications of FEW Nexus Definition to Other Nexus

The question about what Nexus elements to include in the analysis has been extensively debated by the FEW science community and corresponding articles. Some examples of Nexus applications are: Climate-Food-Energy Nexus, Carbon-Food-Energy Nexus, Environment-Food-Water-Energy Nexus, Health-Food-Water Nexus. While there is no consensus about this question, our recommendation is to keep the Nexus simple as the modeling complexity grows with additional elements. Not adding one element to the Nexus system does not mean the impact and interactions of this element are being ignored. These interactions can be included as constraints or other externalities without adding system complexity. The elements that are currently included in the analysis of existing FEW Nexus definitions and descriptions (Fig. 2) can be useful to other Nexus applications as well. The steps for creating the definitions and descriptions for a FEW Nexus in Fig. 3 can be adapted to other Nexus definitions. The nature of connections is also dynamic and they change as the interdependencies change and the specific locale where these components exist also shift. Due to transferability and trade some elements may be important for different locales as in the case for trade of commodities with significant virtual water transfers.

Advantages and Challenges in Conceptualizations And Frameworks

Conceptualizations are carried out using conceptual models or frameworks and regarded as organizational diagrams (Carmona-Moreno et al., 2018; Robinson et al., 2010). These conceptual models and frameworks are useful in collating, visualizing, understanding, and explaining the problems or situations and how they might be solved by bringing together and summarizing information in a standard, logical, and hierarchical way (Anandhi and Bentley, 2018; Patrício et al., 2016). These conceptual models provide the system specifics such as the changes in model state, scope/boundary, how the simulated system should work, the entities that it contains, as well as the interactions, rules, and equations that determine its behavior (Anandhi, 2017; Brooks, 2010). Frameworks guide research to deliver the necessary insights into multiple key system aspects (Bentley and Anandhi, 2020; Stringer et al., 2018). The process of identifying, building, and comparing models at different levels of detail can greatly increase the understanding of the system (Brooks, 2010; Pagan et al., 2020). Conceptual models are the most difficult and least understood, but probably the most important activity to be carried out in a simulation study (Pagan et al., 2020; Robinson, 2017; Schulterbrandt Gragg et al., 2018).

The difficulty increases multiple folds when conceptual models are to be developed for complex concepts such as the FEW Nexus because it encompasses a broad range of issues and a variety of focuses (Anandhi et al., 2020; Anandhi et al., 2018b; Zhang et al., 2018). Further, the effectiveness of the model/framework depends on a comprehensive understanding and translation of indicators, framings, and concepts used from different research traditions (Leck et al., 2015). Furthermore, there is no single cookbook method for "modeling the Nexus". Therefore, no common conceptual model/framework for the Nexus has emerged (Keskinen et al., 2016). Additionally, with so much complexity, it's dangerous for the FEW Nexus to become a rigid concept (Zhang et al., 2019).

What Are Some Existing FEW Nexus Conceptualizations And Frameworks?

There are several existing FEW Nexus conceptualizations and frameworks available in the literature. In this study only some of these are synthesized and framework figure provided (Fig. 4) to help us better understand their applicability by addressing the questions such how can FEW Nexus be conceptualized for a project or an application? Can existing conceptualizations and frameworks be used or adapted or new ones need to be developed? How to adapt existing conceptualizations and frameworks or create new ones for a project or study? Therefore, a very brief description and figures of some conceptualizations are provided. The descriptions highlight certain elements that will be used in the next section and therefore may not be consistent among the descriptions. More details on the conceptualizations and frameworks can be obtained from the references provided.

World Economic Forum 2011 framework: This FEW framework was presented at the World Economic Forum to help decision-makers better understand risks so they can respond proactively and mobilize quickly in times of crisis (WEF, 2011). This framework positions the Nexus at a macro scale through its links to national security and global affairs and moves away from Nexus connections and trade-offs on ecosystems at local and regional scales (Bell et al., 2016). This framework identifies specific relationships, food security, energy security, water security, stressors (environmental pressures, population, and economic growth), economic disparity, and global governance failures (Bizikova et al., 2013). Although this framework aims to help decision-makers to understand and respond to risks, it can be used by other stakeholders as well.

Bonn2011 Nexus framework: Developed as a part of the Bonn2011 Nexus Conference on the Water, Energy and Food Security Nexus: Solutions for the green economy (Hoff, 2011). The Nexus is centered on available water resources (Leck et al., 2015). This framework's goal is achieved from action fields (society, economy, environment) by accounting for global trends (urbanization, population growth, climate change), using finance, governance, and innovations, and it promotes the FEW security, sustainable growth, and a resilient environment (Bizikova et al., 2013). Any stakeholders involved in the implementation can use this framework.

FAO framework: In this framework the role of stakeholders is stressed (Keairns et al., 2016). This framework attempts to represent the FEW Nexus as a balance between the different goals/interests, resource base, the needs of people and the environment as well as the interactions and feedbacks. The goals and interests can be social/economic/environmental and pertain to FEW (FAO, 2014). These are linked to the resource base which is impacted by drivers causing environmental degradation and resource scarcity. These in turn affect and are affected by the goals and interests. The resource base refers to the natural and socio-economic resources relating to land, water, energy, capital, and labor. The interactions and feedbacks take place within the context of drivers. Drivers can be globally relevant drivers (e.g., urbanization, climate change) as well as context-specific drivers (e.g., governance structures and processes, beliefs, and behaviors). The interactions describe the interdependencies, constraints (imposed conditions), synergies (mutually reinforcing or having shared benefits), and trade-offs. Some trade-offs can be enabling for the overall endeavor even though one sector may view them as a constraint. The indicators based approach and role of stakeholders in the assessment process is stressed in the FAO approach, with a trade-off between the ease and rapidity of an indicator-based assessment and more elaborate numerical approaches (Keairns et al., 2016). More information can be obtained from (FAO, 2014).

WEF-PIK framework (Stringer et al., 2018) that combines water-energy-food Nexus (WEF) and resilience thinking - policies, institutions, and knowledge (PIK). It involved multiple academic institutions located across the world (Leeds, UK, Hanoi, Vietnam, Zanzibar, Tanzania, Belém, Brazil, Brighton, UK, and Kathmandu, Nepal). This framework provides useful information to decision-makers using a double helix (two strands in FEW-PIK) emphasizing governance at multiple times (past, present, and future) and spatial scales (local, regional, national, global). The "resilience bases" are defined by the justice and equity across social, economic, and environmental that unite WEF and PIK and determine the interactions between them.

Texas A&M University, Daher and Mohtar, This conceptual framework for the FEW Nexus identifies national food profiles and water and energy portfolios (Daher and Mohtar, 2015). The model tracks the nationally consumed food products that are domestically produced and consumed or exported, as well as the imported foods. It assesses the different costs and risks driven by policy choices in the context of political dimension (security aspect) as well as health threats. Based on these, scenarios are developed by users (elaborated in scenarios sub-section in tools). The framework is the foundation that defines the existing relations (interconnections) between the three systems on which FEW Nexus tools are developed. Any stakeholders involved in the implementation can use this framework.

1. Other specific frameworks are briefly discussed in the paragraphs that follow. Ghodsvali et al. (2019) developed a conceptual framework that shows how a transdisciplinary FEW Nexus could potentially support integration of the SDGs using aspects that shape SDG integration, elements of a transdisciplinary FEW Nexus, and potential outcomes of linkages between elements and aspects. The five different aspects that shape SDG integration are directional-, context-, government-, technology-, and timeframe-dependency. The three elements are key drivers, systems characteristics, and thresholds to actions. Each element is further classified: issues of concern, government setting, and stakeholders (key drivers); human drivers, resource flows, and circular dependency (systems characteristics); and environmental risks and distribution, externalities, and institutional capacity (thresholds to actions). The five potential outcomes are cooperative interaction, localized interventions, resilient alliance, efficient resolution, and adaptive capacity.
2. **International Centre for Integrated Mountain Development (ICIMOD) framework:** It is a system-wide approach centering on ecosystem services contributing to the FEW security (Bizikova et al., 2013). This is elaborated in the case study.
3. **International Institute for Sustainable Development (IISD) framework**: It is centered on ecosystem management focus on biotic components of the landscape to link human well-being and FEW sectors.
4. **Footprint framework:** It focuses on environmental impacts where economical and societal consequences are less explicit. For example, the water footprint framework can link between (1) the planetary boundary fresh water resources (green and blue water resources) and (2) food security, energy security, blue water supply security (Vanham, 2016).

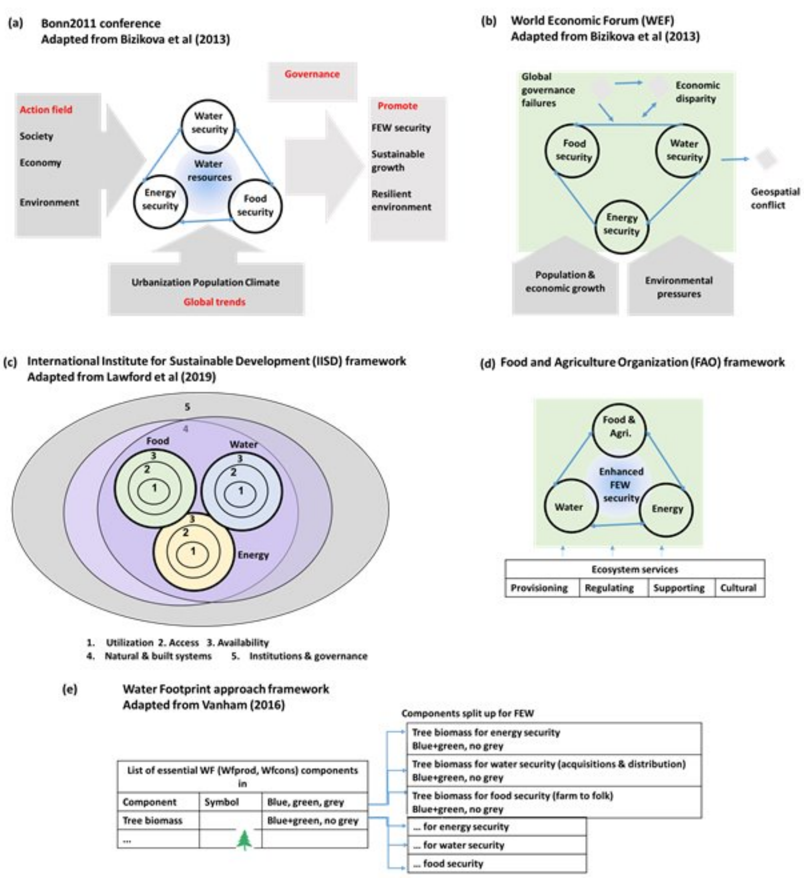


Fig. 4. Selected conceptualizations and frameworks adapted from studies.

Analysis of FEWS Nexus Conceptualizations and Frameworks

As can be observed from the brief framework descriptions and Figure 4, the existing conceptualizations and frameworks have five broad elements: overview information, personnel and organizations involved, scales and disciplines used, elements discussed in the definition, and assessment information. These five elements are synthesized in Figure 5. The overview information in these conceptualizations describes the purpose and focus of the FEW Nexus frameworks, the conceptualization's starting point, and the overall approach taken. Several personnel from various institutions are involved in the framework development and several beneficiaries utilize the conceptual model for assessment. Personnel can be affiliated with multiple organizations. The conceptualizations can represent various spatial and temporal scales involving one or more disciplines. Two or more disciplines can interact in several ways. The conceptualizations identify details described in the three steps used in the definition--the things (e.g., ideas, processes, and/or objects) and connections between them (e.g., linkages, relationships, interdependencies, and connections, the trade-offs can be reduced, synergies)--can be based on properties, perspectives, consequences, and approaches. Finally, the assessment approach must be specified because FEW Nexus conceptualizations and frameworks use different modeling approaches, tools, and data.

The information on the five elements for conceptualization are briefly synthesized in the next five sections and summarized in Figure 6. These sections are intended to explain the direction taken by past studies. They are guidelines and do not include a systematic review of the existing literature.

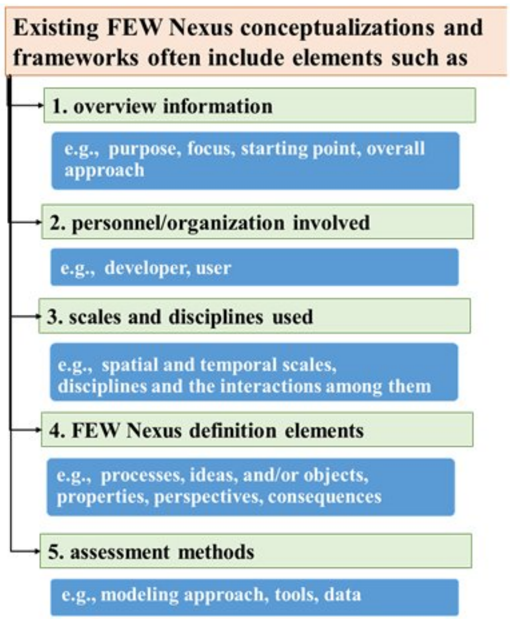


Fig. 5. Elements that are currently included in the FEW Nexus conceptualizations and frameworks

Information on First Element Identified for Conceptualization on FEW Nexus: Overview Information

The first element namely the overview information includes the purpose and focus of the FEW Nexus frameworks, starting point of the conceptualization as well as the overall approach. The purpose can be the reason for which conceptualization of FEW Nexus for a project or application is done or created or for which something exists. An example purpose is to help decision-makers understand risks and make informed decisions proactively or during crisis (Bizikova et al., 2013). Other purposes could be promoting the FEW Nexus: security, system efficiency, productivity, sustainable growth, or a resilient environment (Leck et al., 2015). In the past, productivity based purposes were classified as envisioning, experimenting, and learning (Ghodsvali et al., 2019). Additionally, purpose was classified into internal relationship analysis, external impact analysis, and evaluation when FEW Nexus was viewed as a coupled system (Zhang et al., 2018).

The focus overview information in the past has been just Nexus thinking or combining Nexus thinking with either resilience, SDG, and or ecosystem services. These are briefly described below.

- The FEW uses the "Nexus" approach because representing, understanding, and highlighting the linkages, relationships, interdependencies, and connections means that trade-offs can be reduced, synergies across sectors can be built (Guillaume et al., 2015), interactions in decision processes can be examined (Stringer et al., 2018), and focus on the system, instead of isolated sectors, can be maintained (Keskinen et al., 2016). This approach is particularly important in the coming decades when FEW resources are facing intensified challenges (Mitra and Pham, 2018).
- Ecosystem services provide supply and influence availability and access to water, food, and energy in several ways while restoring, managing, and optimizing FEW (Bizikova et al., 2013). This thinking was used to identify the interrelations among the ecosystem service flows related to the sectors in the Nexus (Karabulut et al., 2018). The study by Karabulut et al. (2018) was the first attempt to include ecosystem services and focuses only on provisioning services. To identify the relationships between sectoral uses of resources and the role of provisioning ecosystem services, they first listed the possible Nexus service flows and the meaning flows for each sectoral use (e.g., water for drinking). Then, the service flows are classified according to types and sub-types of sectoral uses (e.g., final, intermediate services). For example, final services for water for food included water for drinking, water for food production (crop, meat), and water for all household uses for food, while available soil water (green water) was considered an intermediate service supporting food production. The intersection between sectoral service flows and provisioning service flows defines the relationship. The ecosystem services (regulating services, provisioning services) can be at the center of the Nexus to emphasize the key support functions that ecosystems provide for water, energy, and food (Bell et al., 2016).
- Resilience and FEW Nexus approaches were combined to build on the strengths while addressing the weaknesses of each approach. From the past studies, resilience focus has been shock-absorbing capacity (Stringer et al., 2018) or vulnerability (Anandhi et al., 2020). Stringer et al. (2018) assessed the advantages and disadvantages of combining both approaches. The advantages include involving social-ecological systems (e.g., involve different groups in decision-making to different extents) and unpacking relationships and interactions across scales (e.g., spatial, temporal) and levels (e.g., local, national, regional, and global) in a system. The disadvantage in combining is that neither approach puts social justice considerations explicitly at its

core. In another study, Anandhi et al. (2020) developed linkages between FEW sectors centered on land resource vulnerability to stressors using driver-pressure-state-impact-response and the exposure-sensitivity-adaptive capacity vulnerability assessment framework. In the framework, the FEW sectors form components in the definitions of land resources and stressors. The seven steps were involved in combining Nexus thinking and vulnerability detailed in Anandhi et al. (2020).
- If the FEW Nexus uses a transdisciplinary approach, then it can potentially support SDG integration (Ghodsvali et al., 2019). To address sustainable development challenges, some are beginning to employ more integrated approaches. For example, Dahlmann and Bullock (2020) analyzed Nexus thinking and global sustainability challenges' interconnectedness in business.
- The focus of some frameworks has also been security (Leck et al., 2015) or available water resources (Hoff, 2011). These frameworks consider FEW system efficiency rather than the productivity of isolated sectors (Leck et al., 2015).

The starting point overview information in the past has been the top-down, bottom-up, and hybrid. These are briefly described below.

- The **top-down** starting point are most frequently used by economists who use historical market data to determine aggregate relationships as they try to equilibrate markets by maximizing consumer welfare (Semertzidis, 2015). Traditionally, top-down approaches are largely concerned with economic profit (Namany et al., 2019) and they are driven by economic growth, demographic development, price trends, etc. (Semertzidis, 2015). Studies on the FEW Nexus often adopt a broad-scale top-down approach without considering the Nexus' central importance at household or village levels, especially in rural contexts (Leck et al., 2015). The existing top-down institutional approaches seek to manage FEW resources as a (re)discovery by experts who seem to compartmentalize them into individual silos of what practicing stakeholders already know using a narrative that legitimizes existing dominant pathways.
- The **bottom-up starting point** is frequently applied by engineers, physicists, and environmental scientists (Semertzidis, 2015). Traditionally, sustainable features to stakeholders' objectives use a bottom-up methodology (Leck et al., 2015; Namany et al., 2019). The main characteristic of this approach is the high degree of technical detail used in assessing demand and supply. Often, in this approach, information is collected using surveys, questionnaires, etc., from key stakeholders (e.g., producers, managers, planners) (Anandhi, 2017). They are driven by technological progress, innovations, and intra-industrial structural changes (Semertzidis, 2015). By using a bottom-up approach, the FEW concept is re-conceptualized and the framework is more useful for exploring alternative pathways (Allouche et al., 2014). The starting point from the focus of implementation can be based on ecosystem goods and services (Bizikova et al., 2013).
- **Hybrid starting points** are a combination of top-down and bottom-up. They can deliver insights from both which cannot be obtained from individual approaches (Pfenninger et al., 2014). They utilize the technologically rich bottom-up models with top-down general equilibrium economic models (Semertzidis, 2015). For example, in response to changes, these hybrid approaches attempt to integrate cost curves or production functions with the economy. Hybrid approaches can be either soft-linked or hard-linked (Pfenninger et al., 2014). In soft-linking, both are iteratively solved where one approach feeds into the next until convergence is obtained. In hard-link, both approaches are integrated with the solution in a single iteration.

In the past, the overall approach has been to conceptualize the FEW Nexus as a network with things (nodes) and connections. Zhang et al. (2018) conceptualized the FEW Nexus as the arrangement of nodes and interlinkages within the Nexus. A node is a point of intersection/connection within the network. Nodes create, receive, and communicate information and store it or relay it to other nodes. The concept of nodes works on several levels, but the big-picture view defines nodes as the major centers through which traffic is typically routed. This usage can differ depending on what things constitute a node. Zhang et al. (2018) conceptualized the FEW Nexus networks can have a center of interest or activity which in this study could be the focus. These are briefly described below.

- In the **sectoral approach**, the connections between the food, water, and energy sectors are explored. While the FEW Nexus normally deals with three sectors there are opportunities to have a simpler Nexus or a more complex Nexus or one that combines different sectors. A two-node Nexus could be water-energy, or energy-food sectors. The three-node Nexus can be water-energy-climate or climate-land-water sectors. The four-or-more-node Nexus can be food-energy-water-climate, or ecosystem-water-food-land-energy sectors. An example of interconnectivity between the sectors could be based on private sector engagement or data services (Lawford et al., 2019).
- The **system of systems approach** considers nodes as system components and connections as relationships or interactions. In this approach, the nodes could be people, cultures, and socio-ecological systems that differ geographically and spatially. The interactions integrate information flows and collaborations and minimize undesirable trade-offs (Lawford et al., 2019). There is a lack of appropriate tools, data, and knowledge in utilizing this approach (Kulat et al., 2019). Systems approaches have also been widely critiqued because it is inadequately theorized or under-politicized, particularly from historical and relational perspectives (Leck et al., 2015). The general skepticism from adopting these holistic approaches is related to its applicability and ability to save resources and resulting cost-saving (Kulat et al., 2019).

- The **complex systems thinking-based approach** also has components and relationships. However, the number of components and relationships is greater compared to the system-of-systems approach. Mercure et al. (2019) conceptualized FEW Nexus governances as complex where the intervention changes the nature of the problem and the course of events, and the process of solving the problem is identical to the process of understanding its drivers. They identify four key characteristics of wicked problems in the Nexus: 1) the uncertainty in every aspect of the problem (e.g., climate and socio-economic change); 2) there are multiple stakeholders with conflicting values and views; 3) the interdependence of all aspects; 4) the challenges in implementing proposed solutions with existing resources. They utilized the methodology provided by Liu et al. (2015), which stresses system integration to solve wicked problems. Liu et al. (2015) identified stakeholders, sectors, and biotic and abiotic factors as components in human and natural systems. Interaction between the components happens at various spatial and temporal scales as well as at various organizational levels (local to national) and food tropic levels (producer to consumer). These interactions among components can lead to emergent properties that are not observed when the individual components are studied. They used the ecosystem services to quantify societal needs by assigning values to natural components for humans. The ecosystem services were simultaneously considered to quantify the negative impacts that human activities have on natural systems. Spatial integration was carried out by integrated landscape planning for ecosystem services, while temporal integration was by scaling up short-term fluctuations in the key system processes to predict long-term trends. Footprint analysis was used in the quantifications.

In this more subjective and practical network approach, boundaries (topography, national/state policies) play an important role in defining the sector boundary. Multi-nodal approaches are valuable in implementation (e.g., SDGs) because they consider multi-objective criteria for suggesting outcomes.

Information on Second Element Identified for Conceptualization on FEW Nexus: Stakeholders Involved

The second element namely the stakeholder's involvement includes identifying who is involved in the development the conceptualization as well as who is benefitting from the conceptualization. Stakeholders in FEW studies ranges from scientists, and practitioners including policy makers, private sector, and practitioners in the field. They can be users as well as developers. These stakeholders seldom have a common platform to interact. The platforms for convening and agencies involved in framework development and some suggested beneficiaries for which they are intended are briefly described in this section. The developer or beneficiary could be an individual, an agency, an organization, a forum, or a conference. The development of the Bonn2011 Nexus framework involved stakeholders who participated in the conference on the Water, Energy and Food Security Nexus. the World Economic Forum 2011 framework was developed in the forum. FAO, ICIMOD, IISD frameworks were develop by international agencies, private, governmental, or non-profit organizations. Frameworks were developed in academic institutions as well. The beneficiaries from the conceptualizations and the role they play in its development varies. For example, they may be involved in development of elements or partially in a few elements or just end users.

Information on Third Element Identified for Conceptualization on FEW Nexus: Scales and Disciplines

The third element includes information on spatial and temporal scales, the disciplines involved as well as the interactions among the disciplines. The FEW Nexus adapts to the spatial and temporal scale at which it is developed and applied (Bell et al., 2016). The temporal scales in FEW Nexus can technically vary in time scale (from minutes to centuries) and time-periods (past, present, and future). The spatial scales can be based on either hydrological boundaries or on political boundaries. The context where FEW Nexus is applied ranges from cities to transboundary river basins spanning several nations (Keskinen et al., 2016). The scales can vary depending on the underlying mechanisms and processes considered (e.g., physical, chemical) considered in the FEW Nexus. Fertilizer is a good example of an issue which has both national and basin wide implications for the FEW Nexus. Zhang et al. (2019) observed an increasing trend of FEW Nexus publications (from ISI Web of Knowledge) and more studies focused on the global, transboundary, and national scales, with fewer studies on the urban scale. The transboundary scale can be a river basin (basin scale) with the national boundaries (national scale) imposed on it. FEW tools for scientists and policymakers have been developed at the country level (Daher and Mohtar, 2015). World Economic Forum 2011 framework is at a macro scale (e.g., national security, global affairs) (Bell et al., 2016). Higher aggregation is required at larger scales and more detailed inner mechanisms (physical, social) are represented at smaller scales (Zhang et al., 2018). Although the temporal scales in FEW Nexus can technically vary from minutes to centuries and can be across multiple time-periods (past, present, and future). The annual cycle is the dominant time scale, especially for the FEW Nexus at mid and high latitude. The lack of comparative studies of processes and connections at different time scales indicates a need to synthesize the temporal scales involved in FEW Nexus studies.

Additionally, the following scales are highlighted.

- **Field or technology scale** (also referred to as local scale): At this scale, some detailed processes and data that govern the interlinkages of the Nexus are needed and typically represented. The questions must be very focused on either comparing variations in technologies from a system view, or on field trials that allow assessing and analyzing various applications of the Nexus. More specific data and identification of specific interlinkages among the primary elements of the Nexus are required to define and conceptualize the FEW Nexus. Modeling, in this case, can be specific and directed toward these local-scale processes.
- **County, national and macro scale:** At the national scale, the data requirements, system conceptualization, and the gaps in the analysis alter. Specific local data no longer governs the Nexus interactions, but instead, larger-scale interactions are covered. Examples include the 17 SDGs and the interactions between large-scale data that cover the Nexus meta-analysis are essential. At this scale, the processes of the local scale may not be critical to model as are the large-scale processes, tradeoffs, and interactions that exist among these goals or systems.
- **Transboundary scale**: Moving into the transboundary spatial scales adds additional complexity. At this scale, issues include the impact of national decisions related to the Nexus in other nations. Take, for example, a national decision based on local or national priorities to reduce the production of a certain primary resource (i.e., energy, fertilizer, or food). Such decisions may have a transboundary impact, such as the trade of the related commodities. In this sense, looking at transboundary effects adds additional complexity (i.e., the potential impacts on the global mobilization of factors such as pricing, availability, and access). As such, when a FEW framework is being developed, the scales need to be considered. These issues are further elaborated in the knowledge gaps.
- Broadly, disciplinesinvolved can be environmental, ecology, social sciences, economics, etc., (Zhang et al., 2019) or combinations (e.g., socio-economic). Depending on the number of disciplines involved in FEW Nexus assessment and the interactions among them, they can be mono-disciplinary (specialization in isolation), multidisciplinary (many disciplines with no cooperation), pluridisciplinary (cooperation between disciplines, without coordination), interdisciplinary (coordination between upper and lower-level disciplines e.g., planning and ecology), or transdisciplinary (coordination between discipline level) (Max-Neef, 2005). For example,(Ghodsvali et al., 2019) Ghodsvali et al. (2019)'s conceptual framework utilizes transdisciplinary FEW Nexus to potentially support SDGs integration. In general, the FEW is multidimensional if not transdisciplinary. Zhang et al. (2018) summarized the research methods for multiple research scales (global, national, basin, city), interdependency between FEW sectors, and research priorities. For e.g., a higher degree of data aggregation is likely as the system scale moves up. Conversely, more detailed inner mechanisms of the Nexus system with both social and physical disciplines be included, as the system scales down.

Information on Fourth Element Identified for Conceptualization on FEW Nexus: Elements Identified in the Definition

This element of conceptualizations comprises of the details in the three-step definition of FEW Nexus namely: description of the things (e.g., ideas, processes, and/or objects) and connections between them (e.g., linkages, relationships, interdependencies, and connections, the trade-offs can be reduced, synergies). These can be based on properties and perspectives. The approaches are covered in the fifth element of the conceptualization while consequences is covered in the later section. These would vary on the previous three elements selected in the study or application.

Processes representing the FEW Nexus can be a series of actions or steps or operations taken in order to change or preserve the Nexus as well as to achieve a particular end. The processes considered can be physical, biophysical, and chemical processes (Zhang et al., 2019), biological and their combinations. Plant growth and development, runoff, evapotranspiration, heating, and cooling are some example processes. Additionally, flow states (e.g., velocity, temperature), sediment transport, growth of algae and biochemical reaction (e.g. nitration and denitrification), hydropower generation, food production, and decision making mechanisms are some examples.

Keskinen et al. (2016) introduced three perspectives to apply FEW Nexus, namely: as an analytical tool, governance framework, and as an emerging discourse. Their first perspective (the analytical tool) views the Nexus as three sectors (can consider related sectors) and their interconnections, obtained quantitatively based on existing data and models. The analytical tool resonates with physical scientists (Lawford et al., 2019). However, this by itself does not produce effective and accountable policy and management (Weitz et al., 2017). Their second perspective, governance framework, facilitates the planning and management of the Nexus sectors through cross-sectoral collaboration and enhanced policy coherence. Three key gaps relating to this perspective (the conditions for cross-sector coordination and collaboration; dynamics beyond cross-sector interactions; political and cognitive factors as determinants of change) can be closed through integrative environmental governance (Weitz et al., 2017). Keskinen et al. (2016) third perspective views FEW Nexus as a boundary concept that is related to the use and management of FEW, relating to FEW linkages and complimenting dominant sectors (e.g., water-centered).

Each of the three perspectives is connected to four levels of perspectives (value, normative, pragmatic, and empirical) with an overlap in part (Keskinen et al., 2016). Accordingly to Max-Neef (2005), these four levels ask or answer questions such as: What and how should we do (value); what we want to do (normative); what are we capable of doing (pragmatic level); and what exists (empirical level). These levels involve various disciplines. The value level is based on ethics, philosophy, and theology; the normative level involves planning, politics, design of social environmental systems; the pragmatic level includes technology disciplines (e.g., engineering, agriculture); and the empirical level represents disciplines (e.g., physics, biology, chemistry, and psychology).

formation on Fifth Element Identified for Conceptualization on FEW Nexus: Assessment Method

Quantification of the conceptualizations is the critical next step in integrating human and natural systems (Liu et al., 2015). Although several analytics in terms of models and tools available in the literature, only some of the FEW assessment approaches are briefly described here. During selection of models and tools, it is important to understand that 1) they can fall short of capturing interactions among water, energy, and food; 2) they can strongly favor quantitative approaches with fewer social science methods; 3) only selective methods combine methods from diverse disciplines, utilize both quantitative and qualitative approaches, and many Nexus methods are confined to disciplinary silos (e.g., mono-disciplinary); and 4) using specific and reproducible methods for assessment is uncommon (Albrecht et al., 2018). For example, Ghodsvali et al. (2019) has synthesized the different methods for transdisciplinary FEW Nexus based on research purpose (envisioning, experimenting, and learning) and practical scheme (information sharing, consultation, consensus building, decision making, partnership).In another study, Zhang et al. (2019) reviewed and synthesized the FEW tools and models based on the type of method (resource-environmental footprint, assessment and systematic simulation, optimal management) and research purpose (understanding and quantifying, assessing and forecasting, integrating and optimizing). Potential approaches the stakeholders could include in their conceptual framework are listed in Table 2.

Quantification of the conceptualizations is the other critical step in integrating human and natural systems (Liu et al., 2015). There are several assessment approaches used in literature namely: mathematical modeling, ontology modeling, indicator and scenario based approach, footprint/life cycle analysis (LCA)/supply chains based modeling, trade-off analysis and the integrated modeling. The details provided in this element are guidelines and do not include a systematic review of the existing literature.

Table 2: Potential guidelines: The approaches stakeholders could include in their conceptual framework

Stakeholder	**Approach**				
	Mathematical modeling	**Ontology**	**Indicator/scenario based**	**Footprint analysis, LCA, supply chains**	**Integrated**
Researchers/ scientists	x	x	x	x	x
Producers			x		
Municipal: planners and managers	x		x		x
Urban development			x	x	x
Agriculture, food, and energy industries	x		x	x	x
Government policy and administration	x	x	x	x	x

Assessment using mathematical modeling: A mathematical model describes the behavior of a FEW Nexus system using mathematical language. Mathematical models are used extensively. Mathematical models can take many forms, such as dynamical systems, statistical models, numerical simulation models using differential equations for individual processes, or game theoretic models. They can be classified into black box or white box models, according to how much a priori information about the system is available. Often several mathematical models are combined for FEW Nexus. Examples are Soil and Water Assessment Tool (SWAT, (Jayakrishnan et al., 2005)), Water Evaluation and Planning (WEAP, (Yates et al., 2005)), Long-range Energy Alternatives Planning (LEAP), Computable General Equilibrium (CGE, (Zhou et al., 2016)), Water, Energy and Food security Nexus Optimization framework (WEFO, (Zhang and Vesselinov, 2017)), and Climate, Land-use, Energy, and Water Strategies (CLEWS, (Welsch et al., 2014)) tools. Mathematical models and tools are useful to overcome difficult barriers such as mathematical and computational challenges, quantification of impacts, relationships, processes across scales, and to predict emergence properties (Liu et al., 2015). Some challenges still exist. Traditional empirical statistical models (such as econometric models) are fitted to past data and fail when the future differs from the past (Liu et al., 2015). Dynamic stochastic general equilibrium models often assume a perfect world and ignore disturbances or crises (Liu et al., 2015).

Numerical simulation models such as SWAT and CLEWS often frame physical and other processes as differential equations and track the development of patterns as the model steps though the development of the system at discrete time intervals. In cases where processes are not fully known the processes are parametrized based on specific studies in certain area. One challenge that remains for these complex numerical simulation and prediction models arises from the lack of sufficient data for each time step. A balance must be obtained between including every physical and biological process and the set of data inputs supported by the current observational network. A balance needs to be developed between the complexity of the mathematical descriptions of the physical and biological processes and the state of observations. In some cases where physical processes have not been monitored it may be necessary to use an optimization model which integrates a few differential equations describing the system.

Assessment using ontology modeling: This approach uses ontology--a science of acquired knowledge using a set of concepts and categories in a subject area or domain that shows their properties and the relations between them. **Examples of** studies that have used conceptualization based on the ontology engineering method (Semantic Web technology method) for providing common terms, concepts, and semantics are introduced here. using this approach, concepts and relationships to the FEW Nexus describe the problem (Kumazawa et al., 2009). This resulted in a hierarchy of concepts (super-concept, sub-concept) to represent the target world (FEW Nexus) which are organized by relationships between them (part-of relationships, attribute of relationships, and super-sub relationships).

In the second study, Endo et al. (2018) developed the FEW Nexus domain ontology database (definitions of concepts and sub-concepts, trade-offs) and then integrated this qualitative method with the network analyses method (quantitative) to identify linkage hubs in the FEW Nexus domain ontology. It visualizes the human-nature interactions (in terms of linkages between FEW resources and their stakeholders in social and natural systems). It used systems thinking, holistic thinking, and an integrated approach.

In the third study, Babaie et al. (2019) developed the FEW ontology which specifies the FEW system's static structural components (i.e., spatial concepts) and dynamic processes (natural and planned) in classes, and links them through object properties from the complex system perspective (defining the emergent, nonlinear, and scale-invariant state transitions and behaviors of elements). An example from Endo et al. (2018) is used to demonstrate the method. "Groundwater is-a water" statement is a "is-a" relationship. In this relationship, water is called super-concept and groundwater is called a sub-concept. These concepts are basic concepts (class concepts in Hozo, an ontology development tool), because these concepts are defined without referring to any other concepts. Groundwater pumping is represented by "part-of" relationships with groundwater and surface water.

In the fourth study, impredicative loop analysis accommodates the chicken-egg predicament typically encountered in the description of complex systems (Giampietro et al., 2013) such as FEW Nexus. Here, a relation between the characteristics of the whole and those of the parts of the system is established in semantic terms. Using proxy variables, the grammar is formalized in quantitative terms. It generates a set of forced relations of congruence (not a linear causal relation) between the characteristics of the parts and those of the whole implying that these characteristics must be compatible (hence the label "impredicative"). These are described in the Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism (MuSIASEM) tool. The MuSIASEM tool simultaneously characterizes the metabolic pattern of energy, food, and water concerning socio-economic and ecological variables (Giampietro et al., 2013).

Weitz et al. (2017) used the concept of integrative environmental governance [IEG, coined by Visseren-Hamakers (2015)] and extracted three useful insights from theoretical literature. First, rethink the boundaries of Nexus analysis. Second, to guide decision-making towards policy coherence, the shared principles need to be elaborated or an appropriate form of fragmentation in different contexts as needed. Finally, be ready to update because policy coherence is a continuous process of changing values and perceptions rather than as an outcome.

Assessment using indicator-based approach: In the FAO approach, a FEW metric is defined using a set of indicators (Nie et al., 2019). Each indicator is calculated, and its boundaries are estimated (e.g., maximum, minimum values) and standardized. One or more indicators (a set) will quantify an objective function referred to as the decision element. For example, indicators from different stakeholders quantify the multiple criteria for decision-makers which are solved using optimization methods. Indicators can represent the things and their connections (e.g., nodes, processes, relationships). Some example indicators to represent the FEW sectors are available in literature (Anandhi and Bentley, 2018; Anandhi et al., 2018a; Anandhi and Kannan, 2018; Anandhi et al., 2018b; Bentley and Anandhi, 2020; Sinnathamby et al., 2018). Similar indicators for food and energy (e.g., degree days, (Anandhi, 2016; Sharma et al., 2021)) can be estimated. Estimated indicators are then aggregated to form the FEW metric. For example, Martínez-Guido et al. (2019) used the improved Human Development Index (HDI) and new optimization approach which integrated several indicators that represented a healthy life and a decent standard of living that are closely related to quality of life. This approach accounted for the FEW Nexus by increasing the HDI by simultaneously considering economic, environmental and social sustainability criteria.

This approach is advantageous because indicators can be powerful tools to communicate technical data in relatively simple ways. They can support representation of complex systems (e.g., through combination of the system and its environment) in simple aggregated summary statistics (Simpson and Berchner, 2017). They can reveal evidence of already discernible impacts of change and provide important insights into the connections between things. They are valuable for monitoring trends in ecosystems. They are useful in impact studies (e.g., high temperatures, crop yield changes). They can portray inter-relationships between FEW sectors as well as represent cross-scale interactions (Bentley and Anandhi, 2020).

The disadvantage of this approach is the subjectivity in choosing these indicators as well as the methods used for normalizing, weighting, and aggregating them. For example, many the FEW metrics are heavily dependent on the choice of the indicator and system boundary. The FAO's approach to the assessment of the Nexus based on appropriate indicators and information that is readily available without detailed modeling (Keairns et al., 2016). The selected indicators provide operational clarity to the processes in the FEW Nexus. The scale of the indicators selected represent the scale of the system and stressors. Although the indicators can be at various spatial and temporal scales, they are brought to a common scale.

Assessment using scenario-based approach: Scenarios can be a series of events that is projected to occur. Depending on the purpose of the study, they could be all of the possible outcomes or the plausible futures.Many methods have been used to develop scenarios. Scenarios have been derived (i) based on analogies with spatial or historical time periods or (ii) from mathematical models using simple manipulation of observations (e.g., change factor methodology, or CFM) and (iii) more sophisticated

statistical and dynamical downscaling methodologies (Anandhi, 2011; Anandhi et al., 2011; Anandhi et al., 2018b). First, Kulat et al. (2019) usedpossible interventions to form scenarios. The interventions were developed based on local objectives and restrictions and environmental constraints for sustainability. Therefore, they can vary with local necessities and availabilities. They can be feasible, but unsustainable and, therefore, not advisable. Second, in another study, the scenarios were developed by applying the existing/validated/calibrated tools and models in the various sectors (e.g., life cycle assessment, energy, or agro-hydrological modeling) (Carmona-Moreno et al., 2018).

Third, depending on the food product, water requirement, and energy consumed, developed a self-sufficiency scenario (Daher and Mohtar, 2015). In their study, the developed WEF Nexus tool 2.0 uses the scenario-based and complex systems thinking approach to reflect the interconnectedness in FEW Nexus by assessing the distinct resource demands for scenarios useful in developing new management strategies. Here, the user creates multiple variations of scenarios using the WEF Nexus tool by choosing five inputs (self-sufficiency of food products, agriculture conditions in which the food products are grown, different water and energy sources, and sources for importing food). The developed scenarios are assessed based on local characteristics of the area (e.g., yields of food products, water requirements, energy needs). Across multiple FEW sectors, a large number of scenarios can be developed to reflect major possibilities and to draw useful recommendations, however, time and resource restrictions often limit the number of scenarios that are possible (Kulat et al., 2019).

The advantages of this approach is the presence of several scenario generation methods (ranging from simple to complex) in literature (Anandhi, 2010; Anandhi et al., 2018b). Scenarios can be powerful tools to communicate complex changes and interactions in relatively simple ways. They are useful in impact assessments as well as provide important insights on changes in Nexus. They can portray inter-relationships between Nexus sectors as well as represent cross-scale interactions (Bentley and Anandhi, 2020). The disadvantage of his approach is the subjectivity in developing and choosing the scenarios.

Assessment using Trade-offs and trade-off analysis: In the non-linear, interlinked system of Nexus, we begin with stakeholder engagement that identifies key hotspots of the system. This is followed by data collection at the scale related to the system: defining the tools and analytics that will allow us to look at the outcomes of this system. We then identify the footprints and a series of trade-offs that involve the user and the relevant stakeholders. In this section we identify three types of trade-offs.

The first is the data related to the system, to the question to be asked, to the scale, and for the chosen, appropriate tools. This data question is not separate from the entire complex system identified above, and is also related to the second trade-off: the tools and the question of the tool trade-off between a complex tool that looks into the detailed processes versus a simple tool that provides only a high-level outcome for use in the main trade-off analysis in the Nexus. The third trade-off is the main trade-off that will be described in this section: the trade-off between resources.

This third trade-off stems from the fact that within a constrained resource Nexus looking at water, energy, and food, we seldom have all that we need and thus need to have trade-offs between the primary resources. Examples of this include when compensating for water security by drawing on energy security, i.e., generating additional water by using energy for desalination, is often energy-intensive. Thus, we trade water for energy or, trade energy for water. The trade-off between these primary resources is a site-specific application that stems from the analytics of the tool and the footprint generated as an outcome of those analytics, and it governs the dialogue between stakeholders as they make some decisions.

Trade-offs, in this case, are also related to values that the user places on these primary resources, and those values depend on the specific hotspots and the use of one resource to compensate for athe second resource where availability is a constraint. As such, at all levels of trade-offs across all levels of the Nexus occur, therefore Nexus is about trade-offs analysis should play a, prominent across Nexus applications.

Assessment using footprint analysis, LCA, and supply chains: There can be many types of footprint analyses for products that have multiple inputs. Footprint analysis in the FEW Nexus can be carried out for different critical resource inputs including energy, carbon, and water. These analysis usually occur in four phases namely: (i) defining goal and scope of the study (ii) WFP accounting, (iii) sustainability assessment phase and (iv) response formulation phase (Alhashim et al., 2021; Deepa et al., 2021). For example, the water footprint based approach (Vanham, 2016) lists the essential WF components [WF of production (WFprod), WF of consumption (WFcons)] (in a table) that need to be included in WF accounting in order to address the Nexus (Fig. 4). Each component in the list can have blue, green, and greywater combinations. WFprod refers to the total use of domestic water resources within the region (for producing goods and services for either domestic consumption or for export). Then components are split up to clarify the FEW components (Fig. 4). WFcons refers to the use of domestic and foreign water resources behind all goods and services that are consumed domestically.

In the LCA ISO14040 approach (Mannan et al., 2018), the goal and scope (Fig. 4) are first defined to include the functional unit, system boundaries, assumptions and limitations, allocation, and life cycle impact assessment method selection. Second is the life cycle inventory (LCI), which includes inputs of FEW resources and raw materials and releases of by-products to air, land, and water. The third is the LCI assessment and, finally, the interpretation of the three steps (Alhashim et al., 2021). Deepa et al. (2021) and Alhashim et al. (2021) reviewed the role of the LCA in gthe water and food sectors. Depending on the goal and scope, the footprint, LCA, and supply chain analysis can be estimated for individual sectors and used as indicators which in turn can be combined to obtain a FEW metric. They can also be estimated for a FEW Nexus system. For example, LCA and agent-based models (ABM) were combined by incorporating the LCA into each agent's decision (Namany et al., 2019).

The advantages of the footprint/LCA approach are that it can be considered as an indicator or used in developing scenarios or trade-offs. For example, a footprint can be considered as a multi-faceted indicator of human water resource consumption. It is useful for decision-making for sustainable and equitable water use and provides a basis for the local environmental impact assessment from a social and economic viewpoint (Deepa et al., 2021). The interpretation step can be useful in developing scenarios and trade-offs. When the footprint/LCA analysis is used as an indicator/scenarios/trade-offs, it carries the advantages and disadvantages of the approach.

Integrated modeling approach: In this approach, two or more of the above approaches are combined. For example, the modeling approach can be integrated with the scenario-based approach, the indicator-based approach, or the LCA-based approaches. For example, the CLEWS toolintegrates three separate subsystem mathematical models namely: AEZ model (Agro-Ecological Zoning, greenhouse gas), LEAP, and WEAP. AEZ was developed by FAO and International Institute for Applied Systems Analysis (IIASA) over a 30-year period (Keairns et al., 2016). An example of combining approaches can be, modeling approach integrated with scenario-based approach, indicator based as well as LCA based approach. Another example is, Namany et al. (2019) developed an integrated modeling approach that combines optimization methods, Agent based modeling (ABM), and game theory models to quantify the connections, relationships and interactions between the three FEW systems for decision making. They classified optimization methods (best alternative out of a range of options) into 1) multi-objective optimization to solve a multi-objective challenge in decision making; 2) stochastic optimization to solve problems that involve randomness, limited number of scenarios, and strategic and operational uncertainties; 3) robust optimization for long-run strategic and extreme uncertainties and worst-case scenarios; and 4) data-driven optimization where unconventional uncertainty is determined from the observation and analysis of data. They observed that optimization techniques generate useful results when the problem is tractable with limited complexities. ABMs create virtual worlds that mimic the real world and provide information and insights into the complexities (Liu et al., 2015). Namany et al. (2019) observed that ABM quantifies the connections, relationships as well as interactions between the three FEW systems using complex systems thinking approaches while supplementing the optimization methods. The components can be agents with specific functions. They observed, ABM performs well in simulating behavioral characteristics of decision-makers as well as proposing future scenarios to illustrate interactions between FEW Nexus systems in heterogeneous and dynamic environments. The optimization and ABM methods focus on multi-dimensional economic and environmental perspectives of systems, while game theory method considers social implications and governmental policies (Namany et al., 2019).

Nie et al. (2019) developed a framework and a quantitative decision-making tool for stressed interconnected FEW-Nexus networks. This integrated method (e.g., combined data analytics, mixed-integer nonlinear modeling, and optimization methods) established the interdependencies and competing interests among the FEW elements in the system, along with policy, sustainability, and feedback from various stakeholders. This integration facilitates decision-making (e.g., derive trade-offs for land use

decision-making) and was useful to compare alternative processes and technological options.

Leck et al. (2015) proposed 'analytical eclecticism' as a potentially effective lens to guide Nexus research in traversing disciplinary boundaries (disciplinary crossing). 'Analytical eclecticism,' coined by Sil and Katzenstein (2010), is an intellectual stance (an alternate model) that first problematizes a complex phenomenon, then it typically slices the problem into more narrowly circumscribed puzzles into analytic components by adherents of research traditions (e.g., scholars), and searched for theories (explanatory theories, models, and narratives) in them. Finally, causal stories are developed from the linkages between the slices. These linkages can be obtained using several types of causal mechanisms by extricating, translating, and/or selectively recombining by trafficking in multiple theories (Sil and Katzenstein, 2010).

Ghodsvali et al. (2019) ordered the most frequently used methods in transdisciplinary Nexus research (from the highest to the lowest order): interviews, workshops, participant observation, participatory scenario development, and gaming. Endo et al. (2015) classified the interdisciplinary and transdisciplinary research approaches into qualitative or quantitative with functions such as unification, visualization, evaluation, and simulation using primary and secondary data. Further, the qualitative method was divided into primary research methods (e.g., questionnaire surveys) and secondary research methods (e.g., ontology engineering and integrated maps). Examples of quantitative methods are physical models, benefit-cost analysis (BCA), integrated indices, and optimization management indices.

Some FEW Nexus visualization tools and data are very briefly discussed below. Several multivariate visualization techniques have been used to represent the dynamic systems perspective. Bell et al. (2016) used causal loops to provide a dynamic system perspective on the key feedbacks (reinforcing, balancing) in the adoption of pro-environmental behavior in the FEW Nexus. Dynamic scatter plot matrices and dynamic parallel coordinates plots with brushing functions have been used to visualize FEW Nexus and decision support (Yang and Wi, 2018). Brushing is a commonly used mechanism in visualization tools to help people explore the relationship between data and results in a different but related view, as well as for exploring the relationship between data subsets. Interactive parallel coordinate plots have been used for visualization of multidimensional trade-offs in stakeholder interaction games. Sankey, or alluvial, diagrams (similar to parallel coordinate plots), with the addition that the results can also be used to display data with the relatively important results visually enhanced (Ray et al., 2019). Data used in the FEW Nexus assessment depend on the elements chosen for the study and the data source, which can be in-situ observations, model outputs, survey data, expert knowledge, or meta-analysis of published literature (Anandhi, 2017; Anandhi and Kannan, 2018; Anandhi et al., 2018b; Bentley and Anandhi, 2020; Daher et al., 2017; Daher and Mohtar, 2015).

Footprint/LCA analysis is also an integrated approach which is useful in more than one approach (e.g., as an indicator and developing scenarios). Using Figure 6 and explanations of the five elements, stakeholders can be guided in their choice of Nexus conceptualizations/frameworks for the FEW Nexus.

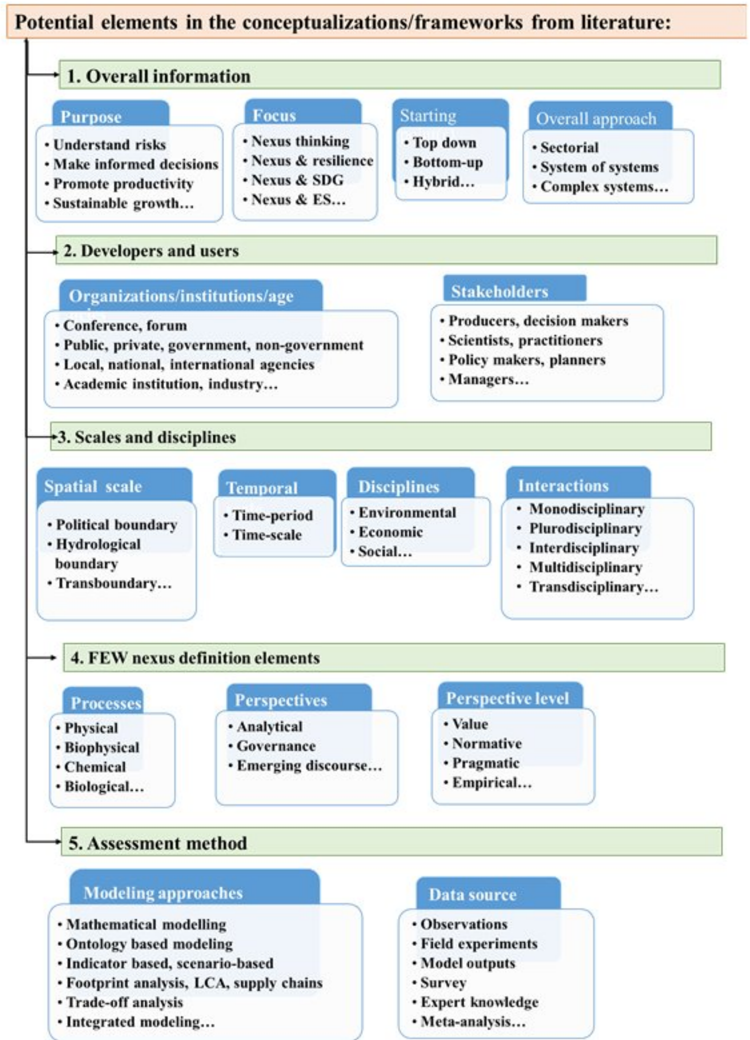


Fig. 6. Synthesis of five elements in the FEW Nexus conceptualizations and frameworks

How Can Stakeholders Conceptualize FEWS Nexus for a Project or an Application?

The stakeholder needs to choose information on the five elements summarized in Fig. 7. These five elements will provide an overview of the project or application to be conceptualized, shortlist the stakeholders involved in development and users, scales, disciplines, interactions, elements in the definition, assessment methods and data source. Choosing the five elements can be iterative. For example, if a stakeholder may choose the purpose of promoting sustainable growth using a sectorial approach while working with a scientist to represent the physical processes using mathematical modeling approach to develop FEW conceptualizations. If only data from a survey is available, the stakeholder may have to revisit the previous elements and choose accordingly.

In circumstances in which the elements in the conceptualizations are not obvious, then these elements can be chosen from the Fig. 6. After identifying the elements, the stakeholder should address the question: “Can existing conceptualizations and frameworks be used or adapted or new ones need to be developed?” To select existing conceptualizations/frameworks the stakeholder can go over the brief overview of existing conceptualization/frameworks presented in this study and get more details from the references provided in this section. If they are not suitable and depending on the available resources, either existing conceptualizations and frameworks can be adapted or new ones need to be created for a project or study. These are explained in the next section.

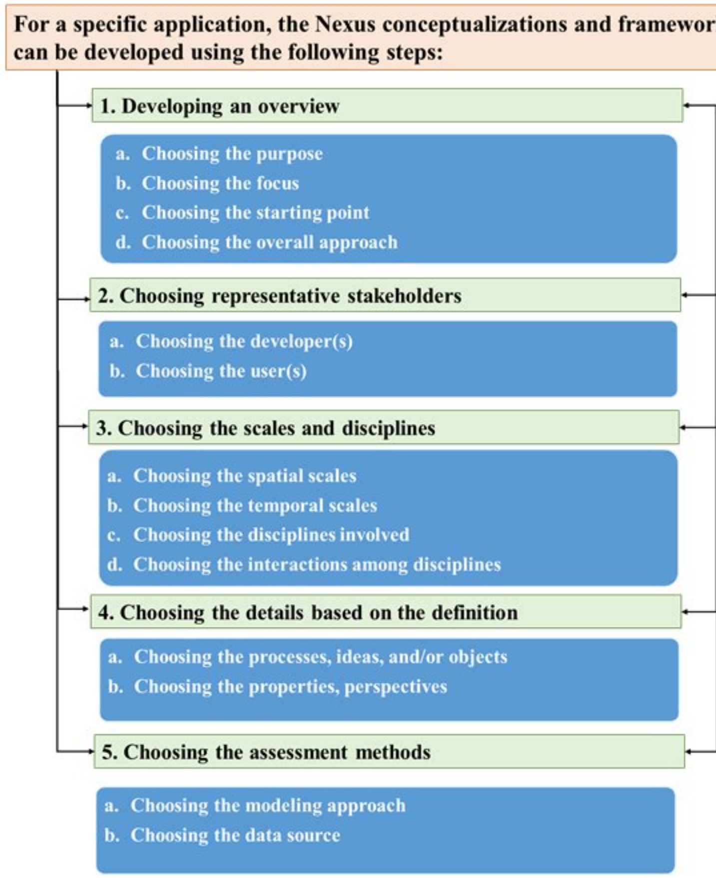


Fig. 7. Steps in developing FEW Nexus conceptualization/framework for FEW Nexus application.

FEW Nexus Conceptualizations: Simple to Complex

It can be observed that depending on the elements chosen, the conceptualizations can range from simple conceptualization with a few elements (e.g., one to three elements) to a complex conceptualization with all elements. Typical simple and complex conceptualizations are shown with examples in Figure 8.

Fig. 8a, depicts a simple FEW conceptualization with one element (Element 1). It provides with information on the focus, nodes and the processes in FEW Nexus. The example of the simple conceptualization (Fig. 8b) focuses on ecosystem services, using sectorial overall approach with food, water, energy sectors as nodes and then identifying the processes connecting them. The processes connecting the sectors are water quality degradation due to fertilizers; potential water depletion for the irrigation of crops; processing, distribution, and treatment of water for domestic use; hydropower generation; cooling water requirements at thermal energy and industrial plants; bioenergy production; energy for pumping, processing, and transporting in food sectors and many others. The example provided can be considered as the adaptation of the existing FAO conceptualization depicted in Fig. 4d.

On the other hand, a complex conceptualization includes all the five elements (Fig. 8c). In addition to the overview information in the simple conceptualization, the complex conceptualization of the FEW Nexus provides information that meets stakeholders' needs in terms of scales, disciplines, interactions, perspectives, consequences, modeling approach, and data sources. An example of a complex conceptualization (Fig. 8d) includes additional information on the five elements beyond simple overview conceptualizations. The complex conceptualization includes more overview information such as purpose (e.g., promoting productivity), a hybrid starting point approach, and a sectoral approach where sectors serve as nodes. In addition, the example states that scientists in academic institutions will be developing the conceptualization for producers and managers (Element 2). The sector connections will be physical-chemical process-based with analytical perspectives and an empirical-pragmatic level if the stakeholder chooses the purpose as promoting sustainable growth using a sectoral approach while working with a scientist to represent the physical processes using a mathematical modeling approach to develop FEW conceptualizations.

It should be noted that these steps are not exclusive to the FEW Nexus and can be applied to any set of disciplines or sectors that interact with each other. The same methodology can be followed in developing a framework for the new Nexus. Other applications could involve the COVID-19 pandemic and its effects on the food and health sectors, or climate change and its effects on resource management and the environment, to name two possible applications.

Fig. 8. Creating FEW Nexus conceptualizations with examples: Simple to Complex. This can be adapted to other Nexus conceptualizations as well.

Table 3: Potential guidelines: List of elements the stakeholders could include in their conceptual framework

Stakeholder	Systems involved	Personnel/ Organization	Definition	Scales	Assessments
Researchers/ scientists	All in the list	Academic institutions, scientific organizations	Listed in Table 1	Multiple scales	Multiple models and tools
Farmers	Bottom-up approach	Individual entrepreneurs	Production	Political (?) boundary (field scale) Time scale: day/seasonal Disciplines:	Experience-based

				economics and environmental science	
Municipal planners, managers, and consultants	Focus is Nexus and resource availability, ecosystem service, top-down and bottom-up approach	Consultant organizations/ institutions Municipal agencies	Management Governance	Political boundary (county scale), annual/decadal	Tailored models and tools (developed in-house)
Urban development	Focus is Nexus and ecosystem service, bottom-up approach	Consultant organizations/ institutions State organizations	Planning Management Governance	Political boundary (city/town scale), annual/decadal	Tailored models and tools developed in-house
Industries (e.g., agriculture and food, energy)	Focus is productivity	Research and consultant organizations/ institutions	Development Marketing Management	Discipline boundary (industry scale), annual/decadal	FEW Nexus futures
Government (administration at national, state and county levels)	Focus is on setting and meeting policy targets Top-down	Parliaments Ministries	Governance	Political scale Nation, state, county All disciplines Annual to decadal	Experience Models and tools FEW Nexus futures

While this approach has been applied to the FEW Nexus because of the urgency in addressing food-water-energy issues, it could be used in a similar way to address the climate-water-health issue or the food-environment-energy issues. Many stakeholders will come from similar functions within their sector (planning, managing, governing, research, etc.) but their specializations will change based on the topics that form the core Nexus issues. The benefit of this approach is that it is a transparent and repeatable way of developing the optimum framework for a given issue or Nexus. Two areas where this approach is likely to have substantial benefits include exploring the linkages of climate change to other sectors and exploring integrated efforts for addressing the SDGs.

Consequences of Choosing a Particular Conceptual Model/Framework

While choosing or developing new conceptualizations or adapting existing conceptualizations, stakeholders need to be aware of the uncertainties associated with the elements used (Fig. 9). These uncertainties can broadly fall into three categories based on Bentley and Anandhi (2020). In the known-knowns category, uncertainty can be known. For example, when the probability is precisely known and specified for the selected elements. The known-unknown category arises when the uncertainty is not currently known but can be obtained by further research. For example, knowledge of selected elements in the conceptualizations is obtained using higher-order expertise and in-depth knowledge requiring extensive expert's involvement. The unknowable-unknown uncertainty category represents a reasonable degree of uncertainty, which is unknown. This uncertainty is challenging to describe and include in an analysis. To model unknown unknowns, probability theory (using a set of prior distributions, updating beliefs using Bayes' rule and decision), deriving decision rules from Dempster–Shafer belief functions, using RDADE (risk-based data acquisition design evaluation) framework for

decision making by communicating uncertainty and risk, dynamic space complex time-varying interdependency dynamic models have been used (Bentley and Anandhi, 2020).

Applications of FEW Nexus Conceptualizations to Other Nexus

The elements that are currently included in the analysis of existing FEW Nexus conceptual frameworks (Fig. 6) can be useful for analyzing other Nexus applications. The steps for creating the conceptualization for a FEW Nexus are not limited to this Nexus but can be applied in other areas where a discrete body of knowledge exists and there is a societal benefit in understanding and managing the interactions between two or more these areas of concern. The procedure outlined in Figure 7 can be adapted to other Nexus definitions as well provided that the affected stakeholders', disciplines, scope of application. perspectives, and values are known. Some examples of other Nexus applications are discussed in the definitions section.

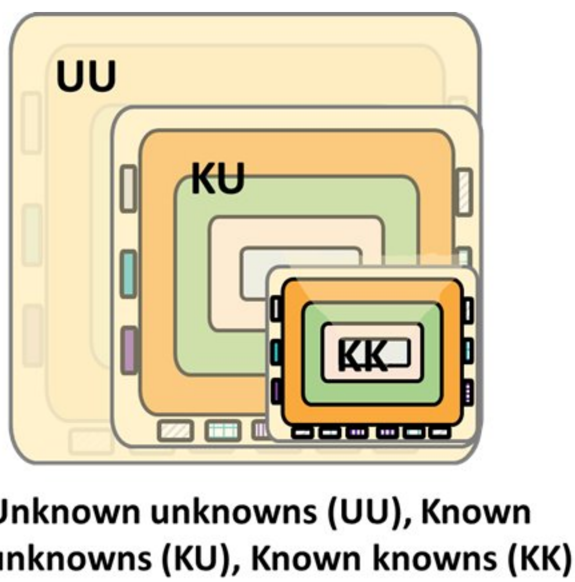


Fig. 9. Consequences of a simple or complex conceptualizations and the associated uncertainties in the interpretation of the elements.

Fig 10. Challenges, limitations, and knowledge gaps in the FEW Nexus definitions and conceptualizations.

Challenges and knowledge gaps in Nexus data analysis

In this study, we address additional challenges and knowledge gaps that are still present in Nexus definitions and conceptualizations (Fig. 10). Even with a systematic approach to the development of frameworks and definitions, gaps still exist. This is not unique to the FEW Nexus but it is a critical part of all Nexus analyses and developments. Addressing this question requires a deeper dive into some of the issues that affect the knowledge gaps of the Nexus.

1. **Who:** Verycritical to the gap analysis is who should be considered. Stakeholders have been identified in general terms but it is important to recognize those who can help close the knowledge gap.
    1. **Science:** If the scientists are looking at a Nexus tool, platform, or knowledge gap, they will be looking at detailed processes, including interactions. The gap is addressed through a conceptualization of the process-based modeling, which forms the basis for the knowledge from a deep understanding of the processes and their interactions. There are also gaps in the data that is available to provide model calibration and validation to ensure the models make a realistic connection with the frameworks and conceptualizations.
    2. **Policymaker:** If the user is a policymaker, the knowledge gap may not be related to detailed processes, but rather arises from assessing the tradeoffs at a larger scale; looking not at the specific interactions at the local scale, but rather at their implications on decision-making and for supporting relevant policies. Here, the challenge lies more in aggregating the implications at the local scale and trade-offs at a larger scale and then looking at the priorities.
    3. **General Public:** In addressing the general public, the challenges lie in understanding the need for a higher level of interaction among the primary resources and the communication needed to provide a logical basis for behavioral changes. When it comes to Nexus meta-analysis, the challenge within the general public domain involves effectively providing the needed information to the public to facilitate behavioral change. Public information and scenarios are two options with potential in this area.
    4. **Private Sector:** Here, intervention requires understanding of the implications and complexity of the systems. This is very critical as resources are mobilized and solutions identified to scale up a success story to a larger scale application. The gap in the private sector domain is related to what is sustainable and will allow proposals for viable commercial solutions (e.g., potential market for certain solutions) based on economic analysis, then integrating the solutions at a larger scale with sustainability intervention and new technologies.
2. **Where:** Has this Nexus meta-analysis been applied or is intended to be applied elsewhere? For the FEW Nexus, this involves two parts:
    1. **Defining the FEW Nexus** using the three elements.
    2. **Conceptualizing the FEW Nexus** using the five elements.

The urgency of the analysis must be considered. Taking the COVID-19 crisis as an example, the urgency to mobilize food, water, and energy is much more critical in terms of how soon we need to mobilize these resources and the implication of one resource when it comes to another of the primary resources. The COVID-19 issue with its impact on supply chains, health systems, and the economy is a Nexus problem where the principles of building a FEWs Nexus could be applied.

1. **Identifying the systems** involved:
    1. **Defining** the system, conceptualizing it, and identifying its elements. As such, we must consider the scale where Nexus knowledge gaps exist for models, data, processes, and actions. There is a limited number of models and frameworks that address the complex conceptualizations and broad definitions of the FEW Nexus. While the FEW Nexus offers a promising conceptual approach, the use of Nexus methods to support the development of socially and politically relevant policies has been limited (Sahle et al., 2019). This can be related in part to the usability gap between what scientists consider useful information and what users consider usable in decision-making (Bentley and Anandhi, 2020). The need to address conceptual tensions across disciplinary boundaries and among many stakeholders, and strategies for moving from theory to practice in operationalizing Nexus goals still exists (Endo et al., 2017). Proponents of the Nexus approach emphasize its potential for "joined-up thinking," recognizing connections, and coordinating policy and decision-making to minimize negative externalities and unforeseen consequences in tackling interconnected local to global challenges (Leck et al., 2015).
    2. **Complexity** versus simplicity and the trade-offs required between the two. This is again related to how much data is available, who is using Nexus tools and analyses, what levels of sophistication are required, and the end-use of the knowledge being generated. The knowledge gap (in terms of understanding, available end-user resources, and their uses of knowledge) results in a lack of understanding of trade-offs between complexity versus simplicity approaches. A proper balance between the two must be maintained (Shannak et al., 2018).
    3. Rigorous **uncertainty analysis** as a standard practice should be performed, which is missing in the majority of studies. This analysis is especially important when a project or process involves science and policymaking.
2. **The communication gap:** As much as the meta-analysis uses very complex tools and models to produce data and knowledge to be integrated, the communication (e.g., between developer and end-user) needs to be in a simple form to facilitate action. Regarding communications to scientists, the knowledge gap is being addressed in the emerging system-of-systems approach to the FEW Nexus. However, communication to end users, whether in the private sector, public sector, or civil society, must also be addressed. Decreasing the communication gap will increase the usability of the Nexus formulation in terms of what scientists provide as information and what end users consider important for decision-making (Anandhi and Bentley, 2018; Bentley and Anandhi, 2020). How can we simplify the message to allow a complex analysis and a universal set of approaches from scientists and academics to a diverse group of end users implementing and managing this system?
3. **The scale** of the processes and interactions varies spatially and temporally, and it is challenging to document the dynamics of this change. Very few studies address the rates and extent of these changes and their causes.

Previous studies have highlighted that transdisciplinary approaches (Bergendahl et al., 2018), development of decision modeling techniques (Namany et al., 2019), compatibility of data being used by stakeholders (Basheer et al., 2018; Xue et al., 2018), and implementation of FEW Nexus strategies on the ground (Albrecht et al., 2018) can help address the limitations in the Nexus.

Conclusions

Food, energy, and water are the fundamental elements for human survival, economic growth, and development, and understanding them is crucial for sustainable development and supporting life on earth. This paper contributes to the fundamental understanding of the FEW Nexus through the developed narrow and broad definition as well as the simple and complex conceptualizations that will help Nexus users to achieve deeper understanding and successful applications. The paper also developed the experience and principles of the FEW Nexus that can be applied more generally to other Nexus definitions and conceptualizations which are dealing with different issues. In this review, several existing definitions and descriptions of the FEW Nexus have been synthesized. Definitions and descriptions of the FEW Nexus impact how conceptualizations and frameworks are chosen. In order for stakeholders to choose or develop their definitions or descriptions, the Nexus is structured into elements with three steps: 1. The way to describe things such as processes, ideas, objects and/or resources. 2. The way the connections between things (e.g., processes) are described. 3. Specifying the chosen properties, perspectives, consequences, and approaches.Further, the three steps as a narrow and broad description were developed for stakeholders to use.

In addition to the definitions, conceptualizations and frameworks in the FEW Nexus were synthesized and analyzed. Five elements identified during the analysis of existing conceptualizations are: 1. developing an overview, 2. choosing the stakeholders involved, 3. choosing scales and disciplines, 4. choosing details in the definition, and 5. choosing the assessment methods. Depending on the number of elements chosen, the conceptualizations can range from a simple conceptualization (one to three elements) to a complex one (all elements). The paper also highlighted the consequences for stakeholders of choosing or developing new conceptualizations or adapting existing conceptualizations. These broadly fall into three categories in which uncertainty can be known. Finally, the knowledge gaps were identified and presented. Although these findings were developed for the FEW Nexus the authors believe they have broader application and can be applied for any Nexus application.

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