IWMI
Working
Paper
186

Unpacking the Water-Energy-Environment-Food Nexus: Working Across Systems

Aditya Sood, Alan Nicol and Indika Arulingam

International Water Management Institute

CGIAR
RESEARCH PROGRAM ON
Water, Land and Ecosystems

Working Papers

The publications in this series record the work and thinking of IWMI researchers, and knowledge that the Institute's scientific management feels is worthy of documenting. This series will ensure that scientific data and other information gathered or prepared as a part of the research work of the Institute are recorded and referenced. Working Papers could include project reports, case studies, conference or workshop proceedings, discussion papers or reports on progress of research, country-specific research reports, monographs, etc. Working Papers may be copublished, by IWMI and partner organizations.

Although most of the reports are published by IWMI staff and their collaborators, we welcome contributions from others. Each report is reviewed internally by IWMI staff. The reports are published and distributed both in hard copy and electronically (www.iwmi.org) and where possible all data and analyses will be available as separate downloadable files. Reports may be copied freely and cited with due acknowledgment.

About IWMI

IWMI's mission is *to provide evidence-based solutions to sustainably manage water and land resources for food security, people's livelihoods and the environment.* IWMI works in partnership with governments, civil society and the private sector to develop scalable agricultural water management solutions that have a tangible impact on poverty reduction, food security and ecosystem health.

IWMI Working Paper 186

Unpacking the Water-Energy-Environment-Food Nexus: Working Across Systems

Aditya Sood, Alan Nicol and Indika Arulingam

International Water Management Institute

The authors: Aditya Sood is a Senior Project Engineer at the University of California, Merced, California, USA; He was Senior Researcher – Integrated Hydrological Modelling at the International Water Management Institute (IWMI), Colombo, Sri Lanka, at the time this research study was conducted; Alan Nicol is Strategic Program Leader – Promoting Sustainable Growth at the East Africa and Nile Basin Office of IWMI, Addis Ababa, Ethiopia; and Indika Arulingam is Research Officer (Social Scientist) at IWMI, Colombo, Sri Lanka.

Sood, A.; Nicol, A.; Arulingam, I. 2019. *Unpacking the water-energy-environment-food nexus: working across systems.* Colombo, Sri Lanka: International Water Management Institute (IWMI). 43p. (IWMI Working Paper 186). doi: 10.5337/2019.210

/ food production / food security / energy generation / energy sources / water availability / water security / water institutions / water policy / water governance / nexus / ecosystem services / stakeholders / socioeconomic environment / environmental impact assessment / risk management / sustainability / legislation / resource management / resource allocation / decision making /

ISSN 2012-5763
e-ISSN 2478-1134
ISBN 978-92-9090-883-8

Please direct inquiries and comments to: *IWMI-Publications@cgiar.org*

A free copy of this publication can be downloaded at www.iwmi.org/publications/iwmi-working-papers

Acknowledgements

The authors gratefully acknowledge the valuable comments and feedback provided by David Wiberg (Hydro-Informatics Leader [HIL], International Water Management Institute [IWMI]) and other anonymous reviewers.

Donors

This research was carried out as part of the CGIAR Research Program on Water, Land and Ecosystems (WLE) and supported by Funders contributing to the CGIAR Trust Fund (https://www.cgiar.org/funders/).

Contents

Executive Summary

The nexus between water, energy and food (WEF) has been well recognized. The few theoretical tools that exist try and optimize resource use between sectors, but usually only between two sectors. There is an enhanced level of interest in more complex relationships and, in particular, ways of addressing them in a more systematic manner under a 'nexus' approach. To prepare for broader discussion at the United Nations Conference on Sustainable Development in 2012, the German government organized a conference on "The Water, Energy and Food Security Nexus – Solutions for the Green Economy" which was held in Bonn in November 2011. Since the 2011 Bonn nexus conference, numerous reports by different organizations have been published highlighting the importance of a nexus approach in solving development issues. According to a review by the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP) of existing literature, WEF nexus issues can be grouped under three themes: (i) nature of relationships between water, energy and food sectors (their analysis suggests that such relationships are usually in terms of resource use efficiency and most of the studies exist between two systems such as water-energy or water-food or energy-food); (ii) institutional and policy dimensions (though their review suggests a lack of sufficient literature in this area); and (iii) implications for policy development and actions to address security issues.

Most of the frameworks developed are inclined towards theory. They share a common theme of adopting a systems approach to tackling (in) security issues across water, energy and food security sectors, and some also include land and minerals in their security framework. The existing frameworks link the WEF systems within their biophysical boundaries and suggest that they work within certain institutional confines. However, they do not delve into the complications that arise due to the confluence of political economy and governance factors, human behavior and perceptions, and institutional issues. The focus within each framework also differs depending on the organizational origin of the framework, e.g., the Bonn 2011 Nexus Conference framework is water-availability centric, the World Economic Forum 2011 framework is risk centric, and the framework by the International Centre for Integrated Mountain Development (ICIMOD) is ecosystem-services centric. This paper builds on these existing frameworks and seeks to find ways of further operationalizing the WEF concept to develop "workable" approaches that can be used to assist in identifying policy measures, defining and setting desirable policy outcomes, establishing measures of success in achieving specific outcomes, and identifying core assumptions and risk factors involved. We consider environment as one of the systems in nexus and define nexus as interactions between Water-Energy-Environment-Food (WEEF) systems. This paper demonstrates how a more quantified approach to interdependencies and relationships between water, energy, environment and food can be achieved, and how this could help link biophysical systems with social systems in pursuit of developing indices that can be used for comparative studies between regions or across time scales.

We first look at the definitions and understanding of key core concepts related to the "Nexus" discussion. Some of the discussion is as follows:

<u>Nexus</u>: The discourse on nexus has been mostly driven by the need to be more efficient with resource use in the face of growing demand and increasing relative scarcity. Most of the above frameworks believe that water is central to the provision of other resources in the nexus (i.e., energy and food) and hence water insecurity is a greater threat. The goal of a nexus approach is to understand the complex relationships between the water, energy, environment and food systems, not just from a

biophysical perspective but also from political-economy and socio-ecological systems perspectives, where perceptions of resource security (and value) are shaped, norms and thresholds are determined, and trade-offs and issues of access to resources are negotiated.

Security: Most nexus frameworks focus on security as a central concept, traditionally defined in terms of water, food and energy security. In the past, security has been looked at in terms of national safety, and the capacity to generate sufficient water, food and energy needs to meet national demand. The use of trade between (and within) national entities has been one of the most common ways of ameliorating insecurities and achieving demand-supply equilibrium. Security may also refer to unequal distribution of resources, even though there is no absolute shortage. From a purely human perspective, a certain minimum threshold to meet basic human needs may be defined as a basic human security. Security is a dynamic concept that is dependent on changing ecosystems, human perceptions, political economy and regional trade. Regional security has to be looked at through a global prism. Security at regional level also depends on trading relationships between regions and rest of the world. Security does not mean having all the resources all the time. Due to unequal distribution of resources, it is not realistic for each region to try to be self-sufficient in all the resources. Security implies reducing risks to a level that is acceptable to a society.

Risk: Risk is an uncertainty that can be measured. Risk is not an absolute term but rather requires the involvement of stakeholders from all sectors to define risks. Risks may be seen as acceptable, tolerable and intolerable, and it needs stakeholder participation to define these levels and trade-offs that need to be made to reach acceptable risk levels.

Sustainability: From an ecosystem perspective, sustainability implies maintaining a long-term ecological balance. In traditional security discourse, sustainability implies uninterrupted flows of resources for human and economic development. There are many questions embedded within the debate of sustainability and reflect the complexity of managing competing demands.

In terms of the WEEF nexus, the question to be addressed can be framed as: “How can decision-makers develop approaches to managing and using water, food and energy resources that lie within publicly-acceptable risk thresholds (social, political, environmental and economic) while ensuring the sustainable production of goods and services in order to maintain acceptable levels of social and economic development?” The question defined above is very broad. The framework that effectively helps to answer the question should be able to include topics related to security, biophysical, finance and trade, socioeconomic, institution and governance, and stakeholder participation.

In this paper, a WEEF nexus framework is suggested as an “ARC” concept. Central to the development of the nexus framework is the idea of “nexus security”, which needs to be quantified to make the framework operational. “Nexus security” is represented by perceived risk. Risk to society may be quantified by “Nexus risk indicators”, which are defined by society’s “access reliability”, “resilience to shock”, and “capacity to change” (ARC). “Access reliability” implies consistency in access to the resources. This is not a static variable, but also depends on a society’s demand. There is access reliability as long as a society’s demand can be met within available resources and infrastructure constraints, and that resources are accessible to all sections of society. “Resilience to shock” implies society’s ability to resist and/or recover from adverse conditions. Such a situation may arise due to either a natural calamity such as a drought or flood, or due to political or financial unrest in any part of the world. “Capacity to change” is the coping capacity of a society and implies society's ability to adapt to change, either through supply-side management or demand-side management. A nexus security index may then be identified as an aggregate of the indices that define the ARC across nexus systems. Nexus security is achieved when perceived risks are within levels acceptable to a society. These three attributes collectively indicate how robust a system is. The three attributes of ARC depend on "resource availability" and "resource accessibility and affordability". Local resource availability may also be classified as "natural" (procured directly from natural systems) and "manufactured" (developed from natural services). The resource availability, accessibility and affordability that help define the attributes of ARC are further dependent on the drivers such as biophysical, institutional and socioeconomic systems.

The framework discussed above merges issues from two system perspectives. One is in terms of nexus systems (such as water, energy, environment, food, etc.) and the other is in the form of integration of biophysical, institutional and socioeconomic systems. The advantage of building up nexus security from a two-system perspective is that it helps in identifying problems at multiple levels within a system, but in a holistic way. Such multi-level analysis helps in providing advice to those engaged in policy development to achieve system-level security. The framework is quantified using multiple indicators across the systems. The indicators help in defining strengths and weaknesses of nexus at different levels within each system. These indices are further used to build a multi-dimensional nexus scorecard. This scorecard provides a snapshot of "weak links" within a system, and becomes a useful tool with which to engage national-level stakeholders in deliberations on policy development and the negotiation of trade-offs. In one dimension, this framework integrates biophysical, institutional and socioeconomic systems. In another dimension, it integrates water, energy, environment and food from a resource security perspective. In a third dimension, it calculates society's collective risk due to the lack of availability and/or lack of access to goods and services provided by these systems. Collective risk is the perceived risk, which is supported by "Nexus Risk Indicators" (NRIs). NRIs are defined by "access reliability", "resilience to shock" and "capacity to change". Sustainability requires an understanding of risk over time. Hence, the fourth dimension is analyzing resource risk and security over time to define sustainability under a specific WEEF nexus. The availability of the ecosystem services and the way they are used define the sustainability of the entire system. Historical data can be used to ascertain the sustainability trends within the nexus system. Sustainability can be measured in terms of reliability, resilience and vulnerability.

The three ARC indices help define the overall Nexus Security Risk Index (NESRIX). Such a scorecard can then help to support decision-making at national/regional levels, unpacking complexity(ies) and providing a tool to engage policy makers in constructive dialogue on: (i) understanding water security in relation to other sectors and the multiple interactions between them; and (ii) identifying 'soft spots' within nexus systems that need to be addressed to improve development outcomes, particularly for the poorest and most marginal. The matrix itself can be applied either within an administrative boundary or a basin unit, or even used as a comparative tool between regions or countries. The indices developed can be plotted along time scales to monitor nexus development and its sustainability over time. The indices may be linked to scenario models to quantify the impacts of policy decisions related to governance, institutions and investments in the nexus systems. The next step would be to implement this framework in selected countries and to undertake a comparative analysis of outputs by country.

INTRODUCTION

Numerous studies have shown the interdependence of the water, energy and food sectors. This includes energy production on water, and water provision on food production (McCornick et al. 2008; Bazilian et al. 2011; Ringler et al. 2013; Arent et al. 2014; Weitz et al. 2014). The few theoretical tools that exist try and optimize resource use between sectors, but usually only between two sectors, such as optimizing water releases for hydropower and agricultural production (Chatterjee et al. 1998; Barbier 2003; Cai et al. 2003a) or agriculture and ecosystems (Cai et al. 2003b; Blanco-Gutiérrez et al. 2013) or energy and ecosystems (Ward and Lynch 1996; Wu et al. 2013). Currently, there is an enhanced level of interest in more complex relationships and, in particular, ways of addressing them in a more systematic manner under a 'nexus' approach (Hoff 2011; Howells et al. 2013; Ringler et al. 2013). A review by UNESCAP (2013) showed 10 policy-based conferences, three academic conferences, and at least 10 documents and initiatives by major organizations on 'nexus' ideas since 2011. Scientists and policy makers have long known of the complex interdependencies between energy and food production and water availability, access and use on the one hand, and the impact on the environment of changes in these interrelationships on the other. However, more often than not, these sectors continue to be managed discretely as if there are few interdependencies and potential negative trade-offs in not managing them as one interrelated system.

As a result and in spite of theoretical analyses (Hoff 2011; ICIMOD 2012; Bizikova et al. 2013; FAO 2014; Weitz et al. 2014), there is a widespread lack of more integrated approaches to resource management across key water, energy and food sectors. The impacts on the environment from energy and food production have been considered externalities and dealt with separately as a "cleanup" or "restoration" project – rather than being addressed at the 'pre-production' stage in planning different management approaches. This silo-based approach within increasingly complex system dynamics as the demand for water and other resources increases results from institutional inertia and existing policies encouraging 'closed-loop' decision-making (Liu et al. 2015; Welsch et al. 2014; Ringler et al. 2013). Recent crises, including the food crisis of 2007-2008 (Headey et al. 2009), has pointed in the other direction towards our understanding of complex interrelationships requiring more complex 'nexus' approaches to resource use planning and management.

As a consequence, and to prepare for broader discussion at the United Nations Conference on Sustainable Development in 2012, the German government organized a conference on "The Water, Energy and Food Security Nexus – Solutions for the Green Economy" which was held in Bonn in November 2011. The conference addressed the role of systems thinking as a means of tackling multiple 'securities' (for water, energy and food) and ecosystem sustainability issues, including the importance of taking a multi-stakeholder and pro-poor approach. The focus of the conference[1] was on three thematic areas: (i) social: accelerating access – integrating the bottom of the pyramid (a human dimension); (ii) economic: creating more with less (an economic dimension); and (iii) ecologic: investing to sustain ecosystem services (an ecological dimension). One of the outcomes of the Bonn conference was the launch of the nexus platform (https://www.water-energy-food.org/nexus-platform-the-water-energy-food-nexus/ - last accessed on January 31, 2019)

[1] The event encapsulated a body of thinking predating the 'crisis' that had urged stronger, more integrated management of water, energy and food systems. Sustainability and resource management and use efficiency was first launched internationally by the Brundtland Commission, set up after the United Nations Conference on the Human Environment held in Stockholm, Sweden, in 1972. Their work, "Our Common Future", provided the momentum for the United Nations Conference on Environmental and Development (UNCED), also known as the Rio Summit or Earth Summit in 1992, followed by the World Summit on Sustainable Development in Johannesburg, South Africa, in 2002 (also known as Rio+10) and the United Nations Conference on Sustainable Development in Rio, Brazil, in 2012 (also known as Rio+20).

to develop a knowledge network and act as a clearinghouse for information on nexus issues. Since the 2011 Bonn nexus conference, numerous reports by different organizations have been published highlighting the importance of a nexus approach in solving development issues (Flammini et al. 2014; ADB 2013; UNESCAP 2013). Key nexus frameworks that have been developed since then include the following:

- A framework constructed by the Stockholm Environment Institute (SEI), while developing the background paper for the Bonn conference (Hoff 2011), highlighted the role of investment in sustainable ecosystem services, the green economy (i.e., resource use efficiency), and integrating the poor in water, energy and food (WEF) frameworks. In their framing of the nexus, water availability is central to water supply security, food security and energy security. Their framework suggests the need for multi-level governance and policies that are coherent across scales.
- An ecosystem-based framework was produced by the International Centre for Integrated Mountain Development (ICIMOD) in 2012 within the context of South Asia and the goods and services provided by the ecosystems of the Himalayan Region (ICIMOD 2012). These include: (i) provisioning services such as food, fuel, freshwater and minerals; (ii) regulating services such as climate and water, and biological control; (iii) supporting services such as recharging groundwater and soil formation; and (iv) cultural services such as traditional knowledge and recreation. South Asia presents a unique perspective on the WEF nexus as it accommodates a disproportionately large number of the global poor and hence has a substantial percentage of the global population lacking access to water, energy and food. The Himalayan massif generates some of the largest rivers in the world with high potential for hydropower generation and provision of water for some of the world's most fertile floodplains. However, due to high population density, there is systemic competition between water, energy and food production. The ICIMOD framework suggests ways of enhancing water, energy and food security through sustaining Himalayan ecosystem services.
- The 2013 position paper by the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP) considers water, food and energy as three "global goods", which are traded globally with global implications, and the scarcity of which engenders human insecurity. The paper suggests that the role of a nexus approach is to improve energy, water and food security, and to deal with "externalities across the sectors" and "support a transition to sustainability" (UNESCAP 2013). In dealing with sustainability, the role of ecosystems is critical. The paper suggests a greater focus on ecosystem services instead of focusing on just economic development. The paper looks at each system in terms of security and defines "nexus" challenges in each sector for Asia and the Pacific region. Within the water system, environmental stress, climate change, water demand and the groundwater table are key nexus challenges. In energy systems, oil scarcity, alternative energy and nuclear power plant proliferation are of concern. In food systems, ageing irrigation infrastructure, low agricultural productivity, environmental stress, land grabbing, food trade and climate change are key nexus challenges. Some of the nexus issues mentioned in the paper include biofuel production, hydropower production, water for thermoelectric power generation, water and energy for irrigation, food trade and virtual water trade, land availability for food production, and energy for water production. The recommendations include deepening knowledge and building institutions to understand the nexus and making the green economy a core of development.

- Without suggesting any framework, the Asian Development Bank (ADB) report on the water-food-energy nexus (ADB 2013) considers water security as central to development in Asia. The report focuses on strong linkages in the water-food-energy nexus and espouses new metrics for water economics to change perceptions on water in terms of water pricing and water rights in Asia.
- The Food and Agriculture Organization of United Nations (FAO) suggested using a WEF nexus approach for managing trade-offs, and building synergies for cost-effective and more integrated planning (FAO 2014). According to their report, since agriculture is responsible for 70% of water withdrawals and 30% of global energy consumption, a WEF nexus framework needs development from a food security angle, defined as comprising four dimensions – availability, access, stability and utilization. In their nexus approach, stakeholder involvement for evidence, scenario development and response options are central to the framework. This links different goals and interests along with drivers of change in WEF relationships to policies related to natural capital (such as water, land and energy) and economic resources (such as labor and capital).
- The United Nations Economic Commission for Europe (UNECE) developed a water-food-energy-ecosystems nexus-based assessment approach to tackle transboundary basin "frictions and conflicts" (UNECE 2014). The report suggests using an ecosystem service approach to assess constraints and opportunities, and to identify market-based transactions to help achieve security. They emphasize developing indicators that fall along a continuum from purely qualitative to highly quantitative methodologies. Such indicators are developed to assess insecurities so that these can be mitigated.
- In 2013, the International Institute for Sustainable Development (IISD) reviewed the existing WEF frameworks and highlighted three frameworks (Bizikova et al. 2013): (i) Bonn 2011 Nexus Conference Framework, (ii) World Economic Forum 2011 Framework (WEF 2011), and (iii) ICIMOD Framework. They subsequently developed their own framework, which takes a more practical approach, considering utilization of each sector as central to the nexus (Bizikova et al. 2013). The framework considers ecosystem goods and services as critical to a WEF framework and requires a "well-functioning" ecosystem. In the framework, various combinations of elements of access and availability of each resource can be formed for its security. These combinations can be chosen based on the regional context. For example, food access can be either through the barter system, purchase or self-production, whereas food availability depends upon food production or food processing and packaging or food distribution and retail, etc. These could lead to nine possible combinations. The three resource securities are influenced by natural and built systems, which are further influenced by institutional and governance factors.

According to a UNESCAP review of existing literature, WEF nexus issues can be grouped under three themes: (i) nature of relationships between water, energy and food sectors (their analysis suggests that such relationships are usually in terms of resource use efficiency and most of the studies exist between two systems, such as water-energy or water-food or energy-food); (ii) institutional and policy dimensions (though their review suggests a lack of sufficient literature in this area); and (iii) implications for policy development and actions to address security issues. Except for a few exceptions (such as recognition of the energy-water nexus at state level in the USA by at least 9 states - Arizona, California, Colorado, Connecticut, Nevada, South Dakota, Washington, West Virginia and Wisconsin [NCSL 2014]), there are constraints in understanding the actions and their implications in the WEF nexus.

Most of the frameworks developed are inclined towards theory. They share a common theme of adopting a systems approach to tackling (in)security issues across water, energy and food security sectors, and some also include land and minerals in their security framework (UNESCAP 2013). The existing frameworks link the WEF systems within their biophysical boundaries and suggest that they work within certain institutional confines. However, they do not delve into the complications that arise due to the confluence of political economy and governance factors, human behavior and perceptions, and institutional issues. For example, to define security within each system, it is necessary to understand differing power structures, human perceptions of risk and vulnerability, and their responses in terms of resilience and adaptation. The fact that the concept of security is not static and changes across different institutional and policy environments (in relation to water, energy and food) requires that any further modeling of WEEF responses is context-specific and, to an extent at least, relative to the cultural and institutional boundaries within which the demand for water, energy and food is generated. The focus within each framework also differs depending on the organizational origin of the framework, e.g., the Bonn 2011 Nexus Conference framework is water-availability centric, the World Economic Forum 2011 framework is risk centric, and the ICIMOD framework is ecosystem-services centric.

This paper builds on these existing frameworks and seeks to find ways of further operationalizing the WEF concept to develop "workable" approaches that can be used to assist in identifying policy measures, defining and setting desirable policy outcomes, establishing measures of success in achieving specific outcomes, and identifying core assumptions and risk factors involved. We consider environment as one of the systems in nexus and define nexus as interactions between Water-Energy-Environment-Food (WEEF) systems. This paper demonstrates how a more quantified approach to interdependencies and relationships between water, energy, environment and food can be achieved, and how this could help link biophysical systems with social systems in pursuit of developing indices that can be used for comparative studies between regions or across time scales. To make the framework policy relevant, the next section, *Understanding the Concepts*, defines some of the core concepts related to the terms nexus, security, risk and sustainability. The section *Defining the Questions* discusses the type of questions such a framework should address and formulates policy questions relevant to the WEEF nexus. The section *Developing the Nexus Framework – the "ARC" Concept* outlines a WEEF framework while the section *Applying the Nexus Framework across Systems and Institutions* discusses the framework in terms of its operationalization across systems and institutions. A multi-dimensional matrix is suggested that quantifies different components of the nexus. Finally, the *Conclusions* section provides future research requirements and outlines any shortcomings in the approach.

UNDERSTANDING THE CONCEPTS

Nexus

It is critical to revisit the precise definition of 'nexus', especially in terms of relationships between resources. The discourse on nexus has been mostly driven by the need to be more efficient with resource use in the face of growing demand and increasing relative scarcity. Most of the above frameworks believe that water is central to the provision of other resources in the nexus (i.e., energy and food) and hence water insecurity is a greater threat (Allouche et al. 2014). As a result, water tends to constitute the major focus in many nexus debates. The nexus is viewed, in particular, in terms of synergies and trade-offs between competing resource-use systems. In reality, resource availability and access are complicated and shaped by economic, legal, social and political structures and rules in which resulting scarcities may be relative to the position held within such structures, i.e., scarcities arising are rarely absolute, but are rather relative to the capacity to access resources, including as costs of resources rise. Synergies and trade-offs, therefore, require the active involvement of stakeholders in all the systems to maintain governance over emerging trade-offs that can insist upon the achievement of equitable outcomes. Without such engagement, elite capture of resources can take place with serious social, environmental and economic consequences. Key stakeholders include policy makers, the private sector, resource user groups and academicians. Therefore, the goal of a nexus approach is to understand the complex relationships between the water, energy, environment and food systems, not just from a biophysical perspective but also from political-economy and socio-ecological systems perspectives, where perceptions of resource security (and value) are shaped, norms and thresholds are determined, and trade-offs and issues of access to resources are negotiated.

Security

Most nexus frameworks focus on security as a central concept, traditionally defined in terms of water, food and energy security. In the past, security has been looked at in terms of national safety and the capacity to generate sufficient water, food and energy needs to meet national demand. The use of trade between (and within) national entities has been one of the most common ways of ameliorating insecurities and achieving demand-supply equilibrium. The 1990s witnessed an increase in environmental security debates linked to climate change and the impact of extreme weather events. Environmental security included arguments that increasing scarcities would drive conflict at different levels, including a "water wars" thesis under which nation states would eventually seek recourse to violent conflict to secure water supplies (mirroring arguments about oil and energy security from the 1970s). These debates have subsequently been challenged on many levels, and there is very little evidence of any major conflict occurring solely as a result of water insecurity. Nevertheless, the fear of scarcity of water and other resources remains a driving force for discussions on security.

At the same time, security may also refer to unequal distribution of resources, even though there is no absolute shortage (Mehta 2010). From a purely human perspective, a certain minimum threshold to meet basic human needs may be defined as a basic human security. The basic human needs concept was introduced in the International Labour Organisation's World Employment Conference in 1976 (Jolly 1976) to measure absolute poverty in developing countries. This originally included food (water), shelter and clothing, but has been broadened to include notions of well-being, health, and economic and social development. The following are traditional definitions of security for water, energy, environment and food:

- **Water security** is defined as "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" (UN-Water 2013).
- **Energy security** is defined by the International Energy Agency (IAE) as uninterrupted availability of energy sources at an affordable price. IAE breaks up energy security into (i) short term – the ability of the energy system to react promptly to sudden changes in the supply-demand balance, and (ii) long term - timely investments to supply energy in line with economic developments and environmental needs (*http://www.iea.org/topics/energysecurity/* - last accessed on January 5, 2015).
- There is less consensus on a definition of **environmental security**. The United Nations Environment Programme (UN Environment) links environmental security and risk to national security that may arise due to environmental degradation, inequitable access to natural resources and movement of hazardous material across the borders (*http://www.unep.org/roe/KeyActivities/EnvironmentalSecurity/tabid/54360/Default.aspx* - last accessed on September 28, 2016). It is also defined as the protection of important ecosystem services and assurance of a supply of natural resources, including water, soil, energy and minerals, in order to enable continued economic and social well-being (http://www.environmentandsecurity.org/view/article/167611/ - last accessed on January 5, 2015).
- According to the definition provided at the World Food Summit, 1996 (and reiterated by FAO for the United Nations Sustainable Development Goals [SDGs]), **Food security** exists "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (*http://www.fao.org/sustainable-development-goals/overview/fao-and-the-post-2015-development-agenda/food-security-and-the-right-to-food/en/* - last accessed on January 31, 2019).

The security definitions of water, energy, environment and food as stated above can be interpreted to have broadly four interlinked themes as shown in Table 1.

In a traditional sense, when security is discussed, it is to sustain the availability of resources. In such a discourse, the availability of resources and hence the security issue is considered as static, and the focus is on developing infrastructure to secure availability. In reality, security is a dynamic concept that is dependent on changing ecosystems, human perceptions, political economy and regional trade. The perception of what is necessary for sustenance, along with changing resilience and adaptation approaches undertaken by societies, alters accepted thresholds of security. These thresholds are further influenced by power structures, institutions and governance systems within countries and regions. Finally, regional security has to be looked at through a global prism. Security at regional level also depends on trading relationships between regions and the rest of the world. The Middle East and North Africa (MENA) region and food imports is a case in point. Existing limited freshwater availability in the region is insufficient to enable food security through local production, so food security is achieved via the importation of food commodities, especially those that have a large water footprint. These imports of virtual water (Allan 1997) demonstrate ways in which nexus trade-offs are also embedded in wider global systems. Security may, therefore, be understood as a state where the system(s) operate within levels of perceived risk that a nation and/or region is willing to accept. The import of large amounts of virtual water in the form of food trade suggests acceptance of the risks involved in moving from own production for food security to reliance on global trade systems. Security does not mean having all the resources all the time. Due to unequal distribution of resources, it is not realistic for each region to try to be self-sufficient in all the resources. Security implies reducing risks to a level that is acceptable to a society (OECD 2013).

TABLE 1. Interpretation of security definitions of water, energy, environment and food.

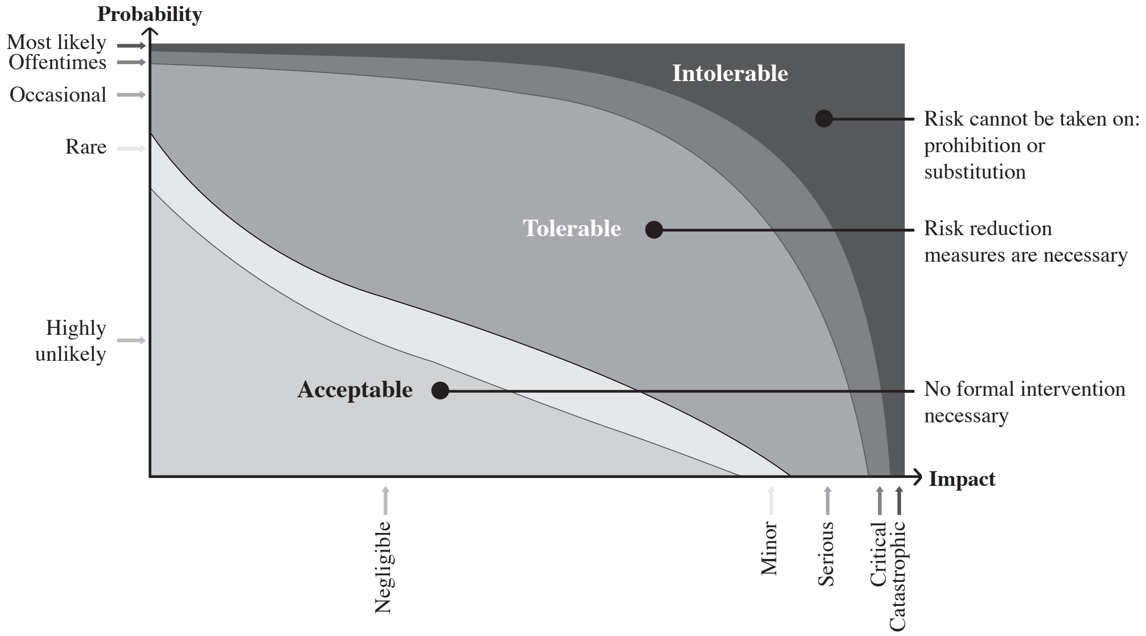
Security type	Availability	Access	Affordability	Sustainability and ecosystem services
Water	Adequate quantities	Sustainable access	Economic and social costs of access	Sustainable access Sustaining livelihoods, human well-being and socioeconomic development
Energy	Availability	Access to clean, reliable and affordable energy services	Affordable price	Uninterrupted - Economic development - Cooking and heating, lighting, communications and productive uses
Environment	Supply of natural resources	Inequitable access	Inequitable access	Environmental degradation and movement of hazardous material
Food	Sufficient	Physical access	Economic access	At all times Dietary needs and food preferences for an active and healthy life

Risk

"*Risk perception and tolerance depend on a person's likelihood of harm, control over harm, extent of harm or hazard, voluntariness of exposure to possible harm, and trust in the sources of risk information*" (WWAP 2012)

Occasionally, the terms 'risk' and 'uncertainty' are used interchangeably. However, from a natural resource management practice, it is critical to understand the difference between these terms. Risk is an uncertainty that can be measured (OECD 2013). While natural resource managers can develop long-term plans to handle risks (known), they can only handle uncertainty (unknown) by developing flexible, adaptable systems. Risk is not an absolute term but rather requires the involvement of stakeholders from all sectors to define risks. Risks may be seen as acceptable, tolerable and intolerable (as shown in Figure 1), and stakeholder participation is required to define these levels and trade-offs that need to be made to reach acceptable risk levels.

FIGURE 1. Levels of risk.



Source: OECD 2013.

Sustainability

Finally, there is the question of sustainability. From an ecosystem perspective, sustainability implies maintaining a long-term ecological balance. In traditional security discourse, sustainability implies uninterrupted flows of resources for human and economic development. Can there be long-term sustainable food-water-energy production and use? If so, what is the measure of sustainability? Should the matrix of sustainability measurement be quantity based or value based? Can there be an ecological balance given rising demands on systems? If sustainability implies generating more value without 'over-exploiting' resources, what is the value/exploitation threshold that is acceptable? This may be a policy/political-economy question and relates to how much we value the ecosystem 'services' described – and hence which services we privilege over others – or how much of a decline in resources or inequality of resource distribution we are willing to accept. These are key questions embedded within the debate of sustainability and reflect the complexity of managing competing demands. IISD mentions "well-functioning" ecosystems, which raises the question of which scale of functioning (so which precise ecosystem is referred to) and therefore what we mean by "well-functioning".

DEFINING THE QUESTIONS

Based on the World Economic Forum reports over the last few years (WEF 2016, 2017, 2018, 2019), water, climate change, extreme weather events and food, along with income disparity and governance, fall within the top ten risks. According to the reports, risks that are "high impact and high likelihood" are mostly related to the environment and the economy. This puts the energy sector also at risk (of system failure) since water is an important component in energy production (as reported in Rodriguez et al. 2013). Occurrence of severe weather events, failure to adapt to climate change and water crises are among the top ten issues in most of the years (Box 1). What this implies is that lack of access to water (exacerbated by climate change) could be a bigger concern to achieving WEEF security, at least from the value perspective of these institutions.

Box 1. Key challenges faced by the world.

"Environmental risks continue to dominate the results of our annual Global Risks Perception Survey (GRPS). This year, they accounted for three of the top five risks by likelihood and four by impact. Extreme weather was the risk of greatest concern, but our survey respondents are increasingly worried about environmental policy failure: having fallen in the rankings after Paris, 'failure of climate-change mitigation and adaptation' jumped back to number two in terms of impact this year. The results of climate inaction are becoming increasingly clear. The accelerating pace of biodiversity loss is a particular concern. Species abundance is down by 60% since 1970. In the human food chain, biodiversity loss is affecting health and socioeconomic development, with implications for well-being, productivity, and even regional security."

Source: WEF 2019.

In our annual Global Risks Perception Survey, **environmental** risks have grown in prominence in recent years. This trend has continued this year, with all five risks in the environmental category being ranked higher than average for both likelihood and impact over a 10-year horizon. This follows a year characterized by high-impact hurricanes, extreme temperatures and the first rise in CO_2 emissions for four years. We have been pushing our planet to the brink and the damage is becoming increasingly clear. Biodiversity is being lost at mass-extinction rates, agricultural systems are under strain and pollution of the air and sea has become an increasingly pressing threat to human health.

Source: WEF 2018.

Due to unsustainable development, we have reached the stage where the biggest constraint to economic development is resource limitation. This is made worse due to resource inequalities, where wealth is concentrated in limited hands. WEF (2014) discussed four perceptions held by experts and decision-makers regarding natural resources: (i) threats of material exhaustion, (ii) concern about rising costs, (iii) long-term abundance, and (iv) social injustice focused on distributional challenges. The reality is more complex. The reality probably involves all the above perceptions. Some of these perceptions are scale dependent and site specific. For example, there may be scarcity of a commodity locally but abundance globally. The research conducted by the World Economic Forum shows that the role of technology, policies and prices is underestimated. Future technologies are difficult to predict, at least in the long term. Prices are dependent on complex value chains and political economy. Also, there is high uncertainty in government policies. Human preferences, values and behavior change over time. Further, inequality also needs to be considered when dealing with development. The distributional issues are as important as the availability of resources. The issue of disproportionate distribution is both an inter- and intra-country problem. The research conducted also found that economic growth has a much bigger impact on resource demand than does population growth, especially at a global scale, thus suggesting that major inequalities are generated by (non-inclusive) growth. The interconnection between different resources leads to the spreading of risks between different sectors or stakeholders. Also, financial systems and services are key to the nexus approach, especially in reducing energy and food security threats. Finally, the unsustainability of ecosystems may become the constraining factor in providing services to humanity. Since this is affecting business, more private sector actors are getting involved in managing ecosystems sustainably. However, the private sector perceives and internalizes this risk and tries to commodify and value these systems in order to protect them.

In terms of the WEEF nexus, the question to be addressed can be framed as: "**How can decision-makers develop approaches to managing and using water, food and energy resources that lie within publicly-acceptable risk thresholds (social, political, environmental and economic) while ensuring the sustainable production of goods and services in order to maintain acceptable levels of social and economic development?**" Approaches may include institutions and governance systems that engage in multi-stakeholder consultations (across the public-to-private spectrum) to ascertain what the 'acceptable levels' of risk are, and the threshold levels for equitable resource distribution across society, where this is not only across economic classes but also gender boundaries. Since all water, energy and food depends upon services provided by ecosystems, the sustainability of ecosystems is similarly central to long-term security. Finally, development is a subjective construct that needs the active participation of stakeholders in different contexts to agree, determine and, where necessary, agree on the measures for desired outcomes.

The question defined above is very broad. The framework that effectively helps to answer the question should be able to include the following topics:

- *Security*: The framework needs some sort of common indicator to compare different securities. A risk-based indicator that encompasses biophysical scarcity, and also the ability of institutions and governance systems to help society to adapt to crises can be a useful metric for trade-off negotiations between stakeholders. This is also known as adaptive capacity or second-order scarcity (first order being resource scarcity; second order being the ability to adapt to changes in variability of resource availability) (Ohlsson and Turton 2000). For a gender and poverty-sensitive analysis, the security indicator will have to include these two dimensions by including resource distribution among different economic classes and gender (depicted by indicators such as the Gini coefficient). For effective negotiations among stakeholders, the framework should be able to define human security and handle risk analysis within each system.

- *Biophysical (and the ecosystem services)*: The first step in any holistic analysis is accounting. Some of the basic information that is required is quantification of the production of water, energy and food within the study area. This can be either calculated within the framework or taken from other models, which are specifically designed for such purposes. The next step, which is critical to the framework, is to define and quantify the ecosystem services within a region that help in maintaining the production of WEEF. The needs of the environment, such as environmental flows, also need to be defined for the region.

- *Finance and trade*: Not all the resources can be produced within a political boundary. Trade helps in bridging the gap between demand and supply, and reducing security risks. Ecosystem services may also be looked at in terms of import/export (including their contribution to trade goods from different locations).

- *Socioeconomic*: The framework should include (either input or derive) information related to demographics (urbanization, gender disparity in terms of access to the resources), and inequalities in the region. It should be able to define and adjust the human demand (based on different drivers) for WEEF for the region. The framework should (i) show levels of social development relative to levels of economic development (gross domestic product [GDP], sector GDP, etc.); (ii) use indices of demand for resources by different population ‘segments’ (gender, and rich, poor, middle-income groups – looking at ‘disproportionate’ demands that may be the basis of unsustainability, and also raising issues of (in)equitable distribution as a sustainability issue); (iii) look at policy goals and strategies – where/what are the levels of aspiration and expectation in national/regional development plans (e.g., thresholds of GDP/capita required to be classified as ‘middle income’).

- *Institution and governance*: Institutions and governance factors act as drivers of change (in terms of both constraints and opportunities) in determining accepted levels of systemic risk. Policies related to investments in infrastructure, such as storage for water, food and the energy mix between hydropower, biofuels and renewables; providing inputs to agriculture, including fertilizer, capital, labor and technology; trade policies; equity and equality; environment; and capacity building, all of which impact system security. The framework should be able to quantify these factors to effectively include the impact of institutions and governance in WEEF.
- *Stakeholder participation*: Scarcities and risks defined in each system are partly subjective. Although these are related to biophysical conditions, they are also based on the perception, and capacity for adaptation, of stakeholders. The framework should allow for differences in stakeholder participation to define and manage scarcity and risks at different stages in determining trade-offs. Stakeholders also reflect a multiplicity of values and ensure commitment to good resource governance.

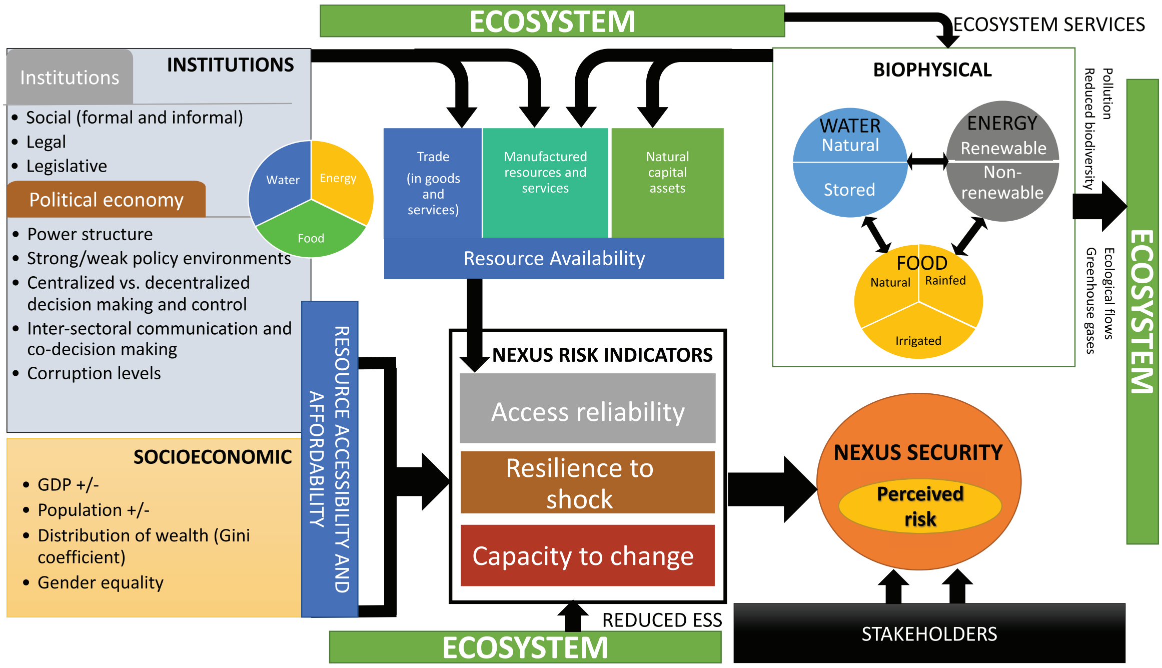
The framework should be able to conduct ex-ante analysis of the impact of policy decisions on the four sectors – WEEF – to provide scientifically-based evidence to stakeholders in order to:

1. understand the risks of (and to inform) different policy decisions – towards achieving ‘optimal’ solutions;
2. conduct trade-offs (and analyzing differential impacts of these trade-offs) to minimize system-level risks and identify where specific risks fall (and, therefore, pinpoint any mitigation measures required); and
3. assess necessary ‘fit-for-purpose’ institutions and/or governance arrangements in order to manage different WEEF scenarios (from the short to long term).

DEVELOPING THE NEXUS FRAMEWORK – THE ‘ARC’ CONCEPT

A WEEF nexus framework is suggested in Figure 2. Central to the development of the nexus framework is the idea of “nexus security”, which needs to be quantified to make the framework operational. “Nexus security” is represented by perceived risk. Every society has a different capacity to handle risk. Therefore, respective perceptions of risk differ. Within each sector of WEEF, the relative importance of one sector over another will also depend upon the society and its relative reliance on these different sectors. Therefore, in this framework, it is necessary to involve stakeholders to define and quantify risk in order to understand the nexus security issues within each region.

FIGURE 2. Water-energy-environment-food nexus framework.



Note: ESS = Ecosystem services.

Risk to society may be quantified by "Nexus risk indicators", which are defined by society's "access reliability", "resilience to shock", and "capacity to change" (ARC). "Access reliability" implies consistency in access to the resources. This is not a static variable, but also depends on a society's demand. There is access reliability as long as a society's demand can be met within available resources and infrastructure constraints, and that resources are accessible to all sections of society. "Resilience to shock" implies society's ability to resist and/or recover from adverse conditions. Such a situation may arise due to either a natural calamity such as a drought or flood or due to political or financial unrest in any part of the world. "Capacity to change" is the coping capacity of a society and implies society's ability to adapt to change, either through supply-side management or demand-side management. A nexus security index may then be identified as an aggregate of the indices that define the ARC across nexus systems. Nexus security is achieved when perceived risks are within levels acceptable to a society. These three attributes collectively indicate how robust a system is.

The three attributes of ARC depend on "resource availability" and "resource accessibility and affordability". Local resource availability may also be classified as "natural" (procured directly from natural systems) and "manufactured" (developed from natural services). Water availability in a region depends on rainfall and other climatic conditions. The only natural source of water within a basin is precipitation, most of which is either lost through evapotranspiration (also known as green water, which supports natural vegetation and rain-fed agriculture) or flows out in the form of river discharge or groundwater (also known as blue water). Some water may be transferred from outside the basin. Energy availability will depend on natural (both renewable and non-renewable) resources in the region. Food produced within a region either comes from rain-fed or irrigated agriculture. Some resources from the natural systems would have to be left untapped for ecological equilibrium purposes. The actual availability of blue water for socioeconomic activity depends on the storage infrastructure (in the case of surface water) and access to energy (in the case of groundwater). Additionally, to use natural resources, some sort of investment or infrastructure development is required. Lack of planning and investment may lead to natural resources not being fully developed. If the actual availability is less than the natural resource stock due to lack of investment, it is called "economic scarcity". Thus, actual availability (usually referred to as economic availability) may be less than physical availability. This may also be due to lack of institutional capacity or political willingness to invest resources in gaining access.

It is usually impractical to meet all local demands from local resources. Trade plays a critical role in filling gaps in local demand and supply. Sometimes direct access to water is substituted by importing virtual water, i.e., importing commodities that have a high water footprint. Trade in food (which also comprises trade in 'virtual water') (Allan 1998a, 1998b; Hoekstra and Hung 2002) plays a critical role in the availability of food in the region, particularly where access to water for agriculture is limited (e.g., the Middle East). Unlike water, energy is traded directly across regions. The global and regional markets, in large part, dictate availability of energy within a region. Resources imported are, in effect, 'second order' ecosystem services from another region (though there are complex issues raised here about the scale and scope of 'nexus' development thinking in terms of how far the boundaries of the 'nexus' extend). For effective trade, strong legal and legislative institutes are required. The aggregation of natural capital, manufactured resources and services, and goods/services traded are the resources available for society.

Resource availability within a region provides "access reliability" but does not guarantee security to all the inhabitants in that region because of inequitable distribution of resources. Access not only depends on the distribution network but also on landownership and water rights. Here, surface water and groundwater are perceived and treated differently. The water tariff structure defines the section of society that can afford water in different quantities, whereas the cost of energy defines the section of society that may be able to access groundwater at different depths. Access to energy depends on the institutions that are responsible for transmission and distribution of energy. This includes regulations and pricing structure. The efficiency within the distribution system defines the energy actually accessible by the community. Additional investment, institutions and policies are required to make the resources accessible to the community. To reduce inequality, enabling access to resources by all sections of society is critical. Due to income disparity, not everyone can afford resources. Affordability of resources depends on the price of the resource as well as the buying power of the household. Affordability itself is a subjective concept and is a balance between needs and wants of an individual or a community. Affordability of water (especially groundwater) to a large extent depends on affordability of energy. Affordability of energy is a function of the regional cost of energy and the buying power of the household. It also depends on subsidies and tariffs set by the institutions. As with energy, the cost of food items and the buying power of the household defines the affordability of food. The ease of access to resources and a society's capability to afford specific resources helps define the resilience of the society to handle short-term shocks within a system. For long-term changes, this also helps in defining a society's capacity to change.

Thus, resource availability, accessibility and affordability that help define the attributes of ARC are further dependent on the following drivers:

- *Biophysical:* The availability of natural resources within a region is critical to meet the demands of society. Within biophysical systems, water, energy and food systems are supported by natural resources, which are derived from the ecosystem. These are the provisional services provided by the ecosystem. The systems are linked together by synergies between them. Water and energy systems are linked together by the need for water for electricity production, such as hydropower generation, water required for cooling; and energy for desalination, purification, groundwater pumping and distribution. Water and food systems are linked together by the need for irrigation in agriculture and the dependence of agriculture on rainfall and soil moisture. Food and energy systems are linked by the need for energy in agriculture for mechanization, distribution of water, fertilizer use and the use of some crops as biofuels for energy generation. There is also competition for water between sectors such as energy and food, for crops between food and energy, for energy between water and food, etc., thus creating avenues for trade-offs among and between systems.

- *Institutional:* The natural resources available in a region need to be harnessed and managed. Legislative and formal social institutions are required to manage resources. Informal social institutions also play a critical role in managing "commons". The resources need to be distributed in an equitable manner, which requires strong legislative and legal institutions. In case of conflict, there should be reliable conflict resolution mechanisms. Clearly-defined property rights also help to improve the management of natural resources. Within each society, there is a political hierarchical structure, although the level of hierarchy may be different. Management of natural resources that includes accessibility to all sections of society depends on power structures and policy environments within a region. Some of the high capital management projects may be suitable for centralized decision-making, whereas management of local resources may be suitable for more decentralized decision-making. A healthy policy environment would imply the development of higher quality institutions related to natural resource management. Good lines of communication between multiple departments within the government would lead to holistic natural resource management. Finally, lower corruption levels indicate that investments in natural resource management are efficiently utilized. The institutional system is classified as institutions and political economy. Institutions comprise of formal and informal social entities, and legal and legislative entities. These also include laws and regulations for extraction, management and distribution of natural resources. In political economy, these include the power structures, state of the policy environment, levels of corruption, and levels of inter-sectoral communication and interaction that impact the decision-making and investment in natural resource management.
- *Socioeconomic:* Due to socioeconomic heterogeneity within society, access to resources is not equitable. Sections of society that are in the lower-income group or marginalized due to social issues have reduced access to resources. Even if resources are available, they may not be affordable to sections of society. These communities are also the least resilient to adverse conditions and hence at higher risk in terms of natural resource security. Socioeconomic systems consist of wealth generation (both absolute and per capita) and distribution within society. Distribution of wealth impacts the ability of a community to access resources equitably. Accessibility and affordability of resources are also impacted by gender, economics, demographics and cultural characteristics within a community. These could be further distorted by government policies over tariffs and subsidies.
- *Ecosystems:* Ecosystems provides ecosystem services, which are classified as provisioning, regulating, habitat and cultural services (WLE 2014). The potential availability of resources within each sector in the framework may also be considered as representative of "provisioning" services. The regulating, habitat and cultural services fall under the environmental system within the WEEF framework. They help provide environmental security. Ecosystem services are reduced due to either the depletion of non-renewable resources or over-exploitation of renewable resources. Reduced ecosystem services leads to lower resilience, higher vulnerability and lower capacity for society to handle risk (hence lower security).

APPLYING THE NEXUS FRAMEWORK ACROSS SYSTEMS AND INSTITUTIONS

The framework discussed above merges issues from two system perspectives. One is in terms of nexus systems (such as water, energy, environment, food, etc.), and the other is in the form of integration of biophysical, institutional and socioeconomic systems. The advantage of building up nexus security from a two-system perspective is that it helps in identifying problems at multiple levels within a system, but in a holistic way. Such multi-level analysis helps in providing advice to those engaged in policy development to achieve system-level security.

The framework discussed in the previous section is quantified using multiple indicators across the systems. Table 2 shows the indicators required to define the status of a nexus due to biophysical conditions across systems. The indicators are as follows:

- *Natural capital assets:* This indicator quantifies the potential of the natural systems to provide ecosystem services to society. This may also be defined as the total resources that can be harnessed within the area of interest, and may also represent the carrying capacity in a system.
- *Manufactured resources and services:* This indicator defines the natural resources actually harnessed for human use. This is in fact the proxy of investments in different systems of the nexus.
- *Trade (in goods and services):* This indicator quantifies a region's reliance on trade to meet its demand (and hence security). It also shows the reliance of a region/country on other regions.

Table 3 shows the indicators used to define institutional and political economy conditions within the nexus systems. The indicators are as follows:

- *Social formal institutions:* Formal institutions are developed by a governing authority to regulate human behavior. The presence of social formal institutions indicates the level of structured social frameworks to manage natural resources and the involvement of government institutions in such matters.
- *Social informal institutions:* Informal institutions are built by stakeholders with a common interest to manage resources within communal standards developed through social interaction. An example of social informal institutions is farmer groups that share irrigation resources. This indicator helps to quantify the social harmony within society and the willingness of the community to work together to manage the "commons".
- *Legal institutions:* Indicators in this category depict the laws and legal structure with which to handle any conflicts arising during resource allocation. A weak legal institutional framework implies less fear of sanctions and hence more disparity in resource allocation, as people with more influence will get a disproportional share of resources.
- *Legislative institutions:* These indicators refer to the development of rules and regulations including commissions created through legislative processes to manage natural resources. This indicates the involvement of political structures in resource management.

- *Property rights:* Property rights are considered as ownership and control over a resource. A lack of well-defined property rights creates a situation where the resources are not managed since there is no incentive to manage. In case of common property, without the existence of proper social institutions, resources may be over-exploited as everyone tries to maximize accrued benefits.
- *Power structures:* This indicator defines the level of hierarchy within a political system. Too many layers may create a bureaucratic bottleneck for implementation of rules and regulations.
- *Policy environment:* this relates to the development and implementation of policy, including sectoral and inter-sectoral (crosscutting) policy. It is both the quantity of policy and the degree to which implementation has been achieved.
- *Inter-sectoral communication:* This indicator defines the level of communication and cooperation between the water, energy, environment and food sectors in a region. A higher level of cooperation indicates a holistic approach to resource management.
- *Corruption levels:* This indicator quantifies the effectiveness and efficiency of investments in managing resources for social use.

TABLE 2. Biophysical indicators to quantify the health of a nexus system.

Nexus agents	Nexus systems			
	Water	Energy	Environment	Food
		Biophysical		
Natural capital assets	Renewable water resources/ population (NCW)	Renewable energy resources/ population (NCR)	In-stream water generated/environmental flow requirement (NCE_S)	Food gathered from forests/ population (NCF)
			Groundwater abstraction/ sustainable groundwater abstraction (NCE_G)	
Manufactured resources and services	(Water abstraction + desalination + water reuse)/ population (MW)	Energy production/ population (MR)	(Desalination + water reuse)/unsustainable surface water withdrawal) (ME_S)	Agricultural production/ population (MF)
			Managed groundwater recharge/unsustainable groundwater abstraction (ME_G)	
Trade (in goods and services)	Virtual water trade/population (TW)	Energy imports/ population (TR)	Ecosystem services traded/total measurable ecosystem services (TE)	Food commodity trade/population (TF)

Note: The codes within brackets under the columns for each nexus system (water, energy, environment and food) are used in Figure 3.

TABLE 3. Institutional indicators to quantify the health of a nexus system.

Nexus agents	Nexus systems			
	Water	Energy	Environment	Food
		Institutional		
Social formal institutions	Formal water-related social institutions/100,000 people (ISFW)	Formal energy-related social institutions/100,000 people (ISFR)	Formal environment-related social institutions/100,000 people (ISFE)	Formal agriculture-related social institutions/100,000 people (ISFF)
	Institutional effectiveness (rating) (ISF_EW)	Institutional effectiveness (rating) (ISF_ER)	Institutional effectiveness (rating) (ISF_EE)	Institutional effectiveness (rating) (ISF_ERF)
Social informal institutions	Informal water-related social institutions/100,000 people (ISIFW)	Informal energy-related social institutions/100,000 people (ISIFR)	Informal environment-related social institutions/100,000 people (ISIFE)	Informal agriculture-related social institutions/100,000 people (ISIFF)
	Institutional effectiveness (rating) (ISIF_EW)	Institutional effectiveness (rating) (ISIF_ER)	Institutional effectiveness (rating) (ISIF_EE)	Institutional effectiveness (rating) (ISIF_EF)
Legal institutions	Number of arbitration institutions/binary for water issues (ILW)	Number of arbitration institutions/binary for energy issues (ILR)	Number of arbitration institutions/binary for environmental issues (ILE)	Number of arbitration institutions/binary for agricultural issues (ILF)
	Institutional effectiveness (rating) (IL_EW)	Institutional effectiveness (rating) (IL_ER)	Institutional effectiveness (rating) (IL_EE)	Institutional effectiveness (rating) (IL_EF)
Legislative institutions	Number of water-related laws (IGNW)	Number of energy-related laws (IGNR)	Number of environment-related laws (IGNE)	Number of agriculture-related laws (IGNF)
	How successful is the enforcement of water-related laws? (rating) (IGN_EW)	How successful is the enforcement of energy-related laws? (rating) (IGN_ER)	How successful is the enforcement of environment-related laws? (rating) (IGN_EE)	How successful is the enforcement of agriculture-related laws? (rating) (IGN_EF)
	Arbitration: Proportion of cases filed that are resolved (IGAW)	Arbitration: Proportion of cases filed that are resolved (IGAR)	Arbitration: Proportion of cases filed that are resolved (IGAE)	Arbitration: Proportion of cases filed that are resolved (IGAF)

(Continued)

TABLE 3. Institutional indicators to quantify the health of a nexus system (continued).

Nexus agents	Nexus systems			
	Water	Energy	Environment	Food
		Institutional		
Legislative institutions (continued)	Source of legislation: (i) national level, (ii) subnational level, and (iii) local level (rating) (IGSW)	Source of legislation: (i) national level, (ii) subnational level, and (iii) local level (rating) (IGSR)	Source of legislation: (i) national level, (ii) subnational level, and (iii) local level (rating) (IGSE)	Source of legislation: (i) national level, (ii) subnational level, and (iii) local level (rating) (IGSF)
	Enforcement of legislation: (i) national level, (ii) subnational level, and (iii) local level (IGS_EW)	Enforcement of legislation: (i) national level, (ii) subnational level, and (iii) local level (IGS_ER)	Enforcement of legislation: (i) national level, (ii) subnational level, and (iii) local level (IGS_EE)	Enforcement of legislation: (i) national level, (ii) subnational level, and (iii) local level (IGS_EF)
Property rights	Percentage of water users covered by water rights (IPW)	Number of private ownerships of energy production (IPR)	Number of laws/ regulations related to right to clean water, land and air (IPE)	Percentage of land area under formal tenure systems (IPF)
				Tenure security: (i) very secure, (ii) average, and (iii) no tenure security (rating) (IP_EF)
		Political economy		
Power structures	Decision-making centralized/ decentralized (PDCW)	Decision-making centralized/ decentralized (PDCR)	Decision-making centralized/ decentralized (PDCE)	Decision-making centralized/ decentralized (PDCF)
	Proportion of decision-making at the different government levels (PDLW)	Proportion of decision-making at the different government levels (PDLR)	Proportion of decision-making at the different government levels (PDLE)	Proportion of decision-making at the different government levels (PDLF)
	Accountability – (i) upward, (b) horizontal, and (iii) downward (PAW)	Accountability – (i) upward, (ii) horizontal, (iii) downward (PAR)	Accountability – (i) upward, (ii) horizontal, and (iii) downward (PAE)	Accountability – (i) upward, (ii) horizontal, and (c) downward (PAF)

(Continued)

TABLE 3. Institutional indicators to quantify the health of a nexus system (continued).

Nexus agents	Nexus systems			
	Water	Energy	Environment	Food
		Institutional		
Policy environment	Degree of integration of policy environment (PPEW)	Degree of integration of policy environment (PPER)	Degree of integration of policy environment (PPEE)	Degree of integration of policy environment (PPEF)
Inter-sectoral communication	Extent of inter-sectoral communication network (PICW)	Extent of inter-sectoral communication network (PICR)	Extent of inter-sectoral communication network (PICE)	Extent of inter-sectoral communication network (PICF)
Corruption levels	Corruption index (PCLW)	Corruption index (PCLR)	Corruption index (PCLE)	Corruption index (PCLF)

Note: The codes within brackets under the columns for each nexus system (water, energy, environment and food) are used in Figure 3.

Table 4 shows the indicators used to quantify the socioeconomic conditions of the nexus systems. The indicators are as follows:

- *Gross Domestic Product (GDP):* GDP represents the wealth and economic activity in a nation. In the context of the nexus, GDP represents the ability of the region to invest in resource management and environmental well-being. On the other hand, higher GDP leads to more affluence in society and hence higher demand for resources (though not necessarily distributed equally).
- *Population:* Population is the driver that creates competition for resources. Higher population also leads to over-exploitation of resources.
- *Distribution of resources:* This indicator refers to the distribution of resources among different sections of society. Unequal distribution implies higher disparity in society.
- *Gender inequality:* Gender inequality may be due to economic or cultural reasons. Gender inequality in the nexus refers to the distribution of resources between genders. An equal distribution indicates gender equality.
- *Affordability:* This indicator points to the cost of resources versus the household income in society. Even if the resources are available, they may not be affordable due to either higher tariffs or lower per capita income.

TABLE 4. Socioeconomic indicators to quantify the health of a nexus system.

Nexus agents	Nexus systems			
	Water	Energy	Environment	Food
		Socioeconomic		
GDP	Income/capita (SEGW)	Income/capita (SEGR)	Income/capita (SEGE)	Income/capita (SEGF)
Population	Population per total water resources (SEPW)	Population per total energy resources (SEPR)	Population density (SEPE)	Population per total food available (SEPF)
Distribution of resources	Percentage of population with access to clean water (SEDW)	Percentage of population with access to energy/electrification rate (SEDR)	Number of species/land area (SEDE)	Percentage of population above hunger level (SEDF)
Gender inequality	Proportion of women with access to water/proportion of men with access to water (domestic use and agriculture) (SEGEW)	Proportion of women with access to clean energy/proportion of men with access to clean energy (SEGER)	Proportion of women with poor health due to unclean water/proportion of men with poor health due to unclean water (SEGEE)	Proportion of women above hunger level/proportion of men above hunger level (SEGEF)
Affordability	Portion of household income spent on water (SEAW)	Portion of household income spent on energy (SEAR)	Portion of public funds spent per household on environmental issues (SEAE)	Portion of household income spent on food (SEAF)

Note: The codes within brackets under the columns for each nexus system (water, energy, environment and food) are used in Figure 3.

Table 5 shows indicators that gauge the health of the environment within the nexus systems. These indicators are as follows:

- *Pollution:* Pollution is an externality that is created by nexus systems while providing benefits to the society. This leads to a reduction in ecosystem services. Indicators related to pollution define the level of these externalities, which also indicates unsustainability in the systems.
- *Climate change:* The indicators related to climate change define the role of each system in contributing to greenhouse gas (GHG) emissions. More energy-intensive systems would contribute to higher GHG emissions. In energy systems, this is the ratio of non-renewable energy generation versus renewable energy production. For ecosystems, the forest cover of the region (as compared to its natural forest cover) help in defining this indicator.

- *Resource use:* The indicators in this category help in defining the level of resources used within each system.
- *Land use:* The indicators for land use are developed to indicate modified land use (to meet the benefits of each system) versus the original land use in a region. Modified land use reduces services provided by the ecosystem.
- *Health:* Lack of benefits from each of the nexus systems creates health issues for society. This indicator quantifies people impacted due to non-availability of benefits or lack of ecosystem services.

TABLE 5. Environmental indicators to measure the health of the nexus systems.

Nexus agents	Nexus systems			
	Water	Energy	Environment	Food
		Socioeconomic		
Pollution	Untreated wastewater/total water withdrawn (EPW)	Polluted water from energy sector/total water withdrawn for energy (EPR)		Pollution (excess fertilizer + pesticides used) in agriculture/1,000 tonnes of food production (EPF)
Climate change	GHG emitted from water sector (ECCW)	GHG emitted from energy sector (ECCR)	Existing forest cover/natural forest cover (ECCE)	GHG emissions from agriculture sector (ECCF)
Resource use	Energy usage (ERUW)	Water usage (ERUE)		Irrigated water + energy usage (ERUF)
Land use	Remaining wetlands, ponds/original wetlands, ponds (ELW)	Land used for biofuel production/total agricultural land (ELR)	Managed land area/total land area (ELE)	Agricultural land/total land area (ELF)
Health	Number of people sick due to lack of clean water/100,000 people (ETW)	Number of people sick due to lack of clean energy/100,000 people (ETR)	Flood loss/GDP (ETE_F) Loss due to drought/GDP (ETE_D)	Number of stunted children/100,000 children (ETF)

Note: The codes within brackets under the columns for each nexus system (water, energy, environment and food) are used in Figure 3.

The indicators discussed above help in defining the strengths and weaknesses of nexus at different levels within each system. These indices are further used to build a multi-dimensional nexus scorecard as shown in Figure 3. This scorecard provides a snapshot of "weak links" within a system, and becomes a useful tool with which to engage national-level stakeholders in deliberations on policy development and the negotiation of trade-offs. In one dimension, this framework integrates biophysical, institutional and socioeconomic systems. In another dimension, it integrates water, energy, environment and food from a resource security perspective. In a third dimension, it calculates society's collective risk due to the lack of availability and/or lack of access to goods and services provided by these systems. Collective risk is the perceived risk, which is supported by "Nexus Risk Indicators" (NRIs). NRIs are defined by "access reliability", "resilience to shock" and "capacity to change". On the biophysical side, these indicators depend on resource availability, which is made up of natural capital assets, manufactured resources and services, and trade (in goods and services). On the social side, these indicators depend on access to and affordability of resources, which is further dependent on institutions, political economy and socioeconomic situations within each study area. The resource availability is dependent on the provision of ecosystem services.

Access reliability is quantified in the Access Reliability Index (ARI), which may be defined as follows:

$$ARI = w_1 * RRI + w_2 * INI$$

Where: RRI is Resource Index, INI is Institutional Index, and w_1 and w_2 are weightings developed based on stakeholder consultations.

Resilience to shock depends on the institutional setup of the region and the socioeconomic condition of society. It is represented by the Resilience Index (RRI) and defined as follows:

$$RRI = w_3 * INI + w_4 * DMI + w_5 * SEI + w_6 * REI$$

Where: INI is Institutional Index, DMI is Decision-Making Index, SEI is Socio-Economic Index, REI is Reduced Ecosystem Services Index, and w_3, w_4, w_5 and w_6 are weightings developed based on stakeholder consultations.

Capacity to change is impacted by institutions and socioeconomic conditions in a region. It is quantified by the Capacity Index (CPI) and defined as follows:

$$CPI = w_7 * INI + w_8 * DMI + w_9 * SEI$$

Where: w_7, w_8 and w_9 are the weightages defined by stakeholders.

The three NRI indicators help define the overall health of the nexus system. They quantify the level of risk to the nexus system. The Nexus Security Risk Index (NESRIX) quantifies the level of risk and is defined as follows:

$$NESRIX = ARI * RRI * CPI$$

The scorecard developed in Figure 3 shows the status (or health) of the nexus system at different levels. For interregional comparison, it also provides high-level indicators (such as NRIs and NSRIX). To operationalize the scorecard, a low and high value for each indicator can be developed based on discussion with the stakeholders. The range can be divided into four color-coded groups: high, mid-high, mid-low and low (with high being green and low being red).

FIGURE 3. "Nexus Security Risk Matrix" developed to measure the health of the nexus system.

NEXUS AGENTS	NEXUS SYSTEMS WATER	 ENERGY	 FOOD	 ECOSYSTEM	HIGH LEVEL NEXUS INDICATORS
BIOPHYSICAL					
Natural capital assets	NCW	NCR	NCF	NCE_S NCE_G	RESOURCE INDEX (RRI)
Manufactured resources and services	MW	MR	MF	ME_S ME_G	
Trade (in goods and services)	TW	TR	TF	TE	
INSTITUTIONAL					
Social formal institutes	ISFW ISF_EW	ISFR ISF_ER	ISFF ISF_ERF	ISFE ISF_EE	INSTITUTIONAL INDEX (INI)
Social informal institutes	ISIFW ISIF_EW	ISIFR ISIF_ER	ISIFF ISIF_EF	ISIFE ISIF_EE	
Legal institutes	ILW IL_EW	ILR IL_ER	ILF IL_EF	ILE IL_EE	
Legislative institutes	IGNW IGN_EW IGAW IGSW IGS_EW	IGNR IGN_ER IGAR IGSR IGS_ER	IGNF IGN_EF IGAF IGSF IGS_EF	IGNE IGN_EE IGAE IGSE IGS_EE	
Property rights	IPW	IPR	IPF IP_EF	IPE	
POLITICAL ECONOMY					
Power structure	PDCW PDLW PAW	PDCR PDLR PAR	PDCF PDLF PAF	PDCE PDLE PAE	DECISION MAKING INDEX (DMI)
Policy environment	PPEW	PPER	PPEF	PPEE	
Intersectoral communication	PICW	PICR	PICF	PICE	
Corruption levels	PCLW	PCLR	PCLF	PCLE	
SOCIO-ECONOMIC					
GDP	SEGW	SEGR	SEGF	SEGE	SOCIO-ECONOMIC INDEX (SEI)
Population	SEPW	SEPR	SEPF	SEPE	
Distribution of Resources	SEDW	SEDR	SEDF	SEDE	
Gender equality	SEGEW	SEGER	SEGEF	SEGEE	
Affordability	SEAW	SEAR	SEAF		
ENVIRONMENT					
Pollution	EPW	EPR	EPF		REDUCED ESS INDEX (REI)
Climate change	ECCW	ECCR	ECCF	ECCE	
Resource use	ERUW	ERUE	ERUF		
Landuse	ELW	ELR	ELF	ELE	
Health	ETW	ETR	ETF	ETE_F ETE_D	
RESOURCE SECURITY INDEX	WATER SECURITY INDEX (WSI)	ENERGY SECURITY INDEX (RSI)	FOOD SECURITY INDEX (FSI)	ENVIRONMENT SECURITY INDEX (ESI)	

ACCESS RELIABILITY INDEX

RESILIENCE INDEX

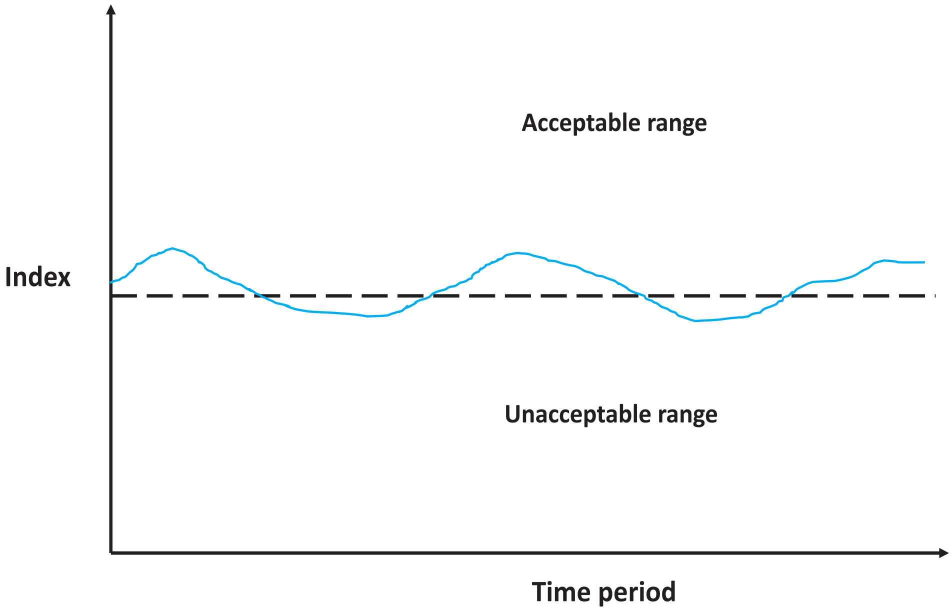
CAPACITY INDEX

NEXUS SECURITY RISK INDEX (NESRIX)

Note: The codes under the columns for each nexus system (water, energy, environment, food) correspond to the codes in Tables 2, 3, 4 and 5.

The aforementioned dimensions provide a snapshot of risk and security within a region. However, sustainability requires an understanding of risk over time. Hence, the fourth dimension is analyzing resource risk and security over time to define sustainability under a specific WEEF nexus. The availability of ecosystem services and the manner in which they are used define the sustainability of the entire system. Historical data can be used to ascertain the sustainability trends within the nexus system. For ex-ante sustainability analysis, this scorecard will need to be linked to modeling activity that can provide scenario-based outputs. Sustainability can be measured in terms of reliability, resilience and vulnerability (Loucks and Gladwell 1999). A mathematical representation of reliability, resilience and vulnerability as developed by Loucks and Gladwell (1999) may be used. To illustrate this further, Figure 4 shows a plot of an index against time. By defining the acceptable range for the index, it can be seen how many times the system fails (i.e., the index falls outside the pre-defined acceptable limits). Thus, reliability has been defined as the probability of a system to be within the range of satisfactory values over the period of time under consideration. Resilience has been defined as a measure of the "speed of recovery" from an unsatisfactory condition. Finally, vulnerability has been defined as the statistical measure of the extent of failure. These three parameters can be used together to measure sustainability in a quantitative way.

FIGURE 4. Plotting index against time.



The reliability, resilience and vulnerability are calculated as follows:

$$Reliability\ (S_{Rel}) = \frac{\text{Number of satisfactory values}}{\text{Total number of values}}$$

$$Resilience\ (S_{Res}) = \frac{\text{Number of times a satisfactory value follows an unsatisfactory value}}{\text{Number of unsatisfactory values}}$$

$$Vulnerability\ (S_{Vul}) = \begin{array}{c}\text{Expected extent given unsatisfactory values}\\ + \\ \text{Expected duration given unsatisfactory values}\end{array}$$

Where:

$$\text{Expected extent given unsatisfactory values} = \frac{\text{Cumulative extent of failure}}{\text{Number of individual failure events}}$$

and

$$\text{Expected duration given unsatisfactory values} = \frac{\text{Total number of failure periods}}{\text{Number of continuous series of failure events}}$$

CONCLUSIONS

Recent activities point to heightened interest in a nexus approach towards development and resource allocation. A review of existing literature shows either theoretical frameworks or mostly bi-system linkages for "nexus" analysis. The layers and complexities of interlinkages between systems make it difficult to include all nexus systems in a detailed analysis. In this report, a Water-Energy-Environment-Food nexus framework is proposed that links social and political systems with biophysical systems. Some of the core concepts of the nexus discourse, such as the 'nexus' itself, security, risk and sustainability, are discussed and defined within the shared space of biophysical and socio-political-economic systems. Understanding these concepts and their relationships helps in defining and outlining a more robust nexus framework of interconnections between multiple systems – which, the authors argue, reflects a truer decision-making reality.

Based on the nexus framework outlined, a "Nexus Security Risk Matrix" is then developed which provides an index of overall 'nexus system security'. The matrix has biophysical systems on one side and institutional and socioeconomic systems on the other. Indicators for each of the shared spaces is considered to gauge the efficiency of the system in that space. Both of these dimensions help define the access reliability index, resilience index and the capacity index of society within the nexus. Each of the indicators within the matrix are given a weighting, either based on historical experience or developed in consultation with stakeholders within the study area. The three ARC indices ("access reliability", "resilience to shock", and "capacity to change") help define the overall Nexus Security Risk Index (NESRIX). Such a scorecard can then help to support decision-making at national/regional levels, unpacking complexity(ies) and providing a tool to engage policy makers in constructive dialogue on: (i) understanding water security in relation to other sectors and the multiple interactions between them; and (ii) identifying 'soft spots' within nexus systems that need to be addressed to improve development outcomes, particularly for the poorest and most marginal. The tool helps to innovate the use of institutional, social capacity and resilience indicators, building a composite of metrics from a number of data sources available on governance and development.

The matrix itself can be applied either within an administrative boundary or a basin unit, or even used as a comparative tool between regions or countries. The indices developed can be plotted along time scales to monitor nexus development and its sustainability over time. The indices may be linked to scenario models to quantify the impacts of policy decisions related to governance, institutions and investments in the nexus systems.

The next step would be to implement this framework in selected countries and to undertake a comparative analysis of outputs by country. Most of the data can be retrieved from web-based research. An initial effort for Sri Lanka indicated that data related to institutions and political economy are not easily available. Thus, a basic questionnaire (see Appendix) has been prepared (to be modified for the country of concern) as an example of surveys that can be sent out to staff of relevant organizations. The country specific data will help to identify ways of linking this framework to the research activity and the research activity to decision-making arenas.

REFERENCES

ADB (Asian Development Bank). 2013. *Thinking about water differently: Managing the water–food–energy nexus*. Mandaluyong City, Philippines: Asian Development Bank (ADB).

Allan, J.A. 1997. *`Virtual water': A long term solution for water short Middle Eastern economies?* Paper presented at the 1997 British Association Festival of Science, Roger Stevens Lecture Theatre, University of Leeds, Water and Development Session, TUE.51, 14.45, September 9, 1997.

Allan, J.A. 1998a. Virtual water: A strategic resource: Global solutions to regional deficits. *Groundwater* 36(4): 545-546. https://doi.org/10.1111/j.1745-6584.1998.tb02825.x

Allan, J.A. 1998b. Moving water to satisfy uneven global needs: "Trading" water as an alternative to engineering it. *ICID Journal* 47(2): 1-8.

Allouche, J.; Middleton, C.; Gyawali, D. 2014. *Nexus nirvana or nexus nullity? A dynamic approach to security and sustainability in the water-energy-food nexus*. STEPS Working Paper 63. Brighton, UK: STEPS Centre, University of Sussex.

Arent, D.J.; Döll, P.; Strzepek, K.M.; Jiménez Cisneros, B.E.; Reisinger, A.; Tóth, F.L.; Oki, T. 2014. Cross-chapter box on the water–energy–food/feed/fiber nexus as linked to climate change. In: *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, (eds.), Field, C.B.; Barros, V.R.; Dokken, D.J.; Mach, K.J.; Mastrandrea, M.D.; Bilir, T.E.; Chatterjee, M.; Ebi, K.L.; Estrada, Y.O.; Genova, R.C.; Girma, B.; Kissel, E.S.; Levy, A.N.; MacCracken, S.; Mastrandrea, P.R.; White, L.L. Cambridge, United Kingdom, and New York, NY, USA: Cambridge University Press. Pp. 163-166.

Barbier, E.B. 2003. Upstream dams and downstream water allocation: The case of the Hadejia-Jama'are floodplain, northern Nigeria. *Water Resources Research* 39(11): WES 1.1-WES 1.9. https://doi.org/10.1029/2003WR002249

Bazilian, M.; Rogner, H.; Howells, M.; Hermann, S.; Arent, D.; Gielen, D.; Steduto, P.; Mueller, A.; Komor, P.; Tol, R.S.J.; Yumkella, K.K. 2011. Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy* 39(12): 7896-7906. https://doi.org/10.1016/j.enpol.2011.09.039

Bizikova, L.; Roy, D.; Swanson, D.; Venema, H.D.; McCandless, M. 2013. *The water–energy–food security nexus: Towards a practical planning and decision-support framework for landscape investment and risk management*. Manitoba, Canada: International Institute for Sustainable Development (IISD).

Blanco-Gutiérrez, I.; Varela-Ortega, C.; Purkey, D.R. 2013. Integrated assessment of policy interventions for promoting sustainable irrigation in semi-arid environments: A hydro-economic modeling approach. *Journal of Environmental Management* 128: 144-160. https://doi.org/10.1016/j.jenvman.2013.04.037

Cai, X.; McKinney, D.C.; Lasdon, L.S. 2003a. Integrated hydrologic-agronomic-economic model for river basin management. *Journal of Water Resources Planning and Management* 129(1): 4-17. https://doi.org/10.1061/(ASCE)0733-9496(2003)129:1(4)

Cai, X.; McKinney, D.C.; Rosegrant M.W. 2003b. Sustainability analysis for irrigation water management in the Aral Sea region. *Agricultural Systems* 76(3): 1043-1066. https://doi.org/10.1016/S0308-521X(02)00028-8

Chatterjee, B.; Howitt, R.E.; Sexton, R.J. 1998. The optimal joint provision of water for irrigation and hydropower. *Journal of Environmental Economics and Management* 36(3): 295-313. https://doi.org/10.1006/jeem.1998.1047

FAO (Food and Agriculture Organization of the United Nations). 2014. *The water-energy-food nexus: A new approach in support of food security and sustainable agriculture*. Rome, Italy: Food and Agriculture Organization of United Nations (FAO).

Flammini, A.; Puri, M.; Pluschke, L.; Olivier, D. 2014. *Walking the nexus talk: Assessing the water-energy-food nexus in the context of the sustainable energy for all initiative.* Environment and Natural Resource Management Working Paper 58. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

Headey, D.D.; Malaiyandi, S.; Fan, S. 2009. *Navigating the perfect storm: Reflections on the food, energy, and financial crises.* IFPRI Discussion Paper 00889. Washington, DC, USA: International Food Policy Research Institute (IFPRI). 24p.

Hoekstra, A.Y.; Hung, P.Q. 2002. *Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade.* Delft, The Netherlands: IHE-Delft. (Value of Water Research Report Series No. 11).

Hoff, H. 2011. *Understanding the nexus*. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm, Sweden: Stockholm Environment Institute.

Howells, M.; Hermann, S.; Welsch, M.; Bazilian, M.; Segerström, R.; Alfstad, T.; Gielen, D.; Rogner, H.; Fischer, G.; van Velthuizen, H.; Wiberg, D.; Young, C.; Roehrl, A.; Mueller, A.; Steduto, P.; Ramma, I. 2013. Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change* 3(7): 621-626. https://doi.org/10.1038/nclimate1789

ICIMOD (International Centre for Integrated Mountain Development). 2012. *Contribution of Himalayan ecosystems to water, energy, and food security in South Asia: A nexus approach*. Kathmandu, Nepal: International Centre for Integrated Mountain Development (ICIMOD).

Jolly, R. 1976. The World Employment Conference: The enthronement of basic needs. *Development Policy Review* A9(2): 31-44. https://doi.org/10.1111/j.1467-7679.1976.tb00338.x

Liu, J.; Mooney, H.; Hull, V.; Davis, S.J.; Gaskell, J.; Hertel, T.; Lubchenco, J.; Seto, K.C.; Gleick, P.; Kremen, C.; Li, S. 2015. Systems integration for global sustainability. *Science* 347(6225): 1258832. https://dx.doi.org/10.1126/science.1258832

Loucks, D.P.; Gladwell, J.S. 1999. *Sustainability criteria for water resource systems*. International Hydrology Series. Cambridge, UK: Cambridge University Press.

McCornick, P.G.; Awulachew, S.B.; Abebe, M. 2008. Water–food–energy–environment synergies and tradeoffs: Major issues and case studies. *Water Policy* 10 (Supplement 1): 23-36. https://doi.org/10.2166/wp.2008.050

Mehta, R. 2010. Re-plumbing China: Leading to the world's first water war? *Journal of the Centre for Land Warfare Studies* Summer 2010: 108-136.

NCSL (National Conference of State Legislatures). 2014. *Overview of the water-energy nexus in the United States*. Available at http://www.ncsl.org/research/environment-and-natural-resources/overviewofthewaterenergynexusintheus.aspx (accessed in January 2017).

OECD (Organisation for Economic Co-operation and Development). 2013. *Water security for better lives*. OECD Studies on Water. Paris: OECD Publishing. 171p. https://doi.org/10.1787/9789264202405-en

Ohlsson, L.; Turton, A.R. 2000. *The turning of a screw: Social resource scarcity as a bottle-neck in adaptation to water scarcity*. Occasional Paper Series. London, UK: School of Oriental and Asian Studies, Water Study Group, University of London.

Ringler, C.; Bhaduri, A.; Lawford, R. 2013. The nexus across water, energy, land and food (WELF): Potential for improved resource use efficiency? *Current Opinion in Environmental Sustainability* 5(6): 617-624. https://doi.org/10.1016/j.cosust.2013.11.002

Rodriguez, D.J.; Delgado, A.; DeLaquil, P.; Sohns, A. 2013. *Thirsty energy*. Water Papers. Washington, DC: World Bank.

UNECE (United Nations Economic Commission for Europe). 2014. *Progress report on the thematic assessment of the water-food-energy-ecosystems nexus*. Economic Commission for Europe Meeting of the Parties to the Convention on the Protection and Use of Transboundary Watercourses and International Lakes, Working Group on Integrated Water Resources Management, Ninth Meeting, Geneva, Switzerland, June 25-26, 2014. Document no. ECE/MP.WAT/WG.1/2014/6.

UNESCAP (United Nations Economic and Social Commission for Asia and the Pacific). 2013. *Water, food and energy nexus in Asia and the Pacific*. A position paper commissioned by the United Nations Economic and Social Commission for Asia and the Pacific. Discussion Paper. Bangkok, Thailand: United Nations.

UN-Water. 2013. *Water security & the global water agenda: A UN-Water Analytical Brief*. Ontario, Canada: United Nations University.

Ward, F.A.; Lynch, T.P. 1996. Integrated river basin optimization: Modeling economic and hydrologic interdependence. *Journal of the American Water Resources Association* 32(6): 1127-1138.

WEF (World Economic Forum). 2011. *Global risks 2011: Sixth Edition. An initiative of the Risk Response Network*. Cologne/Geneva, Switzerland: World Economic Forum.

WEF. 2014. *The future availability of natural resources: A new paradigm for global resource availability*. World Scenario Series. Cologny/Geneva, Switzerland: World Economic Forum.

WEF. 2016. *The global risks report 2016*. 11th Edition. Insight Report. Cologny/Geneva, Switzerland: World Economic Forum.

WEF. 2017. *The global risks report 2017*. 12th Edition. Insight Report. Cologny/Geneva, Switzerland: World Economic Forum.

WEF. 2018. *The global risks report 2018*. 13th Edition. Insight Report. Cologny/Geneva, Switzerland: World Economic Forum.

WEF. 2019. *The global risks report 2019*. 14th Edition. Insight Report. Cologny/Geneva, Switzerland: World Economic Forum.

Welsch, M.; Hermann, S.; Howells, M.; Rogner, H.H.; Young, C.; Ramma, I.; Bazilian, M.; Fischer, G.; Alfstad, T.; Gielen, D.; Le Blanc, D.; Röhrl, A.; Steduto, P.; Müller, A. 2014. Adding value with CLEWS – Modelling the energy system and its interdependencies for Mauritius. *Applied Energy* 113: 1434-1445. https://doi.org/10.1016/j.apenergy.2013.08.083

Weitz, N.; Nilsson, M.; Davis, M. 2014. A nexus approach to the post-2015 agenda: Formulating integrated water, energy, and food SDGs. *SAIS Review of International Affairs* 34(2): 37-50. https://dx.doi.org/10.1353/sais.2014.0022

WLE (CGIAR Research Program on Water, Land and Ecosystems). 2014. *Ecosystem services and resilience framework*. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE). 46p. Available at http://www.iwmi.cgiar.org/Publications/wle/corporate/ecosystem_services_and_resilience_framework.pdf (accessed on January 21, 2019).

Wu, X.; Jeuland, M.; Sadoff, C.; Whittington, D. 2013. Interdependence in water resource development in the Ganges: An economic analysis. *Water Policy* 15(S1): 89-108. https://doi.org/10.2166/wp.2013.003

WWAP (World Water Assessment Programme). 2012. *The United Nations World Water Development Report 4: Managing water under uncertainty and risk (Volume 1)*. Paris: United Nations Educational, Scientific and Cultural Organization (UNESCO).

APPENDIX. QUESTIONNAIRE TO QUANTIFY CERTAIN INSTITUTIONAL AND POLITICAL ECONOMY INDICATORS FOR WHICH DATA WERE NOT OTHERWISE AVAILABLE

Introduction

Numerous studies have shown the interdependence of water, energy, environment and food systems (referred to here as WEEF nexus system). The existing frameworks that try to study these interdependencies contain limited integration between the biophysical and social science aspects of the nexus. They do not fully explore implications for policy development and actions to address resource security issues.

In an attempt to address this, the International Water Management Institute (IWMI) has been exploring a new WEEF nexus framework that seeks to fully integrate biophysical systems with social systems. The framework would be used to develop a "Nexus Health Scorecard" that looks at biophysical, institutional and socioeconomic systems within water, energy, environment and food systems (or sectors). Such a scorecard could then be used in a decision-support tool at national and regional levels to understand the weaknesses in the WEEF nexus system.

For our first attempt in applying this framework, we are looking at Sri Lanka. We would like to seek your assistance in gathering information on institutional systems in the Sri Lankan context. The answers to the survey questions given below will be used to quantify the institutional aspects of the nexus. If you are not aware of exact values, wherever possible, please provide approximations based on your expert knowledge. Your responses will be kept confidential.

We thank you in advance for your participation.

Assessing the institutional health of the WEEF nexus in Sri Lanka

What sector do you currently work in? Please indicate all applicable choices.

1. Water
2. Energy
3. Environment
4. Food

Please provide answers to the sectors that are applicable to you. It could be both the sector/s that you currently work in, as well as the sector/s that you are familiar with.

1. **Social formal institutions**

   Social formal institutions that manage these resources (water, energy, environment, food) can be both governmental (e.g., government ministries, government departments, government authorities) and non-governmental (e.g., nongovernmental organizations, water user associations).

a. In Sri Lanka, are you aware of how many formal institutions exist for the following?

	1-10	10-20	20-30	40-50	>50	Not aware
Formal institutions related to Water						
Formal institutions related to Energy						
Formal institutions related to the Environment						
Formal institutions related to Food						

b. How would you rate the collective effectiveness of these formal institutions in terms of fulfilling the role that they have been set up to perform?
Please rate on a scale of 1-5, with 5 being very effective and 1 being very ineffective.

	Rating (1-5)
Institutions related to Water	
Institutions related to Energy	
Institutions related to the Environment	
Institutions related to Food	

2. Legislative institutions

Legislative institutions refer to the development of rules and regulations and other institutions created through legislative processes to manage natural resources.

Are you aware of how many laws and regulations have been created to manage the use of these resources? In the case of overlapping legislation, please assign it to the resource to which it is more closely related.

	1-10	10-20	20-30	40-50	>50	Not aware
Laws and regulations related to Water						
Laws and regulations related to Energy						
Laws and regulations related to the Environment						
Laws and regulations related to Food						

c. How successful is the enforcement of the laws and regulations that have been created to manage the use of these resources?
Please rate on a scale of 1-5, with 5 being high enforcement and 1 being poor enforcement

	Rating (1-5)
Legislation related to Water	
Legislation related to Energy	
Legislation related to the Environment	
Legislation related to Food	

d. How successful is the resolution of the legal cases associated with the enforcement of legislation mentioned above? (What is the proportion of cases filed that are resolved when compared to the total number filed)

Please give a value between 1-100%, with 100% being all cases resolved and 0% being no cases resolved

	Rating (0-100%)
Arbitration success related to Water	
Arbitration success related to Energy	
Arbitration success related to the Environment	
Arbitration success related to Food	

3. Decision-making at different levels

This refers to the level of hierarchy within the political system and the distribution of power.

a. Is decision-making and the power structure completely centralized, or is it decentralized among different tiers of government - national, subnational (provincial) and local?

	Completely centralized	Decentralized
Decision-making related to Water		
Decision-making related to Energy		
Decision-making related to the Environment		
Decision-making related to Food		

b. If the decision-making is decentralized, of the total decision-making, what proportion occurs at the (i) national level, (ii) provincial level, and (iii) local level? Please give a percentage for each level, with the total adding up to 100%.

	Percentage that occurs at national level (%)	Percentage that occurs at provincial council level (%)	Percentage that occurs at local government level (%)
Decision-making related to Water			
Decision-making related to Energy			
Decision-making related to the Environment			
Decision-making related to Food			

4. Land tenure:

How secure is the land tenure system (land property rights) in Sri Lanka?
Please rate on a scale of 1-5, with 1 being very insecure and 5 being very secure

5. Accountability:

Who are you accountable to when fulfilling your duties at work? Please indicate all applicable choices.

i. Level above you

ii. Same level as you

iii. Level below you

6. Policy environment:

a) How well are you aware of policies by the government (ministries, departments, authorities and other bodies) that are associated with the sector you work in?

Please give a value between 1 and 5, with 5 being very high level of awareness and 1 being very low level of awareness

b) When fulfilling your duties in a particular area, what proportion of time do you take into account these policies?

Please give a value between 0 and 100, with 100 being taken into account all the time and 0 being never taken into account

7. **Inter-sectoral communication:**

a) Which of the other sectors are connected to your sector of work? (please mention all that apply)

i. Water

ii. Energy

iii. Environment

iv. Food

v. None

b) If your answer to the above is one or more sectors, what is the extent of your communication with those working in these sectors?

Please give a value between 1 and 5, with 5 being very high level of communication and 1 being very low level of communication

IWMI Working Papers

186 *Unpacking the Water-Energy-Environment-Food Nexus: Working Across Systems.* Aditya Sood, Alan Nicol and Indika Arulingam. 2019.

185 *Improving the Availability and Effectiveness of Rural and "Micro" Finance for Small-scale Irrigation in Sub-Saharan Africa: A Review of Lessons Learned.* Douglas J. Merrey and Nicole Lefore. 2018.

184 *Gender Dimensions of Community-based Groundwater Governance in Ethiopia: Using Citizen Science as an Entry Point.* Likimyelesh Nigussie, Jennie Barron, Alemseged Tamiru Haile, Nicole Lefore and John Gowing. 2018.

183 *Community-managed Groundwater Irrigation on the Vientiane Plain of Lao PDR: Planning, Implementation and Findings from a Pilot Trial.* Corentin Clément, Jordan Vinckevleugel, Paul Pavelic, Kong Xiong, Lengya Valee, Touleelor Sotoukee, Binaya Raj Shivakoti and Khammai Vongsathiane. 2018.

182 *Highlights of Soil and Water Conservation Investments in Four Regions of Ethiopia.* Zenebe Adimassu, Simon Langan and Jennie Barron. 2018.

181 *Investigation of the Modalities for an Innovative Financing Mechanism for Participatory Natural Resource Management in the Bale Eco-region, Ethiopia.* Fitsum Hagos, Daniel van Rooijen, Amare Haileslassie, Habtamu Yehualashet and Husien Indries. 2018.

180 *Water User Associations: A Review of Approaches and Alternative Management Options for Sub-Saharan Africa.* Eefje Aarnoudse, Alvar Closas and Nicole Lefore. 2018.

179 *Dependence of Riparian Communities on Ecosystem Services in Northern Ghana.* Marloes Mul, Laetitia Pettinotti, Naana Adwoa Amonoo, Emmanuel Bekoe-Obeng and Emmanuel Obuobie. 2017.

178 *Understanding the Hydrological Impacts of Climate Change in the Tana River Basin, Kenya.* Aditya Sood, Lal Muthuwatta, Nishchitha Sandeepana Silva and Matthew McCartney. 2017.

177 *Sticks and Carrots: Managing Groundwater Over-abstraction in La Mancha, Spain.* Alvar Closas, François Molle and Nuria Hernández-Mora. 2017.

Postal Address
P O Box 2075
Colombo
Sri Lanka

Location
127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone
+94-11-2880000

Fax
+94-11-2786854

E-mail
iwmi@cgiar.org

Website
www.iwmi.org

IWMI is a CGIAR Research Center and leads the: CGIAR RESEARCH PROGRAM ON Water, Land and Ecosystems

ISSN: 2012-5763
e-ISSN: 2478-1134
ISBN: 978-92-9090-883-8