THIRD
WORLD IRRIGATION FORUM
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THEME: DEVELOPMENT FOR WATER, FOOD AND NUTRITION SECURITY IN A COMPETITIVE ENVIRONMENT

BACKGROUND PAPER – Sub-Theme 1

ST-1: Enabling Policy Environment for Water, Food and Energy Security

Contributors:

Jelle Beekma, Asian Development Bank, Manila, Philippines
Jeremy Bird, Independent consultant, London, UK
Adey Nigatu Mershaihe, Delft, The Netherlands
Stijn Reinhard, Wageningen University and Research, Wageningen, The Netherlands
Sanmugam A. Prathapar, Asian Development Bank, Manila, Phillipines
Golam Rasul, International Centre for Integrated Mountain Development, Kathmandu, Nepal
Jeffrey Richey, School of Oceanography, University of Washington, Seattle USA
Jouke Van Campen, Wageningen University and Research, Wageningen, The Netherlands
Raqab Ragab, Centre for Ecology and Hydrology, Wallingford, UK
Chris Perry, Independent consultant, London, UK
Rabi Mohtar, University of America, Beirut Lebanon
Laurie Tollefson, Agrl. & Agri-Food Canada Science & Technology, Saskatchewan, Canada;
Fuqiang Tian, Department of Hydraulic Engineering, Tsinghua University, Beijing, China

ICID•CIID

International Commission on Irrigation and Drainage (ICID)
48 Nyaya Marg, Chanakyapuri, New Delhi - 110021, India
E-mail: icid@icid.org, Website: http://www.icid.org

Background Paper

Enabling Policy Environment for Water, Food and Energy Security

ABSTRACT

This paper focuses on sub-theme one: An Enabling Policy Environment for Water, Food and Energy Security. It discusses water food and energy (WFE) security and their interrelations as the background for policy discourse and introduces the WFE nexus and its quantification by modelling as one of the tools for developing a broader approach to resources management.

The complexity of water, food and energy security is analysed mainly from the perspective of (i) water and food and (ii) water and energy and their interconnectivity. We focus ultimately on water as a primary input into processes and analysis since this is the entry point for participants of the Third World Irrigation Forum. Other interrelations will also be touched upon but not analysed in-depth.

The paper first provides a general overview of trends in water, food and energy security, then highlights the interconnectivity between the various elements. This is followed by the introduction of the WFE nexus as a potential analysis tool for improving productivity per unit of resource (water as well as energy) and a basis for improving sector policies including avoiding unintended consequences on other sectors. Invariably, if one of element of the nexus is optimized, there will be trade-offs in the other elements; 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-themes two and three of the irrigation forum are closely connected with the nexus. In our paper we firstly discuss the various technology interventions focusing on agricultural water use which has potential to also improve other nexus outcomes. This is directly related to sub-theme three.[1]Stakeholder interaction, the focus of sub theme two,[2] is essential to contextualise the trade-offs and provide guidance for policy development. The combination of modelling, technology innovations and stakeholder participation should ideally lead to better understanding of linkages and more robust policies for water, food and energy security. Challenges and success and failure of various policies for WFE security are analysed and reviewed and subsequently used to derive recommendations for an enabling policy environment.

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, socio-economic development, all in a climate of peace and political stability, (UN Water, 2013). The world is facing an increasing challenge of water, food and energy security both for those currently with limited or no access, as well as those yet to be born. 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 the sub-theme, the most recent definitions for food, water and energy security are used and a compound definition for all three is proposed for guidance of the forum discussions.

For **food security,** we use the definition as part of sustainable development goal (SDG) 2: zero hunger which reads: *ensure that everyone everywhere has enough good-quality food to lead a healthy life* (UN,

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Jelle Beekma, Asian Development Bank, Sustainable Development and Climate Change Department, 6 AD avenue, 1550 Mandaluyong city, Metro Manila, Philippines, jbeekma@adb.org.

[1] Sub-theme 3: Improving Agricultural Water Productivity with Focus on Rural Transformation.

[2] Sub theme 2: Role of Civil Society and non-state actors with Focus on farmers and Extension Facilities

2015). **Water security** is defined by Grey at al. (2013) as: *the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable and tolerable level of water-related risks to people*. For **energy security** the definition of IEA (2019) is used: *the uninterrupted availability of energy sources at an affordable price*.[3]

Using these individual definitions, the proposed compound definition for water, food and energy security 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

Against these aspirations, 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 percent more water, 35 percent more food and 50 percent more energy (UN, 2014). The world's population is projected to continue growing with approximately 83 million more people being added annually (Gerland et al., 2014; United Nations, 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 percent (FAOstat, 2009; World Bank, 2007).Meeting the demand for food in a sufficient quantity and acceptable nutritious quality underlines the importance of greater efficiencies in agricultural production systems globally. The number of hungry people has been growing during the last three years despite an earlier steady decreasing trend and now amounts to more than 800 million people back to levels of almost a decade ago. This demonstrates the severity of the challenge(FAO, IFAD, UNICEF, WFP and WHO. 2018). These are not just theoretical concepts. The UN sustainable development goals report (UN, 2018) showed food insecurity is on the rise with the proportion of under nourished people worldwide increased from 10.6 per cent in 2015 to 11.0 per cent in 2016. The rise is attributed to conflicts however it also indicates the fragile status of food security. In 2017, 151 million children under age 5 suffered from stunting (low height for their age), while 51 million suffered from wasting (low weight for height), and 38 million were overweight.

Further pressures on food systems will arise from an overall increase in incomes globally with past trends showing changes in dietary habits requiring higher quality food and increased reliance on animal protein (FAOstat, 2009). The rapid rise in milk production in India and meat production in China demonstrate this trend and led to significant increases in agricultural water demand (Thakur et al., 2018, Zhou et al., 2016). In contrast, there is an emerging awareness of the consequences of high meat-based diets on resource use and the environment more generally, but at present and without major changes in perceptions on diet, this is not yet at a scale needed to offset increased resource demand.

1.3 Water security

Global **water demand**, in terms of fresh water withdrawals, is predicted to grow by about 55 percent by 2050 (United Nations, 2016).In 2025, over 40 percent 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 increase in future due to population pressure, higher welfare, and increasing climate variability (Gosling and Arnell, 2016,United Nations, 2016).

According to the sustainable development goals report 2018 (UN, 2018) water insecurity remains high and accelerated progress is needed to meet the SDG targets for SDG 6.1, water supply and sanitation, for SDG 6.4on water use efficiency and for SDG 6.5on water resources management. For example, 30% of people lack safe water supply (844 million people lack basic water supply facilities and 1.5 billion people have only 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

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[3] https://www.iea.org/topics/energysecurity/whatisenergysecurity/

least developed countries, only 27% have basic hand washing facilities. In 2014 water stress was above 70% in 22 countries in Northern Africa, Western Asia and Central and Southern Asia. 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. In the future variability in water supply and risks of drought and floods are expected to increase while at the same time overall competition for water will increase.

1.4 Energy security

Global **energy demand** is projected to rise by 25% until 2040 (IEA, 2019). Although considerable progress has been made in electrification, still just under1 billion people are without electricity. The provision of total clean energy lags far behind. For example, the SDG goals report of 2018 indicates that in 2016, around 2.8 billion people still used solid fuels with inefficient stoves, leading to high levels of household air pollution. It also states that if current trends continue, 2.3 billion people will continue to use highly polluting traditional cooking methods in 2030 with negative health consequences. 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 vapor[4] state, either by agriculture through crop evapotranspiration, evaporation from water and land surfaces, incorporated into products or crops, or consumed directly by humans or livestock (USGS, 2014). Whereas a significant fraction of withdrawn water is generally returned to storage in water bodies or aquifers. For example, in Pakistan the total withdrawal in the Indus Basin Irrigation System is 136 billion cubic meter (BCM), but only 82 BCM of this amount is consumed (World Bank, 2019). The quality of the returned water is affected by its use and recycling for safe re-use downstream can require special attention and incur treatment costs.

Water for food. Over 70% of global freshwater withdrawals is used for food production (Hoekstra and Mekonnen, 2012, D'Odorico et al 2019). 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 percent of the world's food production from approximately 20 percent of all agricultural land (FAO, 2018).

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 about 10% of the total water withdrawals globally (IEA, 2016), while the global water consumption for energy is 4.7% (Hoekstra and Mekonnen, 2012). Water withdrawals for energy production in some parts of the world can be much higher and account for up to 49 percent of all water withdrawals (Kearney at al. 2014). Based on estimates in 2010, approximately 75 percent of the total industrial water withdrawals are used for energy production (WWAP, 2014)..

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.The future water needs for energy production and conversion are likely to increase further because of increased use of unconventional energy generation, such as shale gas, shale oil and oil sands, these require greater amounts of water (Rosa et al., 2018). Similarly, demand will increase through the wider uptake of biofuel energy production as alternatives to existing fossil fuels. In contrast, the expansion of solar and wind power will demand less water. Overall, it is projected that by 2035, water withdrawals by the energy sector could rise by 2 percent to 400 BCM and consumption by 60 percent to 75 BCM(EIA, 2018). Even where water use in energy is non-consumptive, there is modification of return flows, higher temperatures in case of cooling water and changes in river hydrology, water quality and ecosystems for hydropower. Uncertainty of water availability for the energy sector is already evident in some places. For instance, a

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[4] For simplicity, here we assume that the water converted to vapor by evapo-transpiration is "lost" to the atmosphere. Within greenhouses this water can be recycled, (see section 4).

coal-fired power plant was shut down in India due to water shortage (IEA, 2015) and in California electricity generators needed to negotiate a reduction in domestic water supply to maintain adequate availability of cooling water (Keulertz et al. 2018).

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. For example, evaporation from hydropower reservoirs have a global water consumption of 5.41m^3/MWh (Mannan et al. 2018). They can influence the pattern of downstream flows having consequences for both food production, for example in Central Asia where hydropower peak demand is in the winter, while irrigation needs are in the summer, and impact the environment both locally and beyond due to changes in river flows, habitat change and blockage of fish migration routes. Another such case is reported by Rosa et al. (2018) where in south Texas, shale oil and gas extraction, using hydraulic fracturing, have to compete for water with agriculture.

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 is utilised within the bioenergy sector (Garcia, 2016). 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 condition, runoff, groundwater discharge, water quality, and availability of water and land for other purposes, such as natural habitat (Alauddin and Quiggin 2008). Climate policies, globally, can lead to an increased demand of biofuel (Mercure et al., 2019). The biofuels 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, sugarcane 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. Water use for fuel extraction from, for example, corn ethanol is 25.8 m^3/MWh which is more than 50 times higher than for the least efficient conventional source, coal (Mannan et al. 2018).

Agriculture, water and the environment: Over-abstraction from surface water affects the minimum environmental /ecological flow that is required to maintain ecosystem services, water quality, fish communities and leisure. The use of agrochemicals such as fertilizers, herbicides and pesticides affect the environment including water quality. Vörösmarty et al., (2010) found that 65% of global river discharge, and the aquatic habitat supported by this water, is under moderate to high threat. All these dimensions come together in the Aral Sea basin where the Lake Aral recession has largely been due to unsustainable expansion of irrigation abstractions to achieve national production targets of cotton and wheat, much of it pumped to considerable heights using subsidized electricity, (Micklin, 2010, Bhaduri et al., 2015). Although full restoration of the Aral Sea is no longer considered feasible due to the high volumes of water needed and consequences this would have on economies and rural communities (Micklin, 2014)considerable improvements are thought possible as shown by Djumaboev et al. (2019) who found that by better irrigation scheduling alone, more than 575 million cubic meter and 259 KWh can be saved.

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 etal.2011). The global food system is dependent on fertilizer production, for example half of the energy used for nonorganic bread production in the UK 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 utilised for the pumping and treatment of water (Hoff, 2011). Demand of energy for transporting, processing and refining water, particularly in desalinization and wastewater treatment, is very high. The food production and supply chain alone accounts for over 30 percent of total global energy consumption, mainly depending on fossil fuels as its source currently (FAO, 2011). Given the fluctuating energy prices, unreliability of fossil fuel supply, and increasing concern on greenhouse gas (GHG) emissions, there is concern on the ability of the food sector in its current state to meet global demands while minimizing adverse environmental impacts, (FAO, 2011).

According to Lillie (2015) and Mannan et al. (2018), about 10% of the United States of America (USA)energy consumption or 2,283 Gigawatt-hour (GWh), is used in agriculture. Of this energy use, 21% or 479.4 GWh is used for crop cultivation, including fertilizer and pesticide production, and fuel for field preparation and harvesting, another 14% (319.6 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 strongly on the local conditions and irrigation method. For example, Daccache et al (2014) show that 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, compared with more than 10 BCM in Turkey and Syria with more than 10 BCM.

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 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 in Mamman et al. 2018).For countries dependent to some degree on desalinising 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 are summarised 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 the climate uncertainty although some examples are emerging, e.g. 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[5] goals for water, food and energy is already a major challenge in many countries. Lack of an integrating resource management framework, exacerbates this challenge through the risk of inefficient use of resources. The prevailing sectoral approach to planning of energy, food and water often takes place in the absence of meaningful consideration across sectors. For years, sector analysts have emphasized the need to increase productivity, boost production and reduce waste as solutions to meet pressing global challenges of increased demand. However, it is increasingly recognized that the challenges are far more complex than simply producing more food or energy because of increasing resource constraints and interconnectivity of sectors, the levels of stress on environment and ecosystems, and the consequences of carbon emissions.

These 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-organised resources management. Based upon her findings she elaborated attributes of the Social-Ecological Systems (SES) that determine the success of self-organisation: 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, appears to get lost and subdivided when one moves up to district, provincial and state levels of administration.

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[5] SDG Goals 2, 6, 7, 11 and 13 explicitly link to the Nexus and consequences of decisions made will influence Goals 14 and 15.

Ideally, greater competition for water will stimulate more economically efficient use of water and facilitate allocation towards the most appropriate use (though as Ostrom's insights on the tragedy of the commons reveals, this "efficient" reallocation of the scarce resource requires both constraints to access and mechanisms to facilitate reallocation). Such institutional, regulatory and physical systems however take time to develop and respond to increased scarcity. Short term perspectives that protect the status quo often prevail due to political expedience: limiting access to existing water users, for example, does not win many votes. Political decisions can also have unintended consequences, for example in India and Pakistan where energy is subsidised 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. In 1988, the Gujarat Electricity Board changed from metered to flat tariffs, making the marginal cost of electricity for tube-well owners zero. Farmers overused energy and water, leading to lowering groundwater tables and over-usage of the power grid, leading to unreliable supply of electricity both on the farms, but also in villages and for rural industry (Shah and Verma, 2008; Shah et al., 2008).

More recent subsidies for solar irrigation systems as part of government carbon mitigation programs are expected to exacerbate over-pumping 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 other sectors—in this case, aggravating environmental degradation. In Egypt, the Government increased its food subsidy allocation by 20% in May 2016 to mitigate the impact of the rising inflation due to the 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 water pricing are ideally deployed to ensure productive and efficient water use and equitable water distribution. Competition inevitably increases from water users that generate more welfare (e.g. income) with their water use (Scott et al., 2015; Hellegers et al., 2008); e.g. 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 and 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. A number of international forums have been promoting a comprehensive approach to food, water, and energy security, the major ones being the World Economic Forum and the Bonn Nexus Conference, both in 2011. These have been followed by coverage of nexus thinking in several regional conferences, research programs as well as knowledge products of practitioners, for example the analysis of water use in the energy sector by BP (Williams and Simmons, 2010) and of interconnectivity between water and energy in China by the Asian Development Bank (Perera and Zhong, 2017). One representation of the WFE nexus is given in Figure 1 by Rasul (2014).

The nexus approach is based on a 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, Stone, Hughes, & Stewart, 2012; Rasul & Sharma, 2016).

Policy recommendations from the Bonn 2011 conference assessed implications for all sectors including agricultural and irrigation, by emphasizing the need to enhance policy coherence, produce more with less, promote natural infrastructure and increase stakeholder participation.[6]Focussing 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 on improving (crop) water productivity across levels from field level to river basin incorporating energy implications and exploring the multi-functionality of irrigation systems.

By comprehending the complexity of the interconnections among dimensions of the WFE nexus and addressing the trade-offs, a long-term, concerted and sustained strategy can be developed and applied to address issues associated with resource security (Rasul and Sharma, 2015; Al-Saidi and Elagib, 2017; D'Odorico et al., 2019). The nexus can also stimulate innovation and use of new technologies as discussed in section 4.

Achieving synergies and win-wins is not easy and most cases involve trade-offs between sectors. Adopting good practice in one sector can though 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.

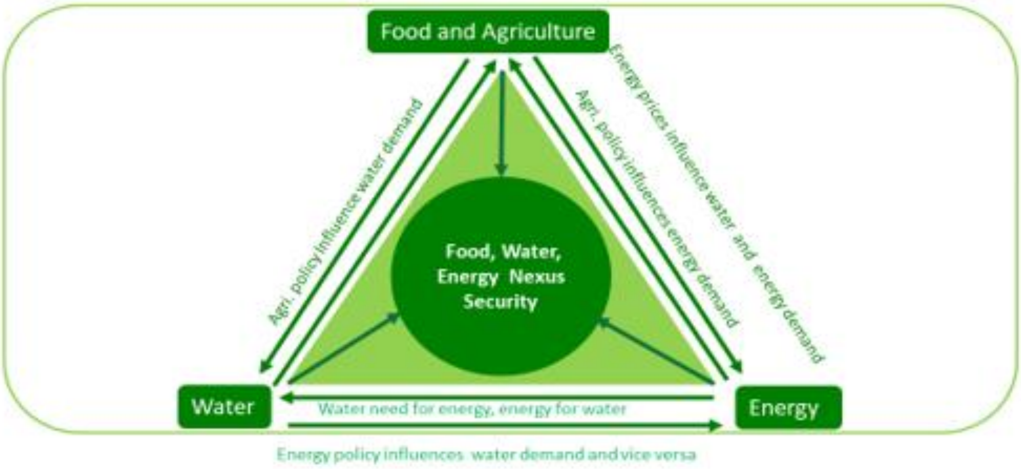

Figure 1: Dynamic relationship among food, water and energy security

2.3 Challenges inherent in adopting an integrated approach

A word of caution about 'integrated' and 'nexus' approaches is also needed to avoid the impression that there is a panacea out there that can solve the world's water, food and energy security challenges by adopting a different approach. There is a risk that 'the nexus' becomes an end in itself rather than a means to recognise these critical challenges. Perry argues that water, 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 (perscomm, 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. Failure by governments to manage water most commonly involves either allowing farmers to access water at the expense of unacceptable environmental damage (which is commonly the case for surface water) or failing to regulate access (which is commonly the case with groundwater). Severe depletion of aquifers leads to irreversible changes to the quality of water in the aquifer and the capacity of the aquifer to accept recharge due to subsidence. There are high risks of salinization due to upcoming of saline water and there is a risk that wells will go dry, or will become too deep for economic exploitation; downstream users from rivers, including for domestic and commercial use will increasingly frequently find the river is dry or too saline for use. This 'disallocation' of water first affects the environment and then irrigated agriculture. These processes will not be orderly, or prioritised. There is

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[6] https://www.water-energy-food.org/fileadmin/user_upload/files/documents/bonn2011_policyrecommendations.pdf

no way to predict whether the most or least productive farmers will suffer—but all farmers will grow 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-offs 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 Competition for water as a scarce good

Scarcity by definition refers to conditions when demand for water is higher than that of supply. IWMI highlighted the global distribution of water scarcity and distinguished between physical scarcity, economic scarcity and institutional scarcity in their comprehensive assessment of water management in agriculture (Molden, 2007). Globally, there is no clear evidence to suggest an absolute scarcity of land-water-energy (LWE) resources. The impacts from LWE bottlenecks, however, vary significantly spatially and temporally. Therefore, the main issue is having the resources at the right time in the right place (OECD 2017), which is a major component of water security. The Asian Water Development Outlook (ADB, 2016) provides a periodic water security assessment in five dimensions, rural, economic, urban, environmental and disaster risk and resilience for 49 countries in Asia and the Pacific as a tool to track water security over time.

As an indication of the scale of the problem, Wada and Bierkens (2014) identified regions where current water use is not sustainable and thus future water security is compromised, because the rate of ground water abstraction exceeds replenishment (see Figure 2b).

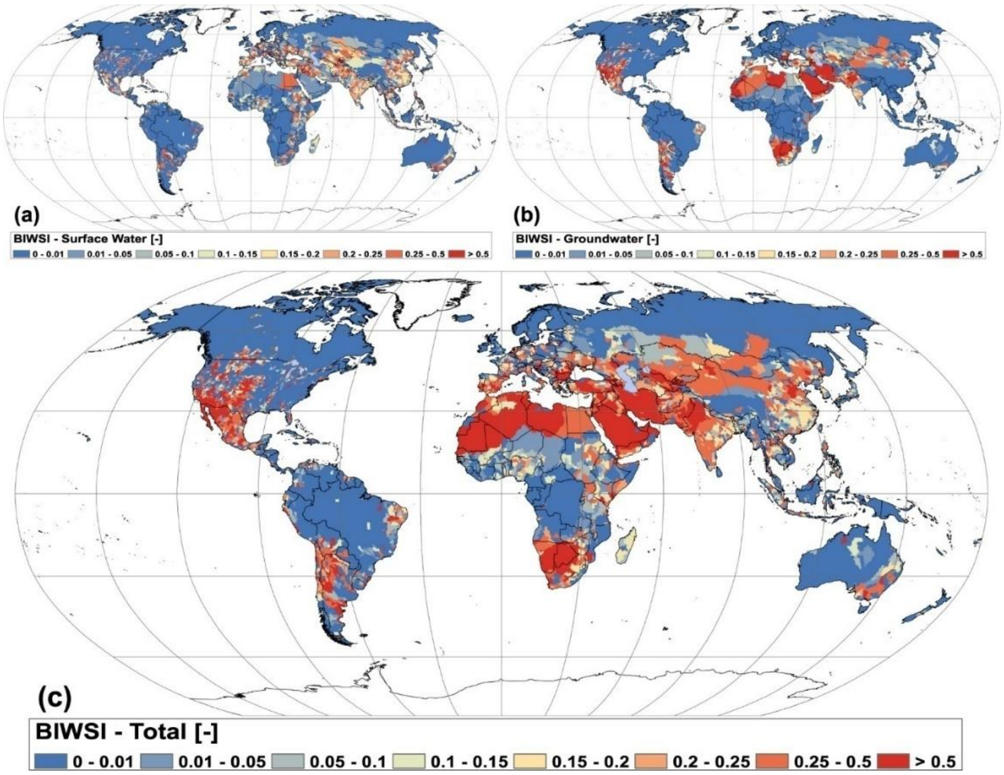

Figure 2: Global maps of historical blue water sustainability indicator (BlWSI) (dimensionless) for (a) surface water, (b) groundwater, and (c) the total at a sub-basin scale (except the Antarctica and Greenland) (1960–2010). The sub-basin dataset was obtained from the FAO AQUASTAT database (www.fao.org/nr/water/aquastat/main/index.stm) that used the HydroSHEDS (http://worldwildlife.org/pages/hydrosheds) to derive the sub-basins.(source Wada and Bierkens, 2014)

The World Resources Institute (WRI) indicated the regions with increased water scarcity in the future based upon the Aqueduct database (Gassert et al., 2014), see Legend: Projected change in water stress (Change from baseline to 2040 business as usual)

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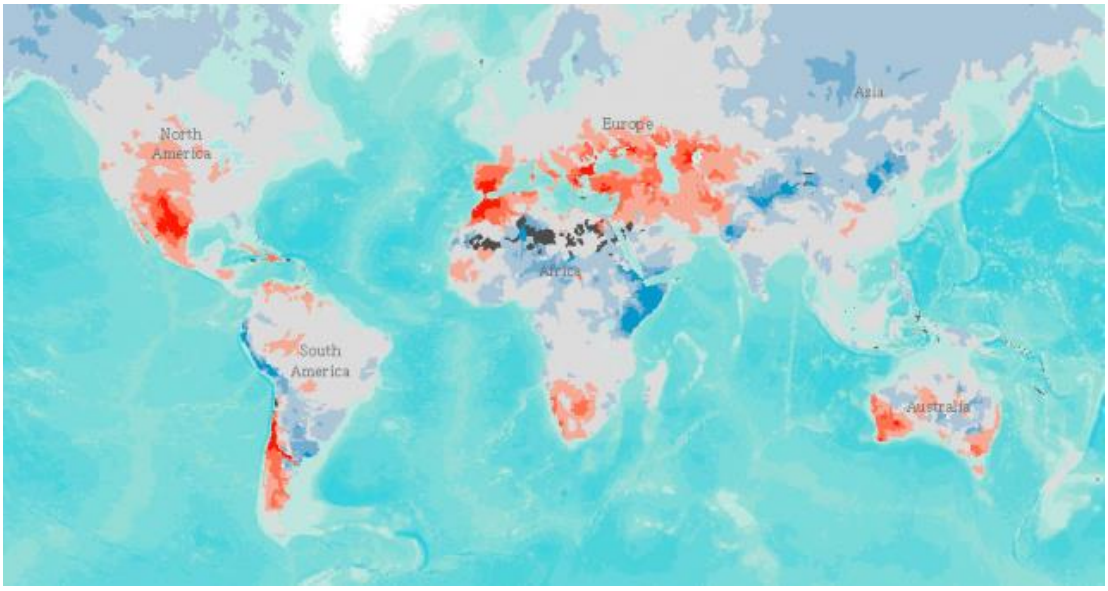
🟦 2x decrease
🟦 1.4x decrease
⬜ Near normal
🟥 1.4 X increase
🟥 2x increase
🟥 2.8x or greater increase

Figure **3** in the regions with increased future water scarcity current levels of water use will have to be reduced by more efficient water management practices.



Legend: Projected change in water stress (Change from baseline to 2040 business as usual)

🟦 2.8x or greater decrease
🟦 2x decrease
🟦 1.4x decrease
⬜ Near normal
🟥 1.4 X increase
🟥 2x increase
🟥 2.8x or greater increase

Figure 3: Future areas of increased water stress (Source: WRI 2015)

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 WFE nexus frameworks, the ICID strategy for implementing the Vision for Water for Food considers the approach from 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.

Submitted papers for sub-theme 1 of the Forum include those dealing with innovations for improving irrigation and agricultural productivity, including smart and high technology approaches, and aspects of the circular economy and sustainability focusing on re-use 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 frame work 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 then require the inclusion of effects on food and energy – are they positive, negative or neutral? The decision-space would then 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 other sectors.

The task of finding win-win solutions is complicated though 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 politics in areas and the need to keep basic food products within the affordability of both urban and rural communities. Energy security is national commitment central to economic and industrial growth, but often follows quite different planning processes and timescales to 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 et al. (2018) distinguish three types of dependencies between them: (i) direct dependencies, (ii) direct competition, and (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 et al., 2018).

The comparison of inter-linked outcomes across three or more different sectors becomes difficult to manage and 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[7],raised the question on how to measure the Bank's effectiveness in influencing outcomes.

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. Stirling (2015) warned that the power dynamics related to individual decisions might seek to understate complexity, neglect uncertainty, deny ambiguity and suppress dissent. 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 et al. (2019) show that in many instances, there is a lack of policy coherence across sectors as well. For example, India has a policy to double agricultural production and thereby rural incomes by 2030 and provides subsidies on agricultural inputs including energy which leads to excessive pumping and use of groundwater, at the same time the water policy promotes water use efficiency and the energy policy emphasizes cost recovery and pricing as a demand management instruments. An important

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[7] https://www.adb.org/sites/default/files/institutional-document/435391/strategy-2030-brochure.pdf

conclusion by Ostrom (2010) is that there is not a general governance system that can be applied to all situations.

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 localised 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)[8]

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 WEF 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 WEF inter-linkages (Liu et al. 2017).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 (Weitz et al. 2017).

3.2.1 Modelling approach

Enabling a robust policy environment for water, food and energy (WFE) security requires the capability of combining detailed knowledge of the physical and transactional dynamics within or between sectors with the requirements of multiple stakeholders. Brazilian et. al. (2011) suggest that robust analytical tools harnessing existing data, can advance scientific understanding in WFE systems and make an analytical resource 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 WFE nexus space by bridging the disconnect between knowledge producers and users (Buizeretal., 2012; Mohtar and Lawford, 2016) as well as the disconnect between communication of uncertainty and the risk at local, national, and international scales (Howarth and Monasterolo, 2016). Andrienko et al. (2007) highlight the need for new computational tools that can translate between the complex space-based resource management problems and the physical boundary spanning nature of human decision-making on resource problems. A cloud-based cyber infrastructure comprised of “modules” linking the water, food and energy water systems would provide such a decision-support toolset. The overall Nexus toolset is then represented by the coupling between the models.

The overarching concept of dynamic modelling for an effective decision information framework can be addressed with the specific models mentioned within this section or other modelling toolsets with equivalent capacity and functionality. 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 not only 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, though, is how to mobilize all that data into useful products across the nexus. 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 of the basin of interest. Different models available within the water module may have differing capabilities, e.g. capturing different hydrologic processes, servicing agriculture, performing

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[8] www.simnexus.eu

additional processing, or producing different resolutions of output but all versions within the water module must provide the water mass output. The **energy module** relies on this to determine the supply of water available for hydro-power generation 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 VIC, CLM, NOAH, Water GAP 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 (i.e. hydropower) or agriculture explicitly, but instead couple to other offline models to simulate these impacts. This approach does not account for the dynamic interaction between the energy, agriculture, and water systems. For example, the energy model EAGERS (see below) provides such coupling to manage reservoir nodes based on a cost-optimization function. Most hydrology models do not explicitly represent groundwater, instead baseflow is produced through the bottom soil moisture layer. A model such as the Simple Groundwater Model (SIMGM) by Niu et al. (2007) is implemented in some hydrologic models to represent an unconfined aquifer layer at base of the soil column. While progress is being made to better represent groundwater in standard hydrology models, it currently remains best represented with separate groundwater models.

3.3.3 Linking models

A priority in capturing the coupled human/natural system dynamics is through quantification of explicit linkages between the basin agricultural practices and the hydrologic cycle (as represented by a hydrology model). The examples given in this section are not intended to be exhaustive, but rather provide a window on some of the current possibilities. A cropping systems model can serve as the corner stone of a high-fidelity food module. Such a model, for example the Cropyst model (Stockle et al., 2003), should be a multi-year model capable of simulating soil water budgets, nutrient budgets (e.g., nitrogen and phosphorus), carbon cycling, crop grow than yield, residue production, and soil erosion at a combination of hourly and daily time intervals.

The explicit linkages between the land use practices and the hydrologic systems have been well established by prior efforts coupling cropping and hydrology models, for example CropSyst with the Variable Infiltration Capacity (VIC) hydrology model, termed VIC-CropSyst (Maleketal.,2017b) or Saltmed (Raqab, 2015). The coupling uses the hydrology model to compute natural water availability in the form of soil moisture and precipitation, while the cropping model determines yield, biomass, transpiration, irrigation water demand, leaf area index, and plant water uptake by soil layer.

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 the irrigation and water storage infrastructure operations in support of crop production, a coupled dynamic captured within an integrated decision information framework combining modelling modules for food, energy, and water. An additional linkage with agriculture, relevant to particular basins, is the production of supplemental biofuel and biogas. Models are available for modelling transport costs of various options based on prevailing fuel costs. Electrification of the transport sector would be a major change, particularly in relation to air quality and carbon emissions

The EAGERS energy module is an example that captures the direct linkage of water runoff and baseflow from the hydrologic modelling as part of a larger simulation of the regional electric network (McLartyetal, inreview). EAGERS co-optimize the management of hydroelectric generators and water reservoirs by computing an hourly resolved receding horizon control solution for the 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. studied how optimization could be an effective response to prolonged severe drought (2010). 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 much the water system could be able to cope with droughts and provide insights regarding institutional instruments and water policy management. Under the Future 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 visualisation 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 basin, a transboundary subbasin of the Ganges basin (with 4 storage and 7 run-of-the-river hydropower dams) 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 (a) incorporated the possibility of using hydropower to pump groundwater for irrigation as well as flood regulation and (b) quantified the resilience of the estimated benefits under future climate scenarios from downscaled general circulation models affecting both river flows and crop growth. The results showed significant potential economic benefits generated from electricity production, increased agricultural production, and flood damage control at the transboundary basin scale.

WEAP (Water Evaluation and Planning System) and LEAP (Long Range Alternatives Planning System) are also software packages developed by the Stockholm Environment Institute (SEI). These tools have been applied in different parts of the world for scenario based evaluation of policy measures for water resources and energy development. These models have been applied separately per their respective designed purpose, however, the models were integrated recently to become 'WEAP-LEAP.' The integrated WEAP-LEAP model can now be applied for water-energy related scenarios evaluation by alternating parameters resulting in different outputs, such as energy generated (hydropower) or water requirements for cooling (Dargin et al., 2019, SEI, 2013, SEI, 2014)

4. Improving the Productivity of The Resource: Examples of Technology, Policy and Governance Interventions

Given the focus of WIF3, in this chapter 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 (Ahadi et al 2013). Various definitions of irrigation efficiency have been developed and used (Israelsen 1944, Jensen 1967, Bos 1985, etc.). However, water productivity in kg/m^3 or \$/m^3, depending on the prevailing development objective and degree of water scarcity, is preferred as this links the production (or benefits) to the water consumption. This is an indicator for the efficiency of actual water use as it links the consumption of water to the crop production or the economic returns. For pressurised systems and through fertilizer efficiency gains it also links to energy usage. It can be used for crop and location specific assessments, (Giordiano 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.[9]

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 2018). In Canada current research focuses on eefficiency measures along the entire agrifood chain to help save energy and water and motivate farmers to invest in their systems to ensure optimal returns from their investment, while also addressing environmental impacts of greenhouse gas emissions. Institutional approaches include the participatory approach, water pricing, training and educational opportunities.

4.2 Innovative technological applications for addressing WFE 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 will be featured at the Forum. These include technologies and management practices that are either well-established in some locations and are available to transfer elsewhere or have shown promising results in pilot testing. For example, improving water use productivity by using suitable and efficient irrigation systems, e.g. subsurface drip, low level sprayer sprinkler, using renewable energy for the required pressure (e.g. solar energy, wind energy or potential energy to pressurize drip and sprinkler systems in the form of reservoirs at a higher elevation, directly connected to the pressurized system).

Reducing field applications through improved water management in the root zone

More efficient application of water for irrigated crops requires energy to pressurise the water delivery system. Energy gains can be obtained through using alternative energy sources to build the pressure, or by reducing the water application. An estimate of water needs at different times of the season and crop growth is needed and conventionally water application has been based on current methods of calculating the crop irrigation water requirements based on equations fed by meteorological data. New technologies such as the Scintillo meters as well as the Eddy Covariance measure actual evaporation values that represent the real crop need for water. Results of Water4Crops project in Southern Europe,[10] showed significant reduction of actual crop water requirement differences when compared with the present practice. On average, obtaining a better understanding of the actual crop water requirement based on the modern technologies could save at least 50% of irrigation water for this region (Ragab et al., 2017a).

Another new technology to determine the crop water requirement through real time continuous soil moisture content and deficit is the COSMOS. The method is based on the use of natural atmospheric cosmic rays, which are non-invasive, non-destructive, and can sense soil moisture for an area of 300 to 700 meters radius. It was tested in the Water4Crops project. The results (Ragab et al., 2017b) showed that soil moisture values obtained by COSMOS were comparable with measured values for the top 0-60 cm. The COSMOS technology provides continuous, integrated, area-based values and solves the problem of spatial variability and can be used to determine when and how much to irrigate to avoid harmful water stress.

These new technologies when accompanied by an efficient irrigation strategy such as Partial Root Drying Method, (PRD) and subsurface drip irrigation has the potential to save even more water, and importantly reduce energy use. The results of the application of only PRD on corn, potato and tomato were water saving with higher productivity and water use efficiency compared to surface drip and sprinkler systems alone without improved soil moisture measurement.

A word of caution is needed. There are limits to the increase of water productivity in open air. When all circumstances are close to ideal (e.g. rootzone nutrition, aeration and absence of pests), water consumption and productivity are almost linearly related and higher production leads to higher consumption. Limiting water supply to the exact crop need, or even belowit will, in the absence of sufficient precipitation, lead to salinization of the rootzone as the salts present in the irrigation water

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[9] http://www.fao.org/in-action/remote-sensing-for-water-productivity/overview/about-the-programme/en/

[10] www.water4crops.org,

need to be leached and a rootzone salt balance maintained. The limiting of water supply in traditionally irrigated areas may also lead to falling water tables and drying of rivers due to reduced percolation. The basin or (sub)-catchment water balance needs to be considered in any move towards efficiency and productivity gains.

4.3 Greenhouse cultivation and optimizing circular use of inputs.

The emerging technology of greenhouse horticulture completely rethinks irrigated agriculture systems and 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, but potentially comes at a threat to water quality in drainage water released into surface water bodies or groundwater. This can partially be offset by better fertilization providing the exact amounts crops need and introducing recapturing systems for the used chemicals.

In open fields, sensors assist the farmers on when to irrigate and case studies have shown that the introduction of innovative technologies may raise water use efficiency by up to 60% while maintaining existing crop yields[11]. The use of fertilizers may be reduced by up to 30%, which reduces costs and limits high concentrations in the environment. Yields often increase due to the new water management system and growers might use this extra income for investment in new technologies.

WUR Greenhouse Horticulture 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.

Internationally these topics were addressed in the EU project EUPHOROS[12] aimed at developing a sustainable greenhouse system that does not need any fossil energy and minimizes carbon footprint of equipment; has no waste of water nor emission of fertilizers and full recycling of the substrate; has a minimal need of plant protective chemicals yet has high productivity and resource use efficiency.

In research in Riyadh where the conventional water use for tomato production is around 300-400 liters per kilogram of tomato, this has been reduced to only 50 litres per kilogram using mid-level technology and only 4 liters per kilogram using high technology solutions

Seawater Greenhouses (Davies, P and C. 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 be expelled from the greenhouse and used to improve growing conditions for outdoor plants orthe water could also be condensed and circulated for re-use.

In places where the available water is not fit for irrigation or human consumption because of salinity and/or other chemical pollutants, the application of SolarDew systems can be considered. SolarDew systems are a purely solar driven membrane distillation systems consisting of a membrane unit in the form of a “plastic bag” in a housing. Such systems can be installed on the roof of a greenhouse for which they also serve as 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 the solar radiation, is around 8 litre of pure water/day/m² or 8 mm. Cost are between €0.01 and €0.02/litre mainly because of the costs of the membrane units that haveto be replaced ever 3- 4 years. (www.solardew.com)

Other promising initiatives are in 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 with minimal interference with the flow systems in small canals. Such systems have been successfully applied to electrify remote villages

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[11] https://www.wur.nl/nl/show/FlowAid-2.htm.

[12] https://www.wur.nl/en/Research-Results/Projects-and-programmes/Euphoros.htm

and are a good example of a positive water, food and energy nexus[13](www.heliosaltas.com/how-micro-hydro-can-aid-farmers-in-developing-countries)

Having dramatically increased food production potential since the 1970's when the limits to growth dominated the development paradigm entirely new possibilities have risen. For example, in 2013 global deaths from obesity with 3 million were three times higher than deaths from hunger (Lancet, 18 December in Harari 2016). The above examples of further improving productivity of water, recycling water and nutrients in greenhouses, desalinizing water using solar energy (due to the conservative nature of salts like NaCl, such salts tend to accumulate during the re-use cycle of circular use) and using potential energy of water in a much wider range than reservoirs for generating power, are all elements of a more circular economy. Circular economy and its underlying principles form a new paradigm in our strive for development and sustainability, get rapidly more attention and provide new positive challenges for further development and progress (e.g. Raworth, 2017, Vanham et al. 2017).

4.4 Policy Instruments for managing WFE 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 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 4.

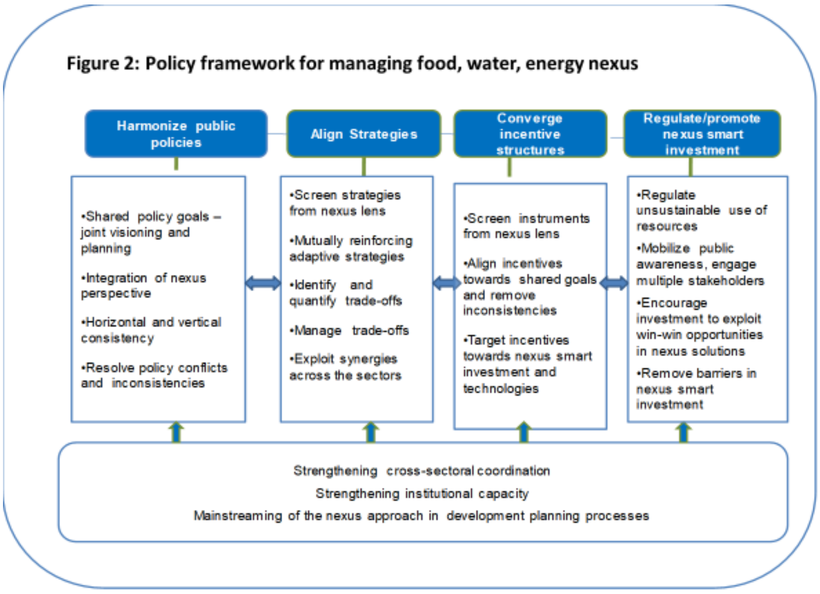

Figure 4: Policy framework for managing the WFE nexus (after Ghulam Rasul, 2018)

4.4.1 Regulatory measures.

Monitoring groundwater use using remote sensing chips. Groundwater is over extracted in many areas of the world (Shah et al., 2003, Feng et al., 2008), for instance, parts of India, where 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 sensor in pumps, which automatically stops pumping water when the water levels drops below a certain limit, or implementing policies where farmers have to pay for groundwater extracted by the unit, would be helpful in managing ground water over extraction (Gupta, 2019).

4.4.2 Market based instrument.

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[13] https://www.heliosaltas.com/how-micro-hydro-can-aid-farmers-in-developing-countries/

Given the limitation of regulatory measures, many market-based innovations are introduced to manage 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 the environmental demands. Water buyback is practiced in Australia's Murray–Darling Basin (MDB), Klamath Basin of southern Oregon and northern California, USA, and the Murcia Plateau, in the south-eastern Segura basin of Spain (Garrick et al., 2009). The Murcia Plateau suffers severe overdraft of the aquifer and Spanish water authorities have implemented buyback of groundwater rights to reduce groundwater abstraction (Calatrava & 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 tariff of electricity supply to agriculture has led to an excessive energy and ground water 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 conjunctive use of water, even for those without their own wells. A pre-paid meter with Smart Cards and installation of underground plastic pipes has changed irrigated agriculture. Introduction of pre-paid meters and Smart Cards has reduced the disparity among the farmers within the irrigation schemes and encouraged timely water supplies and timely repairs. Command area increased by 22%.(Zaman, 2013).Comparable practices are now widely adapted in new irrigation projects funded by the Asian Development Bank in the Eastern Gangetic 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 program. As ground water irrigation has become crucial for ensuring food production in many parts of the word, particularly in South Asia, supplying energy for pumping ground water has become an integral component of food-energy-water nexus. Solar-based power options, have been tried in different parts of the world as an alternative mechanism for supplying water for irrigation. In India, solar pumping was stimulated by subsidizing part of 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 ground water 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 pump to the State electricity grid, which is expected to contribute further in meeting electricity needs of Indian agriculture. 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). However, these findings are challenged and Sahasranaman et al (2018), argue rather the opposite. They state that on the basis of empirical data that solar photo voltaic systems for well irrigation are economically unviable, and that high subsidies for such systems combined with higher feed-in-tariff for the electricity produced than the market price would distort energy markets and incentivise farmers to pump excess groundwater that might be used for water-inefficient crops or sell the excess water for a profit.

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 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 (Allen and Matthews, 2016; p87). An important institutional pre-condition to make nexus solutions work is the political will in the respective country to coordinate and cooperate across sectors, ministries and authorities (ACCWaM,2017). The nexus is useful framing within which to develop policies, strategies and investments to exploit synergies and mitigate trade-offs among development goals, with interactive participation by and among governmental agencies, the private sector, academia and civil society (Dodds and Bartram, 2016). Below some suggestions are given for using a nexus perspective to inform policy development.

4.5.1 Invest strategically for managing water, food and energy security.

It is necessary to make investments in strategic areas which can contribute to a combination of food, water and energy (Pardoe et al., 2018). Development of multi-purpose dams is a nexus example and can generate hydropower, provide water for irrigation, flood management, domestic and other competitive uses (Pardoe et al., 2018; Rasul et al., 2019). For instance, the Durance–Verdon Rivers multipurpose program, besides generating 6.5 billion kWh hydropower per year, 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 has changed over time. (Branche, 2016).

4.5.2 Internalise 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 internalise 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 freshwater, 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.

4.5.3 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.

4.5.5 Promote a circular economy

Increasing efficiency and re-use of water for irrigation has considerable potential as discussed in section 4.3. Extending that concept to the re-use 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 re-use demonstrates the significant potential that can be harnessed providing there is an openness for cross-sectoral cooperation from early stages of planning (Otoo and Drechsel, 2018).

4.5.5 Stimulate development of an overarching research framework

Discussion of the WFE 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. Research is needed to further develop the modelling tools and indicators necessary to describe the trade-offs between socio-economic outcomes and resource sustainability. More insights into system interactions at different spatial levels and the likely responses of agents to market and policy incentives are necessary for coherent policy analysis. Ultimately, this understanding will help (i) reduce trade-offs, (ii) build synergies and (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 is required within each sector to address the intensifying challenges of water of water, food and energy security

Meeting the needs of the hundreds of million 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. Recent progress on implementing the Sustainable Development Goals demonstrates the depth and breadth of the challenge and it is not yet clear that the necessary levels of priority have been assigned to deliver on these goals by 2030. Limits of resource availability in many parts of the world are being reached, stressing ecosystems beyond the point of providing healthy water resources. 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 and the cost of water treatment and new source development. There is however room for optimism in terms of innovations available. Policy-makers will need to take a longer-term horizon to benefit from such sustainable solutions.

5.2 There is a growing body of promising innovations to address insecurity

This background paper and related submissions under this sub-theme of the Forum highlight some of the technological and management innovations that are addressing the scarcity challenge. The WFE security challenge fosters creativity and opens opportunities that were earlier not thought possible. Consider for example the advances in crop breeding decades ago by Norman Borlaug that led to the green revolution. Similarly, 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 There is growing awareness of the inter-connectivity between sector interventions and trade-offs for resource management

International focus on the WFE Nexus as well as the expected consequences of climate change has brought inter connectivity into sharper focus. Policy incoherence between sectors or between larger national objectives of food security and poverty reduction and sector policies aiming at sustainability can have negative impacts. As water resources come under greater pressure, the nexus is useful for raising awareness of a broader approach to seeking solutions, focussing on synergistic outcomes with multiple benefits (*nexus positive outcomes*) and minimizing perverse interventions that can have unintended and adverse consequences for another sector (*nexus negative outcomes*). Trade-offs are inevitable in resource-constrained situations and a new set of support tools and monitoring metrics are required to simulate the consequence of alternative developments choices across a wider set of variables.

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

Existing modelling approaches focus and optimize sectoral interests, whether it be the water balance of a river basin, the provision of food to meet national food security targets or the least cost supply of energy. A new set of modelling tools is being developed that combines elements from the sectoral models and permits a far higher number of development options to be investigated. They aim to produce information on the consequences of a particular development intervention across the WFE nexus space. Their application maysupport decisions to improve coherence of policies and lead to informed and locally appropriate decisions by the prevailing governance structures responsible for individual sectors.

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

Currently nexus analysis is still largely confined to the academic community. Progress needs to be made to involve planning and finance ministries by demonstrating the resource implications of a more joined-up approach. The nexus is a tool for helping to define an overall development trajectory and understanding the implicit trade-offs within which individual sectors can then develop sectoral policy interventions and incentivize sustainable behaviour. 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 resources use.

6. References

ACCWaM, 2017. Nexus Evidence Base. In Preparation (Final Draft). Based on the project Mainstreaming the water-energy-food security nexus into policies and institutions in the MENA region', within the GIZ regional programme: 'Adaptation to Climate Change in the Water Sector in the MENA Region – ACCWaM'.

Aeschbach-Hertig, W., & Gleeson, T. (2012). Regional strategies for the accelerating global problem of groundwater depletion. Nature Geoscience, 5(12), 853.

Ahadia, R., Z. Samani, and R. Skaggs. 2013. Evaluating on farm irrigation efficiency across the watershed: a case study of New Mexico's Lower Rio Grande basin. pp 52-57

Allan, T. and N. Matthews, 2016. The Water, energy And Food Nexus and ecosystems: the Politicaleconomy of food and non-food supply chains. In: Dodds, F., and J. Bartram, (Eds.), 2016. TheWater, Food, Energy and Climate Nexus: Challenges and an Agenda for Action. Routledge, pp 78-90.

Allan, T., Keulertz, M., & Woertz, E. (2015). The water–food–energy nexus: an introduction to nexus concepts and some conceptual and operational problems.

Amjath-Babu, T.S., Bikash Sharmab,, Roy Brouwer, Golam Rasulb, Shahriar M. Wahid, Nilhari Neupane, Utsav Bhattaraif, and Stefan Sieber (2019). Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin. Applied energy 239, 494-503.

Arias ME, Piman T, Lauri H, et al. (2014) Dams on Mekong tributaries as significant contributors of hydrological alterations to the Tonle Sap Floodplain in Cambodia Dams on Mekong tributaries as significant contributors of hydrological alterations to the Tonle Sap Floodplain in Cambodia

Bassel, T. Daher and Rabi H. Mohtar (2015). Water-energy-food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making, Water International, DOI:/02508060.2015.1074148

Bassel Daher, Rabi H. Mohtar, Efstratios N. Pistikopoulos, Kent E. Portney, Ronald Kaiser, Walid Saad. 2018. Developing Socio-Techno-Economic-Political (STEP) Solutions for Addressing Resource Nexus Hotspots. Sustainability. 10:512; doi:10.3390/su10020512.

Bassel, D., W Saad, SA Pierce, S Hülsmann, RH Mohtar. (2017b). Trade-offs and Decision Support Tools for FEW Nexus-Oriented Management. Curr Sust / Renew Energy Reports 4 (3), 153-159.

Bassel, D., Bryce Hanibal; Kent Portney; Rabi H Mohtar (2019) Towards Creating an Environment of Cooperation between Water, Energy, and Food Stakeholders in San Antonio. Science of the Total Environment 651 (2019) 2913–2926. DOI: 10.1016/j.scitotenv.2018.09.395.

Bassel D., RH Mohtar, SH Lee, A Assi. (2017). Modeling the Water-Energy-Food Nexus: A 7-Question Guideline. Water-Energy-Food Nexus: Principles and Practices 229, 57.

Bassi, N. (2014). Assessing potential of water rights and energy pricing in making groundwater usefor irrigation sustainable in India. Water Policy. 16. 442-453. 10.2166/wp.2013.123.

Baran E, Guerin E and Nasielski J. (2015) *Fish, sediment and dams in the Mekong,* Penang, Malaysia: WorldFish and CGIAR Research Program on Water, Land and Ecosystems.

Baumol, W. J. & Oates, W. (1988). The theory of environmental policy. Cambridge university press.

Bazilian, M; Rogner, H; Howells, M; Hermann, S; Arent, D; Gielen, D; Steduto, P; Mueller, A; Komor, P; Tol, S; Yumkella, K., 2011. Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy* 39(12): 7896–7906

Bhaduri, A., Ringler, C., Dombrowski, I., Mohtar, R., & Scheumann, W. (2015). Sustainability in the water–energy–food nexus.

Bos, M.G. 1985. Summary of ICID definitions on irrigation efficiency. ICID Bulletin 34 (10, 28-31)

Bird, J., 2014. The Water, Energy and Food Security Nexus- is it really new? The Gerald Lacey Memorial Lecture. https://iwaterforum.org.uk/gerald-lacey-memorial-lectures/

Branche, E., 2017. The multipurpose water uses of hydropower reservoir: The SHARE conceptLe multi-usage de l'eau des réservoirs hydroélectriques à buts multiples : Le concept SHARE, Comptes Rendus Physique, Volume 18, Issues 7–8, September–October 2017, Pages 469-47, https://doi.org/10.1016/j.crhy.2017.06.001

Burnett, Kimberly & Wada, Christopher. (2018). Accounting for Externalities in the Water Energy Food Nexus. 10.1007/978-981-10-7383-0_18.

Calatrava, J., & Martínez-Granados, D. (2018): Water buybacks to recover depleted aquifers in south-east Spain, International Journal of Water Resources Development, DOI: 10.1080/07900627.2018.1504756

Daccache, A , J S Ciurana , J A Rodriguez Diaz and J. W. Knox (2014). Water and energy footprint of irrigated agriculture in the Mediterranean region. Environ. Res. Lett. 9 1

Dargin, J., Daher, B., & Mohtar, R. H. (2019) Complexity versus simplicity in water energy food nexus (WEF) assessment tools. Science of the Total Environment 650:1566–1575. doi:10.1016/j.scitotenv.2018.09.080.

Davies, Philip & Paton, Charlie. (2005). The Seawater Greenhouse in the United Arab Emirates: thermal modelling and evaluation of design options. Desalination. 173. 103-111. 10.1016/j.desal.2004.06.211

De Fraiture, C., M. Giordano, and Y. Liao. 2008. Biofuels and implications for agricultural water uses: blue impacts of green energy. Water Policy 10 (S1), 67–81

Dodds, F. and J. Bartram, 2016. The history of the Nexus at the intergovernmental level. In: Dodds, F., and J. Bartram, (Eds.), 2016. The Water, Food, Energy and Climate Nexus: Challenges and an Agenda for Action. Routledge, pp 7-46.

D'Odorico, P., Davis, K. F., Rosa, L., Carr, J. A., Chiarelli, D., Dell'Angelo, J., et al. (2018). The global food-energy-water nexus. Reviews of Geophysics, 56,456–531. https://doi.org/10.1029/2017RG000591

FAO. 2003. TRADE REFORMS AND FOOD SECURITY, Conceptualizing the Linkages.

FAO. 2014. The Water-Energy-Food nexus at FAO. Concept Note. pp 1-10

FAO (2006) FAO statistical databases: http://faostat.fao.org/default.aspx, last ccess: 10 October 2006, 2006.

FAO. 2011. In state of the World's Land and Water Resources for Food and Agriculture. Managing systems for risk. pp 5-30

FAO. (2011). Energy-smart food for people and climate Food and Agriculture Organization of the United Nations. Rome, Italy.

FAO (2012) Coping with water scarcity. An action framework for agriculture and food security. pp. 1-40

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

FAO. (2018). WORLD FOOD AND AGRICULTURE – STATISTICAL

POCKETBOOK. Rome. 254 pp. Licence: CC BY-NC-SA 3.0 IGO. .

FAO/IFAD/UNICEF/WFP/WHO. (2017). The State of Food Security and Nutrition in the World 2017. Building resilience for peace and food security. *Rome, FAO*.

FAOstat, F. (2009). agriculture organization of the United Nations. In.

Garrick, D., Siebentritt, M. A., Aylward, B., Bauer, C. J., & Purkey, A. (2009). Water markets andfreshwater ecosystem services: Policy reform and implementation in the Columbia and Murray-Darling Basins. Ecological Economics, 69(2), 366–379. doi:10.1016/j.ecolecon.2009.08.00

Gassert, F., Luck, M., Landis, M., Reig, P., & Shiao, T. (2014). Aqueduct global maps 2.1: Constructing decision-relevant global water risk indicators. World Resources Institute.

Geressu T and Harou, J. (2019). Reservoir system expansion scheduling under conflicting interests. *Env. Modelling Software.* 118, 201-210

Gerland, P., Raftery, A. E., Ševčíková, H., Li, N., Gu, D., Spoorenberg, T., . . . Lalic, N. (2014). World population stabilization unlikely this century. *Science, 346*(6206), 234-237.

Giordano, M.; Turral, H.; Scheierling, S. M.; Tréguer, D. O.; McCornick, P. G. 2017. Beyond "more crop per drop": Evolving thinking on agricultural water productivity. Colombo, Sri Lanka: International Water Management Institute (IWMI); Washington, DC, USA: The World Bank. 53p. (IWMI Research Report 169).

Giordano, Mark; Shah, Tushaar. 2014. From IWRM back to integrated water resources management. International Journal of Water Resources Development, 30(3):364-376.

Grey, D, D. Garrick , D. Blackmore , J. Kelman , M. Muller and C. SadoffWater security in one blue planet: twenty-first century policy challenges for science. https://doi.org/10.1098/rsta.2012.0406

Gosling, S. N., & Arnell, N. W. (2016). A global assessment of the impact of climate change on water scarcity. Climatic Change, 134(3), 371-385.

Gupta, E. (2019). The Impact of solar water pumps on energy-water-food nexus: Evidence from Rajasthan, India. Energy Policy, 129, 598-609.

Hanjra, M. A. and Qureshi, M. E, 2010. Global water crisis and future food security in an era of climate change, Food Policy 35: 365–377

Harari, Y.N. (2016). Home Deus, Vintage, 513pp. London, UK.

Harou JJ, Medellín-Azuara J, Zhu T, et al. (2010) Economic consequences of optimized water management for a prolonged, severe drought in California. *Water Resources Research* 46.

He ZH, Tian FQ, Gupta HV, et al. (2015) Diagnostic calibration of a hydrological model in a mountain area by hydrograph partitioning. *Hydrol. Earth Syst. Sci.* 19: 1807-1826.

Heerman, D., et al. 1990. Irrigation efficiency and uniformity. In ASAE monograph- management of farm irrigation systems. Chapter 6, pp 125-149 Jensen, M.E. 1967.

Hellegers, P., Zilberman, D., Steduto, P., & McCornick, P. (2008). Interactions between water, energy, food and environment: evolving perspectives and policy issues. Water Policy, 10(S1), 1-10.

Hermann, S., Welsch, M., Segerstrom, R. E., Howells, M. I., Young, C., Alfstad, T., Steduto, P. (2012). Climate, land, energy and water (CLEW) interlinkages in Burkina Faso: An analysis of agricultural intensification and bioenergy production. Paper presented at the Natural Resources Forum.

Hoekstra, A.Y and M. Mekonnen (2012). The water footprint of humanity, Proceedings of the national academy of sciences of the United States of America, vol. 109 (9), 3232–3237

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

ICID. (2017). Modernizing Irrigation and Drainage for a new Green Revolution. Transactions of the 23rd ICID Congress on Irrigation and Drainage – Abstract Volume: Question 60 and 61 418 pp.

ICID. 2018. Managing water for sustainable agriculture. In ICID News. p 8

IAEA. 2010. World energy Outlook 2010: Paris : OECD/ international Agency

International Energy Agency (2016). World energy outlook 2016. Paris: International Energy Agency.

IRENA (International Renewable Energy Agency) (2015) *Renewable Energy in the Water, Energy & Food Nexus*, Rabia Ferroukhi, Divyam Nagpal, Alvaro Lopez-Peña and Troy Hodges, Rabi H. Mohtar, Bassel Daher, Samia Mohtar, Martin Keulertz (eds) 124 pages. Abu Dhabi, United Arab Emirates.

Israelesen, O., et al. 1944. Water application efficiencies in irrigation. Agricultural experiment station. Bulletin 311. Utah State Agricultural College. pp 55

Jensen, M.E. 1967. Evaluating irrigation efficiency. Journal of the Irrigation and Drainage Division American Society of Civil Engineers. pp 83-98

Jessoe, K., and L. Badiani. 2017. Electricity prices, groundwater and agriculture: the environmental impact of subsidies in India. Journal of Environmental Development. pp 1-5

Keulertz, M., J Sowers, E Woertz and R. Mohtar. (2018). The water-energy-food nexus in arid regions: The politics of problemsheds. In Conca, K and E. Weinthal. (2018) The Oxford handbook of water Politics and Policy, pp 167-196.

Konikow, L. F. (2011). Contribution of global groundwater depletion since 1900 to sea-level rise. Geophysical Research Letters, 38(17).

Kumar, M.D. (2016). Distressed Elephants: Policy Initiatives for Sustainable Groundwater Management in India. IIM Kozhikode Society & Management Review. 5. 51-62. 10.1177/2277975215617266.

Kumar, M.D. (2018). Water Policy Science and Politics: An Indian Perspective. Elsevier Science; 1 edition

Kummu, M., Ward, P. J., de Moel, H., & Varis, O. (2010). Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. Environmental Research Letters, 5(3), 034006.

Kuwayama, Y., Young, R., & Brozović, N. (2017). Groundwater Scarcity: Management Approaches and Recent Innovations. In Competition for Water Resources (pp. 332-350). Elsevier.

Li H, Sivapalan M and Tian F. (2012) Comparative diagnostic analysis of runoff generation processes in Oklahoma DMIP2 basins: The Blue River and the Illinois River. *Journal of Hydrology* 418-419: 90-109.

Licht, F. 2012. FO Licht's World Ethanol and Biofuels Report, Volume 10. Issue 15

Liu, J., Hull, V., Godfray, H. C. J., Tilman, D., Gleick, P., Hoff, H., ... & Li, S. (2018). Nexus approaches to global sustainable development. Nature Sustainability, 1(9), 466.

Madramootoo, C. 2016. Emerging technologies for promoting food security. Wood head publishing. pp 117-126

Mannan, M, T. Al-Ansari, H. R. Mackey, and S. G. Al-Ghamdi. (2018) Quantifying the energy, water and food nexus: A review of the latest developments based on life-cycle assessment. Journal of Cleaner Production, 193, 300-314.

Mellah, T. (2018). Effectiveness of the water resources allocation institution in Tunisia. Water Policy 20. 429-445.

Mercure, Jean-Francois & Augusta Paim, Maria & Bocquillon, Pierre & Lindner, Sören & Salas, Pablo & Martinelli, Paula & Berchin, Issa & Derani, Cristiane & Junior, Celso & Pereira Ribeiro, João & Knobloch, Florian & Pollitt, Hector & Robert Edwards, Neil & Holden, Philip & Foley, Aideen & Schaphoff, Sibyll & Faraco, Rafael & Vinuales, Jorge & Andrade Guerra, José Baltazar. (2017). System Complexity and Policy Integration Challenges: The Brazilian Energy-Water-Food Nexus. Renewable and Sustainable Energy Reviews. 10.13140/RG.2.2.24806.73286.

Micklin, P. (2010). The past, present, and future Aral Sea. Lakes & Reservoirs: Research & Management, 15(3), 193-213.

Micklin, P. (2014). Efforts to revive the Aral Sea. In The Aral Sea (pp. 361-380). Springer, Berlin, Heidelberg.

Molden, 2007. Comprehensive Assessment of Water Management in Agriculture. Water for Food, Water for Life. London: Earthscan, and Colombo: International Water Management Institute.

Montilla-López, N., Gutiérrez-Martín, C., and Gómez-Limón, J. 2016. Water Banks: What Have We Learnt from the International Experience? Water, 8, 466; doi: 10.3390/w8100466

Nonhebel 2005; oil and gas extraction. Earth's Future, 6(5), 745–756. https://doi.org/10.1002/2018EF000809

OECD (2017), The Land-Water-Energy Nexus: Biophysical and Economic Consequences, OECD Publishing, Paris, https://doi.org/10.1787/9789264279360-en.

OECD. 2018. Managing water supply sustainably is a key to the future of food and agriculture. Better policy for better lives. pp 1-3

Seckler, D., et al. 2003. The concept of efficiency in water resources management and policy. In Kigne, J.W., Barker, R., Molden, D. (ed's) Water Productivity in Agriculture: Limits and opportunities for improvement CABI publishing, Cambridge MA. pp 37-51

Ojeda-Bustamande, W., Garcia-Villanueva, N. & Iniguez-Covarrubias, M. (2019) Modification on Crop Water Demands under Adaptation Actions to Climate Change. 3rd World Irrigation Forum, Indonesia.

Ostrom, E., 2010. Beyond markets and states: polycentric governance of complex economic systems. American economic review, 100(3), pp.641-72.

Otoo, M; Drechsel, P. (Eds.) 2018. Resource recovery from waste: business models for energy, nutrient and water reuse in low- and middle-income countries. Oxon, UK: Routledge - Earthscan. 816p

Pahl Wostl, C. 2017. Environmental Science Policy. pp 1-5

Pardoe, J., Conway, D., Namaganda, E., Vincent, K., Dougill, A.J., & Kashaigili, J.J (2018). Climate change and the water–energy–food nexus: insights from policy and practice in Tanzania. Climate Policy, 18(7), 863-877.

Perera, P. and L. Zhong, 2017. water–energy nexus in the People's Republic of China and emerging issues. ADB, Manila 73pp.

Postel, S. 1993. Water and Agriculture, in PH Gleick ed. Water in crisis: A guide to the world's freshwater resources (Oxford University press)

Prasad, G., Stone, A., Hughes, A., & Stewart, T. (2012). Towards the development of an energy-water-food security nexus based modelling framework as policy and planning tool for South Africa. Paper presented at the Strategies to Overcome Poverty and Inequality Conference, University of Cape Town, Cape Town.

Prayas (Energy Group). (2018). Understanding the Electricity, Water, Agriculture Linkages - Volume 1

Rabi H. Mohtar and Bassel Daher (2016). **Water-Energy-Food Nexus Framework for facilitating multi-stakeholder dialogue**. *Water International,* DOI: 10.1080/02508060.2016.1149759.

R.H. Mohtar (2016) *Developing the Capacity of ESCWA Member Countries to Address the Water and Energy Nexus for Achieving Sustainable Development Goals,* Regional Policy Toolkit. United Nations Economic and Social Commission for Western Asia (UN-ESCWA) Pages 36-65. United Nations, Beirut.

Rabi H. Mohtar and Richard Lawford. (2016). **Present and future of the water-energy-food nexus and the role of the community of practice,** *J. Environ Stud Sci,* 6:192-199. DOI 10.1007/s13412-016-0378-5

Rabi Mohtar (Ed.). (2019). Opportunities in the Water-Energy-Food Nexus Approach: Innovatively driving economic development, social wellbeing, and environmental sustainability. Science of the Total Environment (special issue). ISSN: 0048-9697 Elsevier.

R. Ragab, J.G. Evans, A. Battilani and D. Solimando. 2017a.Towards accurate estimation of crop water requirement without the crop coefficient: New approach using modern technologies.*Irrigation and Drainage:* 66: 469–477. DOI: 10.1002/ird.2153

R. Ragab, J.G. Evans, A. Battilani and D. Solimando. 2017b. The COsmic-ray Soil Moisture Observation System (COSMOS) for estimating the crop water requirement: New approach. *Irrigation and Drainage:* 66: 456–468. DOI: 10.1002/ird.2152.

Ragab R. 2015. Integrated water management tool for water, crop, soil and N-fertilizers: The

SALTMED model. *Irrigation and drainage* 64: 1-12.

Rasul, G. (2014). Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region☆. Environmental Science & Policy, 39, 35-48.

Rasul, G., & Sharma, B. (2016). The nexus approach to water–energy–food security: an option for adaptation to climate change. *Climate Policy, 16*(6), 682-702.

Rasul, G. (2015) Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia, Environmental Development, Volume 18, Pages 14-25, https://doi.org/10.1016/j.envdev.2015.12.001

Raworth, K. (2017). Doughnut Economics: 7 Ways to Think Like a 21st Century Economist. White River Junction, VT, USA. 320 pp.

Reggiani P, Sivapalan M and Majid Hassanizadeh S. (1998) A unifying framework for watershed thermodynamics: balance equations for mass, momentum, energy and entropy, and the second law of thermodynamics. *Advances in Water Resources* 22: 367-398.

Reinhard, S., Verhagen, J., Wolters, W., & Ruben, R. (2017). Water-food-energy nexus: A quick scan (No. 2017-096). Wageningen Economic Research.

Ringler C and Cai X. (2006) Valuing Fisheries and Wetlands Using Integrated Economic-Hydrologic Modeling—Mekong River Basin. *Journal of Water Resources Planning and Management* 132: 480-487.

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.

Rosa, L., Rulli, M. C., Davis, K. F., & D'Odorico, P. (2018). The water-energy nexus of hydraulic fracturing: A global hydrologic analysis for shale

Rulli, M. C., Bellomi, D., Cazzoli, A., De Carolis, G., & D'Odorico, P. (2016). The water-land-food nexus of first-generation biofuels. Scientific Reports, 6, 22521. https://doi.org/10.1038/srep225

Ryan, N. & Sudarshan, A. (2018). The Efficiency of Rationing: Agricultural Power Subsidies, Power Supply and Groundwater Depletion in Rajasthan. (this one says preliminary/do not cite and has no publication)

Sabo JL, Ruhi A, Holtgrieve GW, et al. (2017) Designing river flows to improve food security futures in the Lower Mekong Basin. *SCIENCE* 358.

Sahasranaman, M., D. Kumar, N. Bassi, M. Singh, and A. Ganguly (2018). Solar Irrigation Cooperatives. Creating the Frankenstein's Monsterfor India's Groundwater. Economic & Political Weekly, Vol LIII, No21, 64-68.

Scott, C. A., Kurian, M., & Wescoat, J. L. (2015). The water-energy-food nexus: Enhancing adaptive capacity to complex global challenges. In Governing the nexus (pp. 15-38). Springer, Cham.

SEI 2013. Long range energy alternatives planning system. Tool found on: http://sei-us.org/software/leap.

SEI 2014. Water evaluation and planning. Tool found on: http://www.weap21.org/index.asp?action=200.

Shah, T., and S. Verma, 2008. Co-management of electricity and groundwater: An assessment of Gujarat's Jyotigram Scheme. Economic and Political Weekly, 59-66.

Shah, T., 2010. Taming the anarchy: Groundwater governance in South Asia. Routledge.

Shah,T., and Chowdhury, S., D., 2017. Farm Power Policies and Groundwater Markets Contrasting Gujarat with West Bengal (1990–2015), Economic & Political Weekly EPW Published on Saturday, JUNE 24, 2017 vol lII Nos 25 & 26.

Shah, T, N Durga, G P Rai, S Verma and R Rathod (2017). Promoting Solar Power as a Remunerative Crop. Economic and Political Weekly, Vol 52, No 45, pp 14–19.

Shah, T. et al 2018. Solar pumps and South Asia's energy-groundwater nexus: exploring implications and reimagining its future, Environ. Res. Lett. 13 115003

Tardieu, H., and B. Schulz. 2008. Topic 2.3 Water and Food for ending poverty and hunger, revised draft scoping paper. 5th World water forum. New Delhi, India. Nov. 6 2008

Thakur, A., Kumar, A., Vanita, B., Panchbhai, G., Kumar, N., Kumari, A., & Dogra, P. (2018). Water Footprint A Tool for Sustainable Development of Indian Dairy Industry. International Journal of Livestock Research, 8(10), 1-18

Tian F, Hu H, Lei Z, et al. (2006) Extension of the Representative Elementary Watershed approach for cold regions via explicit treatment of energy related processes. *Hydrol. Earth Syst. Sci.* 10: 619-644.

Tian F, Li H and Sivapalan M. (2012) Model diagnostic analysis of seasonal switching of runoff generation mechanisms in the Blue River basin, Oklahoma. *Journal of Hydrology* 418-419: 136-149.

Tollefson, L., et al. 2014. Policy, Science and Society Interaction. In Irrigation and Drainage. Special Issue: First world irrigation forum: pp. 158-175

Tollefson, L. 2014. Technical Report ICID. Sub topic 59.2. ICID Congress Gwangju, Korea

Tollefson, L. 2018. Agricultural water. A water strategy AAFC

United Nations. 1975. *Report of the World Food Conference, Rome 5-16 November 1974.* New York.

United Nations (UN). (1992). '*The Dublin Statement on Water and the Environment', [online].* Available at: http://www.un-documents.net/h2o-dub.htm .

UN, 2013. Water Security and the Global Water Agenda.

United Nations. (2015). World Population Prospects: The 2015 Revision, Key Findings and Advance Tables. New York: United Nations, Department of Economic and Social Affairs PD. *Population Division*.

United Nations. (2016). World Water Assessment Programme Secretariat (WWAP): Water and jobs.

United Nations Water. (2018). Water, Food and Energy. pp 1-3

USGS, 2014. https://www.usgs.gov/special-topic/water-science-school/science/dictionary-water-terms?qt-science_center_objects=0#qt-science_center_objects, accessed 9/5/2019.Zeng, R. et al. (2017). Hydropower versus irrigation—an analysis of global patterns. Environmental Research Letters. 12 034006

Vanham, D., Gawlik, B.M. and G. Bidoglio. (2017). Cities as hotspots of indirect water consumption: The case study ofHong Kong. J. Hydrol. (2017),https://doi.org/10.1016/j.jhydrol.2017.12.004

Van Meijl, H., Ruben, R., & Reinhard, S. (2017). Towards an inclusive and sustainable economy. Wageningen University & Research.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., ... & Davies, P. M. (2010). Global threats to human water security and river biodiversity. Nature, 467(7315), 555.

Wada, Y., & Bierkens, M. F. (2014). Sustainability of global water use: past reconstruction and future projections. Environmental Research Letters, 9(10), 104003.

Wada, Y., Lo, M. H., Yeh, P. J. F., Reager, J. T., Famiglietti, J. S., Wu, R. J., & Tseng, Y. H. (2016). Fate of water pumped from underground and contributions to sea-level rise. Nature Climate Change, 6(8), 777.

Williams E. D. and Simmons J. E., BP (2013): Water in the energy industry. An introduction. www.bp.com/energysustainabilitychallenge

Woltjer, G., Selnes, T., & Reinhard, S. (2019) The Nexus Approach in Decision Making. Working document. The Hague Wageningen Economic Research.

World Bank. (2007). World development report 2008: Agriculture for development. *The International Bank for Reconstruction and Developm ent, W ashington, DC*.

World Bank. 2010. Liquid Biofuels: Background Brief for the World Bank Group Energy Sector Strategy. World Bank March 2010. 27 pp

WWAP, U. N. W. W. A. P. (2014). The United Nations World Water Development Report 2014: Water and Energy. Paris, UNESCO. https://sustainabledevelopment.un.org/index.php?page=view&type=111&nr=7266&menu=35

Zhuo, L., Mekonnen, M.M. and Hoekstra, A.Y. (2016) Water footprint and virtual water trade of China: Past and future, Value of Water Research Report Series No. 69, UNESCO-IHE, Delft, the Netherlands.

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