



# Enabling policy environment for water, food and energy security

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## Abstract

The complexity of water, food and energy security is analysed from the perspectives of (i) water and food and (ii) water and energy and their interconnectivity and focuses ultimately on water as a primary input into processes, the entry point for participants of the Third World Irrigation Forum.

The paper provides an overview of trends in water, food and energy security, highlights the interconnectivity between the various elements and introduces the water–food–energy nexus as a tool for improving productivity and sector policies, avoiding unintended consequences on other sectors. Invariably, there will be trade-offs and the challenge is to find combinations of measures that have a net positive outcome. In order to quantify security in the three elements and the trade-offs between them, emerging modelling approaches for the nexus are discussed.

Sub-theme 3 of the forum focuses on productivity and technology interventions<sup>1</sup> and sub-theme 2 on stakeholder interaction. The combination of modelling, technology innovations and stakeholder participation in a water–food–energy nexus approach leads to better understanding of linkages and more robust policies and is used to derive recommendations for an enabling policy environment.

<sup>1</sup> Sub-theme 3: Improving Agricultural Water Productivity with Focus on Rural Transformation.

**KEYWORDS**

circular economy, policy, productivity, security, water–food–energy nexus

**Résumé**

La complexité de la sécurité de l'eau, de la nourriture et de l'énergie est analysée du point de vue (i) de l'eau et de la nourriture et (ii) de l'eau et de l'énergie et de leur interconnectivité et se concentre finalement sur l'eau comme intrant principal dans les processus, le point d'entrée pour les participants du Forum d'irrigation du tiers monde. Le document donne un aperçu des tendances en matière de sécurité de l'eau, de l'alimentation et de l'énergie, met en évidence l'interconnectivité entre les différents éléments et présente le lien entre l'énergie alimentaire et l'eau en tant qu'outil pour améliorer la productivité et les politiques sectorielles, en évitant les conséquences involontaires sur d'autres secteurs. Invariablement, il y aura des compromis et le défi est de trouver des combinaisons de mesures qui ont un résultat positif net. Afin de quantifier la sécurité dans les trois éléments et les compromis entre eux, de nouvelles approches de modélisation pour le nexus sont discutées. Le sous-thème 3 du forum se concentre sur la productivité et les interventions technologiques. Sous-thème 2 sur l'interaction avec les parties prenantes. La combinaison de la modélisation, des innovations technologiques et de la participation des parties prenantes dans une approche de lien entre l'eau et l'énergie alimentaire conduit à une meilleure compréhension des liens et des politiques plus robustes et est utilisée pour définir des recommandations pour un environnement politique favorable.

**MOTS CLÉS**

lien entre l'eau, l'alimentation et l'énergie, sécurité, économie circulaire, productivité, politique

## 1 | WATER, FOOD AND ENERGY (WFE) SECURITY—THE BASIS OF LIFE AND SOCIO-ECONOMIC DEVELOPMENT

Food and water are essential elements for human existence and, together with energy, are important for economic growth, poverty reduction and social development. Adequate access to these resources and their sustainable management through preserving the ecosystems that support them are the basis for human well-being and socio-economic development, all in a climate of peace and political stability (United Nations Water, 2014). The world is facing an increasing challenge of water, food and energy security. There is already an imbalance between demand and availability, leaving millions of people with shortages of one or more of these vital resources (FAO/IFAD/UNICEF/WFP/WHO, 2017).

The interrelations between water, food and energy are many. In order to systematically frame discussions in Sub-theme 1, *Enabling Policy Environment for Water, Food and Energy Security*, of the Third World Irrigation Forum (WIF3) the most recent definitions for food, water and energy security are used and a compound definition for all three sub-themes is proposed for guidance of the forum discussions.

Using individual definitions for water, food and energy security respectively (Grey *et al.*, 2012; United Nations (UN), 2015; International Energy Agency (IEA), 2016), the proposed compound definition is:

*Everyone, everywhere has enough good quality food, access to sufficient water of acceptable quality for health, livelihoods, production and ecosystems while having uninterrupted availability of energy sources at an affordable price*

*coupled with acceptable level of water risk and energy failures.*

## 1.1 | Consequences of growth on food, water and energy security

The demand for water, food and energy is continually increasing due to rapid population and economic growth in combination with accelerated urbanization and changing lifestyles. It is estimated that by 2030 the global population will need at least 40% more water, 35% more food and 50% more energy (UN, 2015). The world's population is projected to continue growing with approximately 83 million more people being added annually (Gerland *et al.*, 2014; United Nations (UN), 2015), leading to a global population of nearly 10 billion people by 2050.

### 1.2 | Food security

By 2050, the Food and Agricultural Organization (FAO) predicts an increase of global food demand of 70% (World Bank, 2007; Food and Agriculture Organization of the United Nations (FAO), 2009). Meeting the demand for food in a sufficient quantity and acceptable nutritious quality underlines the importance of greater efficiencies in agricultural production systems globally. These are not just theoretical concepts. The number of hungry people has been growing during the last 3 years despite an earlier steady decreasing trend and now amounts to more than 800 million people, back to levels of almost a decade ago; food insecurity is on the rise with the proportion of undernourished people worldwide increasing from 10.6% in 2015 to 11.0% in 2016 (FAO *et al.*, 2018).

Further pressures on agricultural water demand arise from changing food demand and food systems such as the increasing demand for meat, milk and other water-intensive food; for example, the rapid rise in milk production in India and meat production in China (Thakur *et al.*, 2018; Zhuo *et al.*, 2016).

### 1.3 | Water security

Global *water demand*, in terms of freshwater withdrawals, is predicted to grow by about 55% by 2050 (United Nations (UN), 2015). In 2025, over 40% of the global population is projected to be prone to severe water stress. The number of people affected by water shortages has increased over time (Kummu *et al.*, 2010) and, under current development paradigms, this situation can be expected to continue in future due to population

pressure, higher welfare and increasing climate variability (Gosling and Arnell, 2016, United Nations (UN), 2015).

According to the Sustainable Development Goals report 2018 (United Nations Water, 2018) water insecurity remains high, and accelerated progress is needed to meet the sustainable development goal (SDG) 6 targets. For example 30% of people lack a safe water supply (844 million people lack basic water supply facilities and 1.5 billion people have only a basic water supply), and only 39% of the 84 countries monitored in 2015 had safe sanitation facilities, 29% had basic facilities and 2.3 billion people lacked even basic facilities. In the least developed countries, only 27% have basic handwashing facilities. In 2017 progress in water resources management on average over 157 countries was 48%, ranging from 10 to 100%. The difference in progress was not clearly related to the region or level of development.

### 1.4 | Energy security

Global energy demand is projected to rise by 25% until 2040 (International Energy Agency (IEA), 2016). Although considerable progress has been made in electrification, almost 1 billion people are without electricity. Energy insecurity is likely to continue to constrain human development and local economic development in many locations.

### 1.5 | Recognizing interconnectivity

In assessing water use and availability, particularly across sectors, it is important to distinguish between consumption and withdrawals as they are not the same. Consumption is defined as the conversion of water from its liquid state to a vapour<sup>2</sup> state, either by agriculture through crop evapotranspiration, evaporation from water and land surfaces, being incorporated into products or crops, or consumed directly by humans or livestock (US Geological Survey (USGS), 2014). A significant fraction of withdrawn water is generally returned to storage in water bodies or aquifers. For example, in Pakistan the total withdrawal by the Indus Basin Irrigation System is 136 BCM (billion cubic metres), but only 82 BCM of this amount is consumed (Young *et al.*, 2019). The quality of the returned water is affected by its use, and recycling for

<sup>2</sup>For simplicity, here we assume that the water converted to vapour by evapotranspiration is 'lost' to the atmosphere. Within greenhouses this water can be recycled.

safe reuse downstream can require special attention and incur treatment costs.

### 1.5.1 | Water for food

Over 70% of global freshwater withdrawals is used for food production (Hoekstra and Mekonnen, 2012; D'Odorico *et al.*, 2018). Water for food production, including crops and livestock, accounts for about 92% of the total societal water 'consumption' (Hoekstra and Mekonnen, 2012). The importance of water in agriculture is apparent as irrigation contributes to about 40% of the world's food production from approximately 20% of all agricultural land (FAO, 2018).

### 1.5.2 | Water for energy

Water is needed for the main processes in the energy sector, from energy extraction, electricity generation, refining and processing. Currently, energy withdrawals amount to about 10% of total water withdrawals globally (IEA, 2016), while the global water consumption for energy is 4.7% (Hoekstra and Mekonnen, 2012). Hydropower and biofuel have the highest water footprint; evaporation from hydropower reservoirs consumes on average 5.41 m<sup>3</sup> MWh<sup>-1</sup> while corn for ethanol consumes 25.8 m<sup>3</sup> MWh<sup>-1</sup> (Mannan *et al.*, 2018). Water withdrawals for energy production in some parts of the world can be much higher and account for up to 49% of all water withdrawals. Based on estimates in 2010, approximately 75% of total industrial water withdrawals are used for energy production (UN World Water Assessment Programme Secretariat (WWAP), 2016).

The picture on water consumption and withdrawal for energy is mixed. In some cases, it is expected that withdrawals for energy will increase much less than consumption because of a switch to more sophisticated cooling technologies that withdraw less but consume more water. Overall, it is projected that by 2035 water withdrawals by the energy sector could rise by 2% to 400 BCM and consumption by 60% to 75 BCM (IEA, 2018). Uncertainty of water availability for the energy sector is already evident in some places. For instance, a coal-fired power plant was shut down in India due to water shortage (IEA, 2015), in California electricity generators needed to negotiate a reduction in domestic water supply to maintain adequate availability of cooling water (Keulertz *et al.*, 2018), while in Texas, shale oil and gas extraction, using hydraulic fracturing, have to compete for water with agriculture (Rosa *et al.*, 2018).

### 1.5.3 | Water for energy and food

Hydropower generation is a clear energy–water–food–environment connectivity case. Many hydropower projects have multiple uses including irrigation and flood management, leading to tensions in operating rules of the reservoirs due to different priorities. But even single-purpose hydropower projects have cross-sectoral implications. They can influence the pattern of downstream flows that have consequences for food production and the environment. For example, in central Asia hydropower peak demand is in the winter, while peak irrigation needs are in the summer. Hydropower dams also impact the environment both locally and beyond due to changes in river flows, habitat change and blockage of fish migration routes.

### 1.5.4 | Agriculture and land for energy and water

Agriculture has a dual role as an energy user and as an energy supplier in the form of bioenergy. Over 1% of crops produced are utilized within the bioenergy sector. Sustainable agricultural practices can also save energy, for example by reducing the use of energy-intensive fertilizers. Agriculture and food production have a further impact on the water sector through their effects on land conditions, runoff, groundwater discharge, water quality, and availability of water and land for other purposes, such as natural habitats (Alauddin and Quiggin, 2008). Climate policies, globally, can lead to an increased demand for biofuel (Mercure *et al.*, 2017). The biofuel industry is rapidly expanding leading to the increasing diversion of crop supply towards the production of bioethanol and biodiesel, mainly maize in the United States, sugar cane in Brazil, rapeseed in Europe, and oil palm in Indonesia and Malaysia (e.g. Rulli *et al.*, 2016). Since the demand for energy can be partially met by biofuels, if this approach expands significantly, energy and food production will increasingly compete for water, challenging our ability to produce sufficient food and fibre on limited land and with diminishing mineral nutrients and water.

### 1.5.5 | Energy for food and water

Energy is required for food production, transportation, processing, packaging and for water supply, including extraction, purification and distribution of water (Nonhebel, 2005; Bazilian *et al.*, 2011). The global food system is dependent on fertilizer production; for example, half of the energy used for non-organic bread production

in the United Kingdom is used for the production of nitrogen-based fertilizer inputs (Mannan *et al.*, 2018). Agriculture production is increasingly dependent on energy, principally on oil and natural gas, due to ever-increasing mechanization, intensification and increasing reliance on agro-chemicals. Groundwater irrigation is more energy-intensive than surface water irrigation and about 8% of all energy generated is utilized for the pumping and treatment of water (Hoff, 2011). The food production and supply chain alone accounts for over 30% of total global energy consumption, mainly depending on fossil fuels as its source currently (FAO, 2011a).

According to Mannan *et al.* (2018), about 10% of the United States of America (USA) energy consumption or 2,28 gigawatt hours (GWh), is used in agriculture. Of this energy use, 21% or 479 GWh is used for crop cultivation, including fertilizer and pesticide production, and fuel for field preparation and harvesting, another 14% (320 GWh) is used for transportation of the produce, 11–16% for food processing and 50% for food handling, such as packaging, services and sales.

Energy used in irrigation depends greatly on the local conditions and irrigation method. For example, Daccache *et al.* (2014) show that Spain ranks highest in the Mediterranean region in terms of energy demand for irrigation (>774 GWh) followed by Turkey (570 GWh) and Syria (529 GWh), even though irrigation water demand in Spain is 8 BCM, while in Turkey and Syria it is around 10 BCM. Central Asia also has high energy use for irrigation due to pumping of water to a considerable height. Significant improvements are shown to be possible by Djumaboev *et al.* (2019) who found that by better irrigation scheduling alone, more than 575 MCM (million cubic metres) and 259 GWh can be saved.

### 1.5.6 | Energy for water supply and sanitation

Pumping of water from the source and for distribution in water supply networks is needed. Energy is also needed for treatment of raw water to a potable standard and the treatment of wastewater. The entire process is energy-intensive; for example, the USA consumes about 4% of the total energy production in water supply and sanitation (Copeland and Carter, 2017). For countries dependent to some degree on desalinating seawater for their water supply, energy requirements are much higher, for example in the Persian/Arabian Gulf countries (Keulertz *et al.*, 2018).

Increasing stress on water resources and the multiple and complex interrelations between food, water and energy security were summarized in the previous

paragraphs. Climate change adds to uncertainty and further complicates resource management and allocation. Limited guidance exists on how to potentially plan for climate uncertainty although some examples are emerging, for example the recent National Water Initiative of Australia (2017) and the Netherlands Delta programme (2019).

The linkages outlined above demonstrate the need for effective management tools such as data and information, policies and institutions that are able to recognize and systematically address competing pressures on the resource.

## 2 | CONTEXT: WATER, FOOD AND ENERGY SECURITY WITHIN THE BROADER DEVELOPMENT AGENDA—ADOPTING A NEXUS PERSPECTIVE?

### 2.1 | Need for a broader perspective

Meeting each of the sectoral SDG<sup>3</sup> goals for water, food and energy is a major challenge in many countries. The lack of an integrating resource management framework exacerbates this challenge through the risk of inefficient use of resources. Prevailing sectoral approaches to planning of energy, food and water often take place in the absence of meaningful consideration across sectors.

Inter-sectoral considerations are very evident at a local scale and are recognized by researchers and practitioners supporting the delivery of development services at community level. Ostrom (2010) found multiple cases where local resource users had successfully self-organized resources management. Based upon her findings, she elaborated attributes of the social–ecological systems (SES) that determine the success of self-organization: e.g. the number of users, the size and predictability of the resource system. Hence, the Ostrom (2010) model explains what seems evident at community scale, but appears to get lost and subdivided when one moves up to district, provincial and state levels of administration.

Ideally, greater competition for water will stimulate its more economically efficient use and facilitate allocation towards the most appropriate use that Ostrom's insights reveal, that 'efficient' reallocation of a scarce resource requires both constraints to access and mechanisms to facilitate reallocation. Institutional, regulatory and physical systems take time to develop and respond to

<sup>3</sup>SDG Goals 2, 6, 7, 11 and 13 explicitly link to the nexus and consequences of decisions made will influence Goals 14 and 15.

increased scarcity. Short-term perspectives that protect the status quo often prevail due to political expediency: political decisions can also have unintended consequences, for example in India and Pakistan where energy is subsidized as part of their rural income policies. Ringler *et al.* (2013) show that the poor benefit least from energy subsidies and they lead to over-extraction of groundwater, excessive water use and a misallocation of water.

More recent subsidies for solar irrigation systems as part of government carbon mitigation programmes are expected to exacerbate overpumping of groundwater because the marginal cost of pumping will essentially be zero (Shah, 2018). This demonstrates how subsidies designed to address problems in one sector can have unintended consequences in others. In Egypt, the government increased its food subsidy allocation by 20% in May 2016 to mitigate the impact of rising inflation due to devaluation of the currency. Currently, 67 million citizens (out of a total population of 92 million) benefit from the food subsidy system. Such subsidies may be important politically, but do not encourage efficiency of resource use (Reinhard *et al.*, 2017).

The ways that water is consumed by society have rarely been shaped by awareness of their scarcity or their value (Allan *et al.*, 2015). Water governance and pricing are ideally deployed to ensure productive and efficient water use and equitable water distribution. Competition inevitably increases from water users who generate more welfare (e.g. income) with their water use (Hellegers *et al.*, 2008; Scott *et al.*, 2015); for example, people in municipalities are able to pay far more for the use of water than subsistence farmers can.

The challenge, therefore, remains how to achieve a balance between using the water resource to meet growing and competing demands of food, water and energy security, meeting a nation's development aspirations, while at the same time ensuring the integrity of ecosystems, and tackling the challenges of climate change and increased variability.

## 2.2 | Introducing the food, water and energy nexus

Recognizing the urgent need for efficient use of the existing limited or declining natural resources base to achieve sustainable development goals, the global community has turned its attention to the concept of the water, food and energy nexus. The World Economic Forum and the Bonn Nexus Conference, both in 2011, promoted this concept and were followed by coverage of nexus thinking in several regional conferences, research

programmes as well as knowledge products of practitioners.

The nexus approach is based on system-wide thinking for the sustainable use and management of interlinking resources and processes within water food and energy systems. It is aimed at providing tools to assess the use of a broader set of resources than conventionally has been the case, as well as managing the inevitable trade-offs and exploring synergies for planning of sustainable adaptation responses (Bazilian *et al.*, 2011; Hermann *et al.*, 2012; Prasad *et al.*, 2012; Rasul and Sharma, 2016). One representation of the water, food and energy nexus is given in Figure 1 by Rasul and Sharma (2016).

Policy recommendations from the Bonn 2011 conference include the need to enhance policy coherence, produce more with less, promote natural infrastructure and increase stakeholder participation.<sup>4</sup> Focusing on the nexus aims to provide an evidence base of approaches and solutions to meet the challenge of a future with limited natural resources. In agricultural water management it places the challenge in improving (crop) water productivity across levels from field level to river basin, incorporating energy implications.

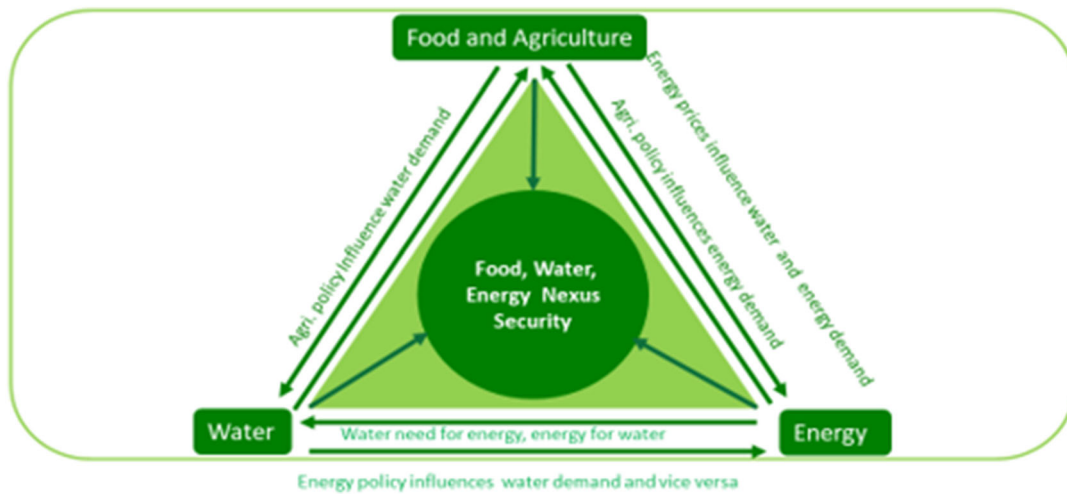
By comprehending the complexity of the interconnections between dimensions of the WFE nexus and addressing the trade-offs, a long-term, concerted and sustained strategy can be developed and applied to achieve resource security (Rasul and Sharma, 2016; D'Odorico *et al.*, 2018). The nexus can also stimulate innovation and use of new technologies as discussed below.

Achieving synergies and win-wins is not easy—most cases involve trade-offs between sectors. Adopting good practice in one sector can however lead to benefits in others. For example, well-established improvements in agronomic, land management and water management practices can lead to reductions in both water use and energy consumption. These include land preparation techniques, soil conservation practices and pressurized irrigation systems. The question though remains as to whether there are sufficient incentives, including price signals, for farmers to adopt such practices.

## 2.3 | Challenges inherent in adopting an integrated approach

A word of caution about 'integrated' and 'nexus' approaches is also needed. There is a risk that 'the nexus' becomes an end in itself rather than a means to recognize

<sup>4</sup>[https://www.water-energy-food.org/fileadmin/user\\_upload/files/documents/bonn2011\\_policyrecommendations.pdf](https://www.water-energy-food.org/fileadmin/user_upload/files/documents/bonn2011_policyrecommendations.pdf)



**FIGURE 1** Dynamic relationship between food, water and energy security (adapted from Rasul and Sharma, 2016)

critical challenges. Food security and energy are three separate policy areas that interact with each other in unpredictable ways and require differing approaches to address their differing challenges (Perry, 2019). In the case of water, if governments fail to restrict currently excessive demand through an orderly, managed process, the unavoidable outcome will be ‘chaotic disallocation’ of water from irrigated agriculture as aquifers become unusable and rivers run dry. This ‘disallocation’ of water first affects the environment and then irrigated agriculture. These processes will not be orderly, or prioritized. There is no way to predict whether the most or least productive farmers will suffer—but all farmers will become more risk-averse and less willing to invest in highly productive agriculture as uncertainty begins to dominate their access to water.

This perspective demonstrates the complexities of overcoming a lack of institutional commitment to address issues of over-abstraction and at the same time reinforces the need for a different approach, where solutions in one sector do not exacerbate insecurity in another and where the trade-off discussions look for synergies. In cases where resources are not constrained, then single-sector solutions may suffice, although still cost savings may be apparent by taking a broader perspective.

## 2.4 | Linkage to the ICID discourse

The International Commission on Irrigation and Drainage (ICID) is working collectively towards a common goal of realizing a more integrated and holistic approach to water resources management. Among the number of existing water, food and energy nexus frameworks, the ICID strategy for implementing the Vision for Water for

Food considers the approach from the FAO (2014) as appropriate to harness the food, water, energy systems in the agricultural sector (ICID, 2017). This framework describes nexus interactions as how we use and manage resource systems as well as explore interdependencies, trade-offs and synergies pertaining to water, energy and food. It mainly focuses on the biophysical and socio-economic resources base on which we rely to sustain life and achieve socio-economic development goals.

Papers submitted for Sub-theme 1 of the Forum include those dealing with the consequences of resource overuse and practical reallocation of resources, with water innovations for improving irrigation and agricultural productivity, including smart and high-technology approaches, and aspects of the circular economy and sustainability focusing on reuse and reductions in impacts on water quality. Beyond this sector focus, there are a number of papers dealing with modelling the broader nexus dimensions and monitoring nexus outcomes.

## 3 | UNLOCKING THE NEXUS—FRAMING OF AN ANALYTIC APPROACH

### 3.1 | Call for a framework within which alternative development decisions can be evaluated

The nexus approach to decision making encourages decisions on one sector to take into account other sectors or internalize the externalities to the extent possible. Decisions on water would require the inclusion of effects on food and energy—are they positive, negative or neutral? The decision space would expand, depending on the level

of cross-sectoral influence and the search for trade-offs. Beyond that, more creative thinking is encouraged to move towards 'nexus-positive' outcomes where actions in one sector have a mutually beneficial outcome in others.

The task of finding win-win solutions is complicated however by quite different and separate institutional frameworks and planning processes in the main water, food and energy sectors. For example, the agricultural sector is dominated by rural policies to sustain livelihoods in rural areas and the need to keep basic food products within the affordability of both urban and rural communities. Energy security is a national commitment central to economic and industrial growth, but often follows quite different planning processes and timescales from food and water. In many cases, it is a regulated private sector arrangement where developers respond to market signals for the provision of a new power station. Private sector processes make it more complex to factor in planning considerations for other predominately public sector services and has to be done through regulatory signals and in the upstream framing of projects.

Such an integrated approach is neither new, even for the nexus topics of water, food and energy, nor are they restricted to these in a narrow sense (Woltjer *et al.*, 2019). Burnett and Wada (2018) distinguish three types of dependencies between them: (i) direct dependencies; (ii) direct competition; (iii) externalities. Direct dependencies and direct competition gain most attention in nexus research, mainly when analysed from a physical perspective. Externalities are often difficult to physically quantify, and even more difficult to monetize (Burnett and Wada, 2018).

Although conventional cost-benefit analysis can provide an insight into the viability of any outcome, more nuanced indicators are needed to distinguish between them and the degree that overall development objectives are being met. The search for an all-embracing single 'nexus indicator' is challenging due to the multiple dimensions involved and indeed it may not be possible to end up with a single measure. Some suggestions include a monetary measure or one that focuses on efficiency of resource use. So far, the authors are not aware of a satisfactory approach to nexus indicators. This challenge recently faced the Asian Development Bank which, having embraced the concept of the nexus in its recent Strategy 2030,<sup>5</sup> raised the question of how to measure the bank's effectiveness in improving integrated resource use efficiency.

It is in general difficult to measure marginal external costs, and assessing the effects of several domains in one integrated analysis would inevitably include uncertainties and ambiguities. Currently the research discussion is predominantly based on availability or scarcity of resources and projected costs and benefits in related sectors but a reality test is also needed, taking into account the practicalities of implementing potential solutions within prevailing institutional and governance systems. Many earlier attempts at greater integration across sectors have been successful at policy level only to fail in implementation (Giordano and Shah, 2014). Rasul and Sharma (2016) show that in many instances there is a lack of policy coherence across sectors as well.

Although most research has been devoted to quantifying the nexus (Keulertz *et al.*, 2018) there are only limited examples of the results of such a quantification. In this paper we argue that due to the complexity of quantifying direct dependencies, direct competition and externalities, models are required to assess potential trade-offs at local scale. Such an approach could provide quantifiable indicators for progress monitoring, and also inform stakeholder engagement by focusing on localized solutions on the basis of physically quantifiable information and indicators. The SIM4NEXUS project aims to predict society-wide impacts of resource use and relevant policies on sectors such as agriculture, water, biodiversity and ecosystem services through a model-based analysis (e.g. serious gaming).<sup>6</sup>

### 3.2 | Examples of potential decision support tools—using models to provide a window on the consequences and benefits of alternative actions

Despite the progress in recent years, there remain many challenges in scientific research on the food, water and energy nexus, while implementation as a management tool is just beginning. The scientific challenges are primarily related to data, information and knowledge gaps in our understanding of the food, water and energy interlinkages (Liu *et al.*, 2018). Furthermore, despite the nexus literature identifying some barriers to achieving coherence it does not clearly explain why the barriers are present, what influences them and how they can be acted upon. These gaps disconnect the nexus literature from the governance processes it ultimately seeks to influence.

<sup>5</sup><https://www.adb.org/sites/default/files/institutional-document/435391/strategy-2030-brochure.pdf>

<sup>6</sup>[www.simnexus.eu](http://www.simnexus.eu)



### 3.2.1 | Modelling approach

Enabling a robust policy environment for food, water and energy security requires the capability of combining detailed knowledge of the physical and transactional dynamics within or between sectors with the requirements of multiple stakeholders. Bazilian *et al.* (2011) suggest that robust analytical tools harnessing existing data can advance scientific understanding and make analytical resources accessible to a range of end-users, particularly in regions with limited data availability and computing resources. Communication and collaboration are key components for successfully managing shocks in the food, water and energy nexus space by bridging the disconnect between knowledge producers and users (Mohtar and Lawford, 2016) as well as the disconnect between communication of uncertainty and the risk at local, national and international scales. To be effective, the processes and data required have to be of sufficient resolution to accurately and robustly address the problem. The lack of data and knowledge of cross-sector understanding have long been considered an impediment to the implementation of such models. But the advent of advanced informatics technology and data from multiple sources greatly increases the power of the nexus models. Information products that use remote sensing and advanced models to interpolate field observations provide invaluable input data. The challenge is how to mobilize all those data into useful products. Here, we represent examples of contemporary models that combine to form the modules addressing nexus issues.

### 3.2.2 | Individual components

Starting with water resources as the central thread across all sectors, the responsibility of a *water module* includes overall water accounting and the water footprint by determining the mass of water entering and exiting the river network. The *energy module* relies on this to determine the supply of water available for hydropower generation or cooling of thermal plants, and the *cropping model* relies on this to determine water available for either rainfed or irrigated agricultural conditions. The water module needs to be represented by a spatially explicit model of sufficient resolution to capture basin processes relevant to the decision maker. Open-source, large-scale hydrological modes can be used to quantify regional energy and water balances. For example, such models as variable infiltration capacity (VIC), the crop land model (CLM), the model developed by the National Center for Environmental Prediction (NCEP), Oregon State University (Dept of Atmospheric Sciences), Air

Force (both AFWA and AFRL—formerly AFGL, PL) and Hydrologic Research Lab—NWS (now Office of Hydrologic Dev—(OHD)), with the acronym NOAH, and their brethren use the high-resolution climate forcing, soil and vegetation information that is now available.

Spatially explicit hydrology models do not usually represent human impacts from energy or agriculture explicitly, but instead couple to other offline models to simulate these impacts. This approach does not account for the dynamic interaction between energy, agricultural and water systems. Most hydrology models do not explicitly represent groundwater; instead base flow is produced through the bottom soil moisture layer. While progress is being made to better represent groundwater in standard hydrology models, it currently remains best represented with separate groundwater models.

### 3.2.3 | Linking models

A priority in capturing coupled human/natural system dynamics is through quantification of explicit linkages between basin agricultural practices and the hydrological cycle. The examples given in this section are not exhaustive, but rather provide a window on some of the current possibilities. A cropping systems model can serve as the cornerstone of a high-fidelity food module. Such a model, should be a multi-year model capable of simulating soil water budgets, nutrient budgets, carbon cycling, crop growth and yield, residue production and soil erosion at a combination of hourly and daily time intervals.

The explicit linkages between land use practices and hydrological systems have been well established by prior efforts coupling cropping and hydrology models, for example SALTMED (Ragab, 2015), a program developed under the project on a systems approach to a sustainable increase in crop production in salinity-prone areas of the Mediterranean region.

An energy sector module is needed to capture the energy consumption of buildings, industry and transportation, while being sensitive to energy market prices at the regional boundary and direct or indirect linkages with the food and water sectors. The highest fidelity version of an energy module captures direct linkages with the food module through the energy consumption of industrial fertilizer production, refrigerated food storage and retail food outlets. Indirect linkages to food arise through the electric demands of irrigation and water storage infrastructure operations in support of crop production, a coupled dynamic captured within an integrated decision information framework combining modules for food, energy and water. An additional linkage with agriculture is the production of supplemental

biofuel and biogas. Models are available for modelling transport costs of various options based on prevailing fuel costs.

The EAGERS energy module is an example that captures the direct linkage of water runoff and base flow from the hydrologic modelling as part of a larger simulation of the regional electric network (McLarty, 2019, personal communication). EAGERS co-optimizes the management of hydroelectric generators and water for energy generation and storage systems. In an unperturbed simulation this solution represents the optimal management strategy for the maximum economic output of the reservoir system for electricity production. Management practicalities are introduced through system-wide and reservoir-specific constraints for flood control capacity, agricultural diversions or treaty requirements. The constrained optimization efficiently computes the Pareto horizon of management decisions which illustrates the trade-off potential between different basin priorities.

Harou *et al.* (2010) studied how optimization could be an effective response to prolonged severe drought. Using a hydro-economic model covering the entire water supply system of California, they minimized state-wide costs from water scarcity and water operations by allocating, storing and trading water throughout the network. This kind of model is useful to determine how well the water system could be able to cope with droughts and provides insights regarding institutional instruments and water policy management. Under the future design and assessment of water–energy–food–environment mega systems (DAMS) research project, modellers are using river basin simulation across multiple scenarios and metrics to explore the trade-offs involved in setting and revising reservoir operating rules. The trade-offs of alternative development scenarios are presented through innovative visualization of the results demonstrating the trends for downstream environmental flows, energy generated and financial benefits. It extends conventional planning modelling through its ability to represent many more dimensions of the river basin with energy generation models (Geressu and Harou, 2019).

As an example of applying more broadly defined models, Amjath-Babu *et al.* (2019) aimed to quantify the benefits of proposed water resource development projects in the Koshi River basin, a transboundary sub-basin of the Ganges River basin, in terms of hydroelectric power generation, crop production and flood damage reduction. A hydro-economic model was constructed by soft coupling hydrological and crop growth simulation models to an economic optimization model. The model assessed the potential of the interventions to break the vicious cycle of poverty and water, food and energy insecurity. Unlike

previous studies, the model: (i) incorporated the possibility of using hydropower to pump groundwater for irrigation as well as flood regulation; (ii) quantified the resilience of the estimated benefits under future climate scenarios. The results showed significant potential economic benefits generated from electricity production, increased agricultural production, and flood damage control at the transboundary basin scale and the potential to contribute to minimizing trade-offs and improve water, food and energy security.

Water evaluation and planning system (WEAP) and long-range alternatives planning system (LEAP) are also software packages developed by the Stockholm Environment Institute (SEI). These models have been applied separately as per their respective designed purpose. However, the models were recently integrated to become ‘WEAP–LEAP.’ The integrated WEAP–LEAP model can now be applied for waterenergy related scenarios, evaluation by alternating parameters resulting in different outputs, such as energy generated (hydropower) or water requirements for cooling (SEI, 2013; SEI, 2014; Dargin *et al.*, 2019).

Other applications evaluate the change of land use scenarios on the water balance. For example in the Frome catchment, United Kingdom, Afzal and Ragab (2019) found that converting other uses to broad-leaf trees would lead to a decrease in stream flow by 5–16% and groundwater recharge by 1–21%, replacing barley by oilseed rape (biofuel) would lead to a decrease in stream flow by 4–16% and groundwater recharge by 2–23%, and replacing grass by oilseed rape would lead to a decrease in stream flow by 6–21% and groundwater recharge by 5–21%, depending on the season. Montenegro and Ragab (2012) in another catchment in the semi-arid north-east of Brazil reported that changing land use from vegetables to sugar cane (biofuel) would result in decreasing groundwater recharge by almost 11% and increasing stream flow by almost 5%. Such results are expected to affect the environmental policies for north-east Brazil and biofuel production perspectives in the region.

#### 4 | IMPROVING THE PRODUCTIVITY OF THE RESOURCE: EXAMPLES OF TECHNOLOGY, POLICY AND GOVERNANCE INTERVENTIONS

Given the focus of WIF3, in this section we focus on innovations in the agricultural production dimension of the nexus, in its broadest sense such as water and energy use for food crops, fodder, biomass, and aquaculture

rather than the water supply or energy production dimensions.

#### 4.1 | Water productivity

Irrigation efficiency has for a long time been a measure used to help gauge the effectiveness of irrigation and is used to help define irrigation performance at various levels of the system (Ahadia *et al.*, 2013). Various definitions of irrigation efficiency have been developed and used (Israelsen *et al.*, 1944; Jensen, 1967; Bos, 1985, etc.). However, water productivity in kg m<sup>3</sup> or US\$ m<sup>3</sup>, depending on the prevailing development objective and degree of water scarcity, is preferred, as this links the production (or benefits) to the water consumption. It can be used for crop- and location-specific assessments (Giordano *et al.*, 2017). The advent of more cheaply available satellite imagery with a higher resolution and wider spectral coverage has led to remote sensing systems for assessing water productivity at field scale.<sup>7</sup>

The productivity of water in irrigation increases with the adoption of precision technologies such as variable rate irrigation, lower energy irrigation, drip irrigation, irrigation scheduling, fertigation and chemigation (Tollefson *et al.*, 2014).

#### 4.2 | Innovative technological applications for addressing food, water–energy nexus challenges

A whole range of technical and management interventions that have been characterized as ‘good practice’ or ‘sustainable water management’ are available, many of which have been featured at the Forum.

*Reducing field applications through improved water management in the root zone.* More efficient application of water for irrigated crops requires energy to pressurize the water delivery system. Energy gains can be obtained by using alternative energy sources to build the pressure, or by reducing the water application. New technologies for estimating water needs at different times of the season and crop growth stages include scintillometers and eddy covariance to measure actual evaporation values that represent the real crop need for water. Results of the Water4-Crops project in southern Europe<sup>8</sup> showed that at least 50% of irrigation water could be saved by better quantification of actual crop water requirements using modern

technologies (Ragab *et al.*, 2017a). In the same project the cosmic ray soil moisture sensor (COSMOS), which uses non-invasive, non-destructive natural atmospheric cosmic rays, was shown to accurately sense soil moisture for an area of 300–700 m radius from 0 to 60 cm depth; this solves the problem of spatial variability and can be used to avoid harmful water stress under irrigation (Ragab *et al.*, 2017b).

These new technologies when accompanied by an efficient irrigation strategy such as the partial root drying method (PRD, Ragab *et al.*, 2015) and subsurface drip irrigation has the potential to save even more water, and importantly reduce energy use.

A word of caution is needed. There are limits to the increase of water productivity in the open air; highly efficient irrigation may, in the absence of sufficient precipitation, lead to salinization of the root zone. The limiting of water supply in traditionally irrigated areas may also lead to falling groundwater tables and drying up of rivers.

#### 4.3 | Greenhouse cultivation and optimizing circular use of inputs

The emerging technology of greenhouse horticulture has the potential to radically reduce crop water demand, particularly in arid countries. The reduction of water (irrigation) and energy (pumping) inputs to produce food is a clear nexus case, and better fertilization providing the exact amounts crops need and introducing recapturing systems for the used chemicals can lead to systems highly efficient for external inputs.

The Wageningen University and Research (WUR) Greenhouse Horticulture business unit has studied, developed and made applicable numerous innovations in the field of energy conservation and novel energy conversion techniques. Proven examples are greenhouse covering materials that keep a good transparency while improving insulation and development of improved strategies for using thermal screens to save energy without the risk of problems with pests and diseases. New fossil fuel free greenhouse designs are made and tested for the future.

In research in Riyadh where conventional water use for tomato production is around 300–400 l kg<sup>1</sup> of tomato, this has been reduced to only 50 l kg<sup>1</sup> using mid-level technology and only 4 l kg<sup>1</sup> using high-technology solutions.

Seawater greenhouses (Davies and Paton, 2005) can be used to desalinate seawater without external energy inputs. Seawater is also let into a greenhouse and subsequently evaporated by solar heating and condensed to produce fresh water. The remaining humidified air can

<sup>7</sup><http://www.fao.org/in-action/remote-sensing-for-water-productivity/overview/about-the-programme/en/>

<sup>8</sup>[www.water4crops.org](http://www.water4crops.org)

be expelled from the greenhouse and used to improve growing conditions for outdoor plants or the water could also be condensed and circulated for reuse. For saline chemically polluted water, the application of SolarDew systems can be considered as well. SolarDew systems are purely solar-driven membrane distillation systems that consist of a membrane unit in the form of a 'plastic bag' in a housing. They can be installed on the roof of a greenhouse for which they also serve as a cooling unit. Of the source water that flows into the system, 10–20% flows out as brine and the remaining 80–90% is pure water fit for irrigation. The daily production, depending on solar radiation, is around 8 l of pure water day<sup>-1</sup> m<sup>-2</sup> or 8 mm. Cost are between €0.01 and €0.02 l<sup>-1</sup> mainly because of the costs of the membrane units that have to be replaced every 3–4 years ([www.solar dew.com](http://www.solar dew.com)).

Other promising initiatives include the use of the potential energy of water in irrigation systems to electrify off-grid and remote villages. Techniques have been developed to develop easily installed portable turbines, adapted to variable flows, requiring limited head loss and causing minimal interference with the flow systems in small canals. Such systems have been successfully applied to electrify remote villages and are a good example of a positive water, food and energy nexus<sup>9</sup> ([www.heliosaltas.com/how-micro-hydro-can-aid-farmers-in-developing-countries](http://www.heliosaltas.com/how-micro-hydro-can-aid-farmers-in-developing-countries)).

After the dramatically increased food production potential since the 1970s when the limits to growth dominated the development paradigm, entirely new possibilities have risen. The above examples of further improving productivity of water, recycling water and nutrients in greenhouses, desalinizing water using solar energy and using potential energy of water in a much wider range than reservoirs for generating power, are all elements of a more circular economy. A circular economy and its underlying principles form a new paradigm in our striving for development and sustainability, gaining rapidly more attention and providing new positive challenges for further development and progress (e.g. Raworth, 2017; Vanham *et al.*, 2017).

#### 4.4 | Policy instruments for managing water–food–energy nexus challenges

Using the nexus approach to improve trade-offs requires a major shift in the decision-making process towards taking a holistic view and an integrated approach, as well as developing institutional mechanisms to coordinate the

actions of diverse actors and strengthen complementarities and synergies among the three sectors. Both regulatory and market-based instruments need to be aligned to incentivize nexus-positive activities. Below a policy framework is introduced, following Figure 2.

##### 4.4.1 | Regulatory measures

###### *Monitoring groundwater use using remote sensing chips*

In parts of India, the government has recently initiated an innovative approach to monitor and measure extraction of groundwater through remote sensor chips installed in new solar water pumps (Gupta, 2019). Installing level sensors in pumps, which automatically stop pumping water when the water level drops below a certain limit, or implementing policies where farmers have to pay for groundwater extracted by the unit, would be helpful in managing groundwater over-extraction (Gupta, 2019).

##### 4.4.2 | Market-based instrument

Given the limitation of regulatory measures, many market-based innovations are introduced to manage the water–agriculture–energy nexus.

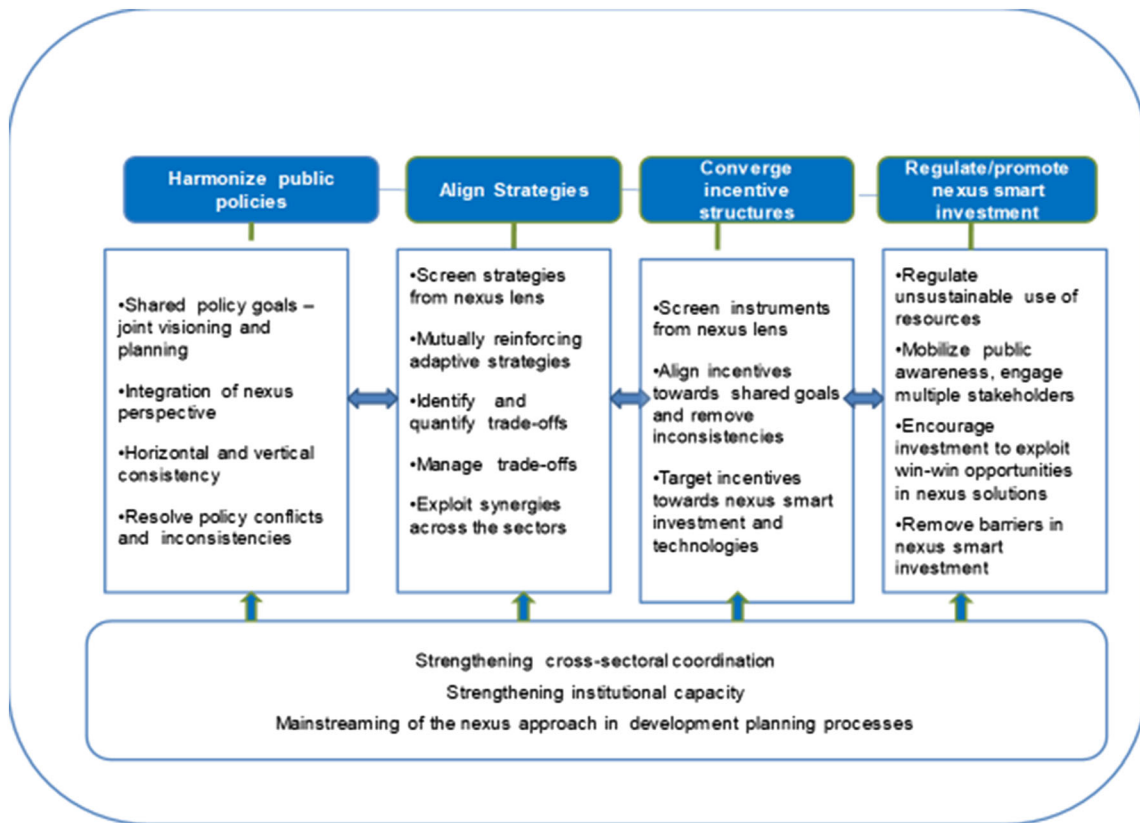
###### *Water buybacks*

Water withdrawal has been increasing for consumptive uses, and with it so has the demand to conserve water for maintaining environmental flows. Market-based instruments are used in several developed countries where water rights are purchased (buyback) to meet environmental demands, for example in Australia's Murray–Darling Basin (MDB), the Klamath Basin of southern Oregon and northern California, USA and the Murcia Plateau in the south-eastern Segura River basin of Spain (Garrick *et al.*, 2009; Calatrava and Martínez-Granados, 2018). Though costly, potential benefits of this market-based approach are considerable in addressing environmental purposes.

###### *Electricity pricing and metering*

Subsidized and unmetered tariffs of electricity supply to agriculture have led to excessive energy and groundwater use in many countries, but a better quality of power supply and metering in combination with increased unit pricing can conserve groundwater (Bassi, 2014; Kumar, 2016). In the 1980s in the Barind region of Bangladesh, farmers with few resources were only able to grow a single crop and had no access to groundwater. Technological advances have opened possibilities for

<sup>9</sup><https://www.heliosaltas.com/how-micro-hydro-can-aid-farmers-in-developing-countries/>



**FIGURE 2** Policy framework for managing the water–food–energy nexus (after Ghulam Rasul, 2016)

conjunctive use of water, even for those without their own wells. A pre-paid meter with smart cards and installation of underground plastic pipes have changed irrigated agriculture and reduced disparity among the farmers and encouraged timely water supplies and timely repairs while the command area increased by 22% (Zaman, 2013). Comparable practices are now widely adopted in new irrigation projects funded by the Asian Development Bank in the eastern Gangetic River basin. The state government of West Bengal in India has initiated tariff reform in agriculture by installing meters on all its new electric irrigation pump sets and changed from a flat tariff per user to a consumption-based tariff.

#### *Solar pumping programme*

Supplying energy for pumping groundwater for irrigation has become an integral component of the food–energy–water nexus. In India, solar pumping as part of the climate mitigation policy was stimulated by subsidizing part of the capital cost to farmers. Studies indicate that solar pumps have led to increased crop productivity in some areas and reduced electricity and diesel consumption. However, it has also increased the extraction of groundwater in some areas (Gupta, 2019). Inspired by the success of solar pump irrigation, the state government

of Maharashtra adopted a new approach—the solar agricultural feeder, under which farmers can export surplus electricity generated by solar pumps to the state electricity grid. Similar arrangements have been trialled in Gujarat involving cooperatives of solar-producing farmers as an intermediary institution. The resulting incentive framework has had impressive results in curbing water use and providing an additional source of income for farmers while maintaining agricultural production levels (Shah *et al.*, 2017). These findings are challenged by Sahasranaman *et al.* (2018), questioning economic viability and cautioning about potential effects on either lack of food production or over-extraction of groundwater.

#### **4.5 | Policy interventions—incentives to address the competing environment**

Best results in the complex food–water–energy trade-offs require us to abandon silo thinking and vested interests (Ringler *et al.*, 2013). At the same time, the dominance of sector-based planning systems is likely to continue, and so a compromise is needed where strengthening resilience of the water sector means better coordination and integration with other sectors' activities and plans,

including the agriculture, energy, urban and trade sectors, each of which depends on and/or affects water resources. Hence all water measures need to be aligned to the greatest extent possible with other sectoral plans, strategies, policies and measures (Reinhard *et al.*, 2017). The main issues in the nexus are not so much 'technical', they are largely institutional. It is necessary to take into account political and market forces in the form of subsidies, profit seeking and state agendas (Allan and Matthews, 2016). An important institutional precondition to make nexus solutions work is the political will in the respective country to coordinate and cooperate across sectors, ministries and authorities (ACCWaM, 2017). Below some suggestions are given for using a nexus perspective to inform policy development.

#### **4.6 | Invest strategically for managing water, food and energy security**

Investment in strategic areas can contribute to a combination of food, water and energy. For example, the development of multi-purpose dams is a nexus example generating hydropower, providing water for irrigation, flood management, domestic and other competitive uses (Pardoe *et al.*, 2018; Rasul and Sharma, 2016). For instance, the Durance–Verdon rivers multi-purpose programme, besides generating 6.5 billion kWh yr<sup>-1</sup> hydropower, also supplies water for drinking, agriculture, industry and provides tourism services around the reservoirs, which contributes to the region's business activities and attractiveness. Flexibility in operation is needed as the importance and priority of different reservoir uses have changed over time (Branche, 2016).

##### **4.6.1 | Internalize external effects**

The water, energy and food nexus is dominated by market mechanisms and supply value chains that are not yet equipped to expose the environmental and social risks associated with the otherwise rather effective market systems that produce and provide foods and services (Allan *et al.*, 2015). Market signals and the reporting and accounting systems that track them are dangerously partial and blind to the values of water and they do not capture the costs of mismanaging them (Allan *et al.*, 2015). It is necessary to quantify external effects, make them transparent and develop policies such as water pricing to internalize external effects. It is primarily the role of governments to ensure that the price mechanism works properly and to correct distortions in the pricing systems regarding fresh water, climate change and natural

resource depletion (Van Meijl *et al.*, 2017). The farmer or farm household is the decision maker at lower spatial level and decisions are based on the resources at the farm, taking into account the trade-offs and synergies. The farmer (entrepreneur) makes integrated decisions if he receives the correct (price) signals.

##### **4.6.2 | Create incentives**

Given that agriculture and nature will be competing more for water resources in the future, policy interventions should align to this development (Ringler *et al.*, 2013). Shifting taxation to natural resources to reflect the scarcity value and to emissions in order to promote sustainability is one approach. This would strengthen implementation of the 'polluter pays' principle within the market mechanism, creating suitable incentives to substitute resources and induce innovation. Policy interventions can similarly aim to create incentives for firms to increase and steer their innovation capacity towards developments that have positive, or at least neutral, nexus outcomes.

##### **4.6.3 | Promote a circular economy**

Increasing efficiency and reuse of water for irrigation has considerable potential, as discussed above. Extending that concept to the reuse and recycling of waste for energy or for use as an organic fertilizer offers similar positive nexus outcomes such as reduced pollution of natural resources and need for expensive treatment costs, the foregone energy and water costs of producing energy and fertilizer that is displaced by reusing waste products, and reduced energy and emissions embedded in transport. A recent review of more than 150 business cases for nutrient, energy and water reuse demonstrates the significant potential that can be harnessed providing there is an openness to cross-sectoral cooperation from the early stages of planning (Otoo and Drechsel, 2018).

#### **4.7 | Stimulate development of an overarching research framework**

Discussion of the water–food–energy nexus in practical terms is still in its infancy and there is a need to stimulate further understanding of the nature and extent of interactions and identify when taking a broader intersectoral perspective is preferable to a more conventional method. Ultimately, this understanding will help: (i) reduce trade-offs; (ii) build synergies; (iii) improve governance across

sectors. Dealing with increasing complexity comes at a cost and there is therefore a need for careful cost–benefit assessment of the right strategy to design capacity development for the nexus in relation to its effectiveness and efficiency at improving outcomes (Bhaduri *et al.*, 2015).

## 5 | CONCLUSIONS AND FUTURE OUTLOOK

### 5.1 | Concerted effort required within each sector to address the intensifying challenges of water, food and energy security

Meeting the needs of the hundreds of millions of people who are already water, food and energy insecure, as well as the rapidly increasing demands of an increasing global population with higher expectations for their standard of living, remains a key challenge. Limits of resource availability in many parts of the world are being reached. This in turn has negative consequences for the poor, who cannot afford alternative sources of supply, for the environment where degradation can take decades to recover, and for the economy due to lost opportunities for growth. There is, however, room for optimism in terms of innovations available. Policy-makers will need to take a longer-term view.

### 5.2 | A growing body of promising innovations to address insecurity

The water, food and energy security challenge fosters creativity and opens up opportunities that were earlier not thought possible. A range of agronomic and water management innovations possible now in laboratory and pilot trials that promote resource efficiency, adopt concepts of a more circular economy and reduce externalities, are likely to be available for more widespread adoption in the coming years. The pace of change and underlying investments needs to keep up with the scale of new demand.

### 5.3 | Growing awareness of the interconnectivity between sector interventions and trade-offs for resource management

International focus on the water–food–energy nexus as well as the expected consequences of climate change has brought interconnectivity into sharper focus. Policy

incoherence between sectors can have negative impacts. As water resources come under greater pressure, the nexus is useful for raising awareness of a broader planning approach, focusing on synergistic outcomes with multiple benefits (*nexus positive outcomes*) and minimizing perverse interventions that can have unintended and adverse consequences (*nexus negative outcomes*). A new set of support tools and monitoring metrics are required to simulate the consequence of alternative development choices across a wider set of variables.

### 5.4 | New modelling approaches developed to simulate cross-sectoral consequences of alternative development choices in support of decision-making

A new set of modelling tools is being developed that combines elements from the sectoral models and permits more development options to be investigated. Further research is needed to develop the modelling tools and indicators necessary to describe the trade-offs between socio-economic and resource sustainability. Insights into system interactions at different spatial levels and the likely responses to market and policy incentives are necessary for coherent policy analysis.

### 5.5 | From research frameworks to improved policy direction and incentives for change

Progress needs to be made to involve planning and finance ministries by demonstrating the resource implications of a more joined-up approach. If the right policy and regulatory conditions exist for valuing natural resources and ecosystems, then market mechanisms and supply value chains may play an important role in increasing the efficiency of resource use. Dealing with increasing complexity comes at a cost and there is therefore a need for careful cost–benefit analysis of strategies in relation to their effectiveness and efficiency in improving outcomes.

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