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Water centrality to enabling water-energy-food systems

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Abstract Water is a key enabler of global water-energy-food nexus systems. The role of water in energy generation and its role in food provision, is made explicit. These are aspects that are often overlooked, or 'embedded' in assessments, skimming over the critical role that water plays in societal-enabling systems. The historical role of water in enabling agriculture, settlements, civilization, and development is discussed. The role of water in the achievement of the United Nations Sustainable Development Goals is discussed, showing that in some cases, achieving water-related goals in de-facto necessary for the accomplishment of others. Water may be the most important resource needed in a broader water-energy-food context, as well as in the scope of human development. The review highlights the consequences of 'water going wrong'. The paper ends with a call for greater 'nexus awareness' in policy and decision making, while cautioning against the potential ironic situation of returning to a sectoral, water-centric view of resource management.

Keywords: nexus; systems thinking; water centrality; water-energy-food.

1. Introduction: the water-energy-food nexus

Water (W) supply and demand, energy (E) generation and consumption, and food (F) demand and production, linked to land availability, form a coherent global network, referred to as the WEF nexus (Hoff, 2011) which is pressured by population growth, climate change, policy implementation, and socio-economic development. About 1 billion people lack access to clean water, 2.5 billion people lack basic sanitation, 1.4 billion have no electricity and over 850 million are chronically malnourished while global food waste is estimated at 30% of production (World Bank, 2013). Overexploitation of WEF resources is a critical issue (WEF 2016; Carmona-Morena et al. 2018). This is important as nexus impacts may be non-linearly related to the shock and may not be anticipated (Purwanto et al. 2019). Impacts are being felt as shocks in global economic systems, in water (supply) crises (Cape Town and Maputo 2018, Chennai, 2019, European and Chinese droughts in 2022, Pakistan floods in 2022), energy shortages (global energy crises 2021-22; Cozzi et al. 2022), and in food supply and fuel/food price surges (the spring/summer of 2011). There are signs of stress. Globally, aquifers are overexploited (Gleeson et al. 2012). Atmospheric CO2 concentrations reached 400ppm in early 2015 and it is suggested that remaining below the Paris Agreement's 2-degree warming target may now be unrealistic (Rogelj et al. 2016). Water is increasingly moved between basins and countries (Chapagain and Hoekstra, 2004; Konar et al. 2011; McDonald et. al. 2014), leading to a physical shifting of resources stress burden between locations. Fossil fuel resources are finite and being depleted, while land is a finite resource, with some arguing that certain proportions of the ice-free land-cover should remain unexploited (Henry et al 2018). Shortage or collapse in any WEF sector has the potential to cause dramatic changes in: availability of essential resources; production/distribution of goods; social and geopolitical instability; and irreparable environmental damage. It is posited that water is centrally important in the wider functioning of the WEF nexus, and in the ability to provide other services to humanity. The main objective is to show just how central water is to enabling food and energy provision, and indeed it's central position to enabling human civilization and development. This is critical as it is increasingly recognized that water is linked to many sectors of the global economy.

2. Water and the WEF nexus

Water is a critical enabler in the energy sector, being used for fuels extraction and processing, and for energy conversion, including electricity generation (Olsson, 2012). For extraction and processing, water use depends on the extraction type as well as the fuel. Average values of water use for primary fuel production range from 0.1 l MJ^{-1} for natural gas to 45 l MJ^{-1} for biomass (World Energy Council, 2010). Water is essential in fuels processing. For example, coal washing in the US uses 13-26 l GWh^{-1} (Mielke et al. 2020). Biofuels, while often seen as clean, are very water intensive (Gerbens-Leenes et al., 2009). Water is central to electricity generation. In Europe, thermal power plant cooling for electricity production accounts for over 40% of water withdrawals (WWAP, 2014). A comprehensive review of the differences between operational water withdrawals and consumption across a range of electricity generating technologies is given in Macknick et al. (2012). Solar electricity and wind power have almost zero operational

water requirements. On average, across all electricity-generating sources, it is reported that in the USA about 7.6 m^3 water is used to generate 1 kWh of electricity, while in China, this value is 1.9-2.4 $m^3 kWh^{-1}$ (Feng et al. 2014). Globally, it is estimated that 1500 km^3 water is withdrawn and 300 km^3 consumed for energy production, with these number expected to approximately double by 2100 (Bijl et al. 2016).

Water is crucial for food production, being withdrawn for irrigated agriculture, which accounts for 69% of freshwater withdrawals globally (Gleick, 2011). Sufficient water and appropriate, well-maintained, and organized irrigation systems can lead to significant improvements in food production. While about 19% of agricultural land is irrigated, irrigated agriculture supplies 40% of the world's food (Hanjra and Qureshi, 2010). Irrigation and farm management practice improvements could lead to significant water savings (Jagermeyer et al., 2016). Water is central in global food production systems that support human activity and socio-economic development.

Water is connected in enabling energy and food provision, playing a central role in support human activities and socio-economic development. Despite this, recent global data show that c. 4000 km^3 water was withdrawn in 2014, with 2500 km^3 consumed. This needs to be placed in the context of 'planetary boundaries' (Steffan et al., 2015) which places sustainable thresholds on various parameters, which if exceeded may lead to serious and potentially irreversible impacts. For water withdrawal, the planetary boundary has been proposed as 4000 $km^3 yr^{-1}$, suggesting that current withdrawal is close to the boundary. Water demand is expected to increase by 20-30% (Sušnik 2018), with unknown consequences on water supply security, water for food production, and water for energy generation.

3. Water and civilization, human development, and progress towards the SDGs

This section explores the central role of water at three stages of human history: i) the dawn of agriculture and sedentary life; ii) the industrial revolution; and iii) 21st Century challenges in human development gains.

i) The role of water in agriculture (food) and settlement. Water has been integral to enabling the nexus since antiquity. As early foragers experimented with and refined irrigated agriculture to enhance crop yields and mediate the uncertainty of local rainfall patterns, food surplus grew, nutrition improved, and the shift to a sedentary lifestyle and the development of organized settlements followed, exemplified by early Mesopotamian culture (Rost, 2017; Boccaletti, 2021). Although absolute water volumes utilised were small, agricultural organization and trade led to increasing technological, managerial, and institutional complexity (Rost, 2017). The societal impacts were transformative, starting humanity's path towards urbanisation.

ii) The industrial revolution and how water enabled transformational gains in energy and work. Especially important was the invention of the steam engine (Smil, 2019), with water wheels and water turbines contributing to energy generation and technological advance (Smil, 2019). Water constituted a critical ingredient in the development of the steam engine, leading to transformational changes in how work was accomplished, as well as the efficiency, replicability, and scale of that work. This goes some way to demonstrating the role of water in enabling the industrial revolution energy transformation as well as the current role of water in providing energy, to enabling modern society and contributing to human development ambitions.

iii) The role of water in enabling human development gains. Water contributes to human well-being by helping ensure human health, enabling productive activities (cf. Chenoweth, 2008; Metha, 2014). Lack of access to safe drinking water inhibits health and well-being (United Nations, 2010), and that water supply and sanitation infrastructure are preconditions for human development. Amorocho-Daza et al. (Accepted) explore the relationship between human development as measured by the UN HDI and water-related variables including access to water supply and sanitation, intra- and inter-seasonal rainfall variability, and water storage. Although the development of dams and reservoirs often enables agricultural expansion and urban growth (di Baldassarre et al. 2021), water storage variables have no statistical influence on HDI progress (Amorocho-Daza, 2021; Amorocho-Daza et al. Accepted), suggesting that storing large volumes of water is insufficient to boost HDI opportunities. It is the widespread supply of that water and its services via supply and sanitation infrastructure that have much larger human development benefits.

Closely related is the role that water plays in ambitions towards meeting the UN SDGs and their targets. The SDGs have been shown to form an interconnected system in themselves (Pham-Truffert et al., 2020). From a water standpoint, Pham-Truffert et al. (2020) show that water (SDG6) represents a safe SDG, meaning that achieving targets therein would lead to multiple co-benefits in other SDGs without risk of significant trade-offs (Fader et al. 2018). Water was found to play a key role in a potentially important feedback loop: climate influences water which influences energy (production). Energy production typologies then feedback to influence the climate (Pham-Truffert et al., 2020). From a water lens, Bhaduri et al. (2016) highlight how water is linked in some way to many SDGs, some more explicitly than others, and go as far as to argue that attaining SDG 6 targets is a precondition to meeting targets in other SDGs. Similarly, Brengtsson and Shivakoti (2015) highlight the role of water in enabling the achievement of multiple SDGs, but show how governance of other resources can feedback to influence the water SDG. All these studies demonstrate that: (a) water is critical to enabling achievement of many SDGs, and may even be a precondition for other SDGs; and (b) SDG achievement

and their prioritization, must be carefully thought through to maximise attainment in other SDGs, something that will need tailoring for each country.

4. Water going wrong

To underscore the central role that water plays in enabling nexus resources, it is necessary to consider some consequences of 'water going wrong'. The 2022 drought event in Europe was unprecedented. The impacts of this drought highlight the critical role of water in enabling WEF nexus resource provision. Dry conditions led to reductions in soil moisture throughout much of Europe (Toreti et al. 2022), contributing to agricultural production losses throughout northern, central, and western Europe. Water levels in many rivers fell to historical low levels. This situation directly impacted on shipping and the wider EU economy, (hydro-)power generation, and ecosystems (Vinke et al. 2022). These examples illustrate the 'cascade' impacts (Lawrence et al. 2020) resulting from water shortages. The link between the WEF nexus and ecosystems has been shown to be underrepresented in the literature, with the 2022 events demonstrating the need to better integrate ecosystems and their services into nexus studies (Hülsmann et al. 2019; Sušnik and Staddon, 2021). Such water-supported roles often go under-appreciated until periods of severe stress, shortage, and resource competition, situations that are expected to become more frequent and acute in the future, with increasingly global consequences (World Economic Forum, 2022).

5. Summary

This review has highlighted the interconnected nature of the water-energy-food (WEF) nexus, and the centrality of water within the nexus to enabling food and energy provision. This connectedness, and of the central role of water, is becoming ever more acute as society becomes increasingly hyperconnected. Taking this into consideration, there is a greater need than ever for a systems perspective (Capra and Luisi, 2014). The WEF nexus operates at a vast range of spatial scales from the household up to the globe, and everything in between. A wide variety of approaches are available, some of which are outlined Sušnik et al. (2022). There is no single one-size-fits-all methodological approach that can study 'the nexus' as an entity. Although substantial progress has been made in understanding the WEF nexus, much remains to be done, especially in relation to the ongoing challenge in integrating the role of, and impact upon, ecosystems in nexus assessments (Hülsmann et al., 2019), and frontier research seeking to explore the links between WEF nexus resources security and accessibility and human health consequences. Water is at the very heart of enabling progress in modern society. This strong relationship is argued to stretch back far in time, with the ever-more sophisticated use of water being crucial to the development of agriculture, settlements, large-scale and efficient energy generation, poverty eradication, economic growth, and ultimately to enabling modern society. Water plays an important role, often overlooked, in human development gains, and access to water-related services are a critical driver in this regard. It will be crucial not to, ironically, fall into the trap of reverting to a 'water-centric' worldview. All WEF sectors should stand on an equal footing in nexus assessments and during policy design if a true systems-thinking mentality is to be encouraged and promoted. Ultimately, the central role of water in enabling the WEF nexus is here to stay, and managing it appropriately in a 'thirstier' world will grow in importance to satisfy societal progress.

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