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Water as a key enabler of nexus systems (water–energy–food)

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Review

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Abstract

This review article positions water front-and-center as a key enabler of water–energy–food (WEF) nexus systems. It demonstrates the critical role of water in human civilization, progress, and development, including how water is central to the achievement of many of the United Nations' sustainable development goals. It is suggested that water may in fact be *the* most important resource needed in a broader WEF nexus context, as well as in the broader scope of human development. The review shows the consequences of 'water going wrong' – when there is too much or too little, and the global impacts of increasing frequency of such events, largely due to an ever more 'hyperconnected' world. The review concludes by urging greater 'nexus awareness' and systems thinking, especially in policy and decision-making, while cautioning against the potentially ironic situation of returning to a sectoral, water-centric view of resources management.

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 and land use, form a coherent 'hyperconnected' global network, referred to as the WEF nexus (Hoff, 2011) governed by complexity and feedback (WEF, 2013, 2016; Bleischwitz et al., 2018), and pressured by population growth, climate change, policy implementation, and socioeconomic development. The effective functioning and sustainability of nexus resources are essential for human well-being, and human development demands abundant, high-quality, easily accessible resources (cf. Sušnik and van der Zaag, 2017). Yet 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 (Moe and Rheingans, 2006; IMechE, 2013; World Bank, 2013a, 2013b; World Hunger, 2013). At the same time, demands for water, food (i.e., land), and energy (including fossil fuel resources) are expected to increase over the coming century (RAEng, 2010). Overexploitation of WEF resources is a critical global issue, gaining attention in policy and academia (IMechE, 2013; WEF, 2013, 2015, 2016; World Bank, 2013a, 2013b; WWF, 2014; EEA, 2015; UNISDR, 2015; Carmona-Morena et al., 2019; Sood et al., 2019). Nexus impacts may be nonlinearly related to the shock (e.g., climate change, a sudden policy switch) and may not be anticipated (cf. Purwanto et al., 2019). Impacts are being felt 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 2021–2022; Cozzi et al., 2022; Zakeri et al., 2022), and in food supply and fuel/food price surges (the spring/summer of 2011). Despite the life-supporting nature of WEF resources, there are obvious signs of stress. Globally, aquifers are overexploited (Gleeson et al., 2012). Atmospheric CO_2 concentrations reached 400 ppm in early 2015 (http://www.esrl.noaa.gov) and it is suggested that remaining below the Paris Agreement's 2° warming target may now be unrealistic (Rogelj et al., 2016; Wollenberg et al., 2016), even though 1.5° of warming is recommended as a safe maximum (IPCC, 2018). Water is increasingly moved between basins and countries, whether physically or through the 'virtual water trade' (Chapagain and Hoekstra, 2004; Konar et al., 2011; McDonald et al., 2014; Jiang, 2015; Chen et al., 2018). This leads to a physical shifting of the resources stress burden between locations. Fossil fuel resources are finite and being depleted (see https://ourworldindata.org/fossil-fuels), 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). Due to WEF resource interconnectedness, shortage or collapse in the functioning of any WEF sector has the potential to cause dramatic changes in the availability of essential resources, production/distribution of goods, social and geopolitical instability, and irreparable environmental damage. Here, 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. This review analyses this ‘water centrality’, arguing it to be one of, if not the, critical resources enabling wider resources provision and human development.

Water in the WEF nexus

Water is arguably central to enabling WEF nexus activities, human development, and progress toward the sustainable development goals (SDGs). Water is a critical enabler in the energy sector, being used for fuel extraction and processing, and for energy conversion, including electricity generation (Olsson, 2021). For extraction and processing, water use depends on the extraction type as well as the fuel. Apart from the volume of water use, wastewater produced from these processes must be properly treated. Failing to do so can lead to harmful impacts on ecosystems and on drinking water supplies. For oil production, water use depends on geology, the recovery technique, and on reservoir depletion techniques (Mielke et al., 2010). Secondary and tertiary recovery techniques are water-intensive due to the need for water (re-)injection as well as handling and treatment facilities for produced wastewater. 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; Olsson, 2021). Water is essential in subsequent fuel processing. For example, coal washing in the US uses 13–26 l GWh^{-1} (Mielke et al., 2010). Petroleum refineries use considerable water volumes for cooling, distillation, cracking, and reforming, ranging between 25 and 65 m^3 TJ^{-1} thermal energy produced (Gleick, 1994). Biofuels (e.g., ethanol, methanol, biodiesel), while often seen as relatively clean, are very water intensive, with water use depending on crop type, climate, soil conditions, farm practices, and so forth (Gerbens-Leenes et al., 2009). Biofuel crops also compete for land with food crops. An interesting future bio-based fuel is that derived from algae, with a much lower water demand than from ‘traditional’ bio-based fuel sources and does not compete for land resources (Gerbens-Leenes et al., 2014).

Aside from fuel extraction and processing, water is central to electricity generation. In Europe, thermal power plant cooling for electricity production accounts for over 40% of water withdrawals, with a similar fraction in the USA (WWAP, 2014). For thermal power plant cooling, a distinction must be made between the water withdrawn (i.e., the total amount of water physically removed from supply) and the water consumed (i.e., the part of withdrawn water that is ‘lost’ for near-term future use, in this case mainly evaporation from cooling towers). In many thermal power plants, the withdrawn volume can be very high, while the consumptive use is very low (i.e., only a small percentage gets evaporated, with most water being returned to the environment, albeit often with differing quality). Both cooling technology and water source have a significant impact on withdrawals and consumption. Close-loop cooling reduces withdrawals but increases water consumption, while dry cooling, which relies entirely on air to cool, considerably lowers the amount of water used while increasing energy demand and capital costs. Installing carbon capture and storage (CCS) systems within power plants to lower CO_2 emissions might increase water usage by up to 90% (Hoff, 2011). A comprehensive review of the differences between operational water withdrawals and consumption across a range of electricity-generating technologies is given by Macknick et al. (2012) and Olsson (2021).

Solar electricity and wind power have almost zero *operational* water requirements. However, it should be recognized that water is heavily involved in the minerals and metals extraction and processing stages to produce the materials needed for the solar panels themselves and wind turbine shafts and blades (cf. Mekonnen et al., 2015; Ding et al., 2018). On average, across all electricity-generating sources, it is reported that in the USA about 7.6 m^3 of 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). The lower Chinese value may reflect the increasing use of solar power. In hydropower reservoirs, water is lost via evaporation (e.g., Destouni et al., 2012; Scherer and Pfister, 2016), and can be globally substantial, but is often ignored. Mekonnen and Hoekstra (2012a) demonstrate that for a sample of 35 reservoirs, the water footprint was 90 Gm^3 $yr.^{-1}$, equal to 10% of the blue water footprint (i.e., irrigated global crop production water withdrawals). Given the sample size, the global total must be significantly larger. Globally, it is estimated that 1,500 km^3 of water is withdrawn and 300 km^3 is consumed for energy production, with these numbers expected to approximately double by 2,100 (Bijl et al., 2016). Water is therefore intrinsically ‘embodied’ in the energy that human society consumes (cf. Liu et al., 2020, 2021).

Water is crucial for enabling food production (cf. Rodell et al., 2018), being withdrawn for use in irrigated agriculture, which accounts for c. 69% of freshwater withdrawals globally (Gleick, 2011). It is therefore implicitly connection to land use and land cover, with water demand and impacts to water quality being impacted by how land is utilized, including that for agricultural production. About of 7,100 km^3 water is consumed by crop production annually (green and blue water combined, where green water is that held as soil moisture and not using additional withdrawn water from surface or groundwater sources; de Fraiture et al., 2018). This could rise to 13,500 km^3 by 2050 (de Fraiture et al., 2018). 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). The amount of water used for food production is influenced by supply and demand factors. On the supply side, the water requirements for irrigation differ widely, depending on the type of crops or crop varieties, the irrigation method and efficiency, local climate conditions, cropping and irrigation scheduling, soil conditions, and on-farm water management practices (Allen et al., 1998; Hoekstra, 2005; IAASTD, 2009; WWAP, 2012; Masia et al., 2021). It is shown that irrigation and farm management practice improvements could lead to significant water savings (Jägermeyer et al., 2015, 2016). On the demand side, the water ‘embodied’ in food production is highly dependent on dietary preferences, with vegetarian and vegan diets being less water-demanding than meat-intensive diets (Mekonnen and Hoekstra, 2012b). The fraction of food wasted, estimated as about one-third of the total production (Moe and Rheingans, 2006; IMechE, 2013) represents a considerable water ‘loss’ through the water embodied in the production of that food. International trade in food products implies trade in ‘virtual water’ (the water directly or indirectly needed for the production; cf. Chapagain and Hoekstra, 2004; Konar et al., 2011; Chen et al., 2018), allowing the calculation of ‘water footprints’ and showing, for different food products, which countries are implicit water ‘importers’ or water ‘exporters’ (Chapagain and Hoekstra, 2004). It is clear of the critical role that water plays in global food production systems that support human activity and socioeconomic development.

The central role of water in modulating energy and food provision can be illustrated through case studies. Elsayed et al. (2022) develop a system dynamics model (cf. Sterman, 2000; Ford, 2009) to assess how hypothetical governance approaches of the Grand Ethiopian Renaissance Dam (GERD) in Ethiopia could lead to water, energy, and food implications in Nile-basin countries. The case study serves to illustrate firstly the role of water in energy and food production in this vast river basin, and secondly how different approaches to reservoir (i.e., water) management can affect the outcomes of this role. The analysis shows that differing reservoir operation rules would lead to differing levels of water security, food production, and hydropower production, and interestingly that the benefits are unequally distributed among riparian nations. Specific outcomes depend somewhat on the governance position adopted (e.g., unilateral vs. cooperative modes of operation) and on the country being considered. The research shows how central water, and in particular the GERD, might be in wider Nile basin regional development issues in the near future.

Payet-Burin et al. (2019) develop a nexus model for the Zambezi River Basin, in which the connections between water and the food and energy sectors are critical, especially in considering the basin-wide impacts of climate change in the three sectors. From a water perspective, the benefits of hydropower development which include energy production increases, agricultural production benefits, and CO_2 emissions reductions, are nonetheless mediated in part by exogeneous factors such as fuel prices and carbon offset policies. While water in this basin is indeed key to enabling nexus sectors' developments, it (in the form of reservoir storage) is influenced by wider systems.

Bakhshianlamouki et al. (2020) explore WEF nexus wide impacts resulting from the potential implementation of restoration measures in Urmia Lake, Iran. Water (lake level and extent, irrigation water demand), energy (diesel demand), and food (crop production and income) are considered. While restoration measures might meet their goal of (partially) restoring Urmia Lake water levels, there may be unintended consequences for energy demand as irrigated areas expand. To combat this effect, cropland retirement and yield improvement via upgrades to irrigation technologies, could counter-act this negative effect. This highlights the need for systems thinking not just in food production, but also in the way that land is used. As with the studies above, this work demonstrates the interconnected nature of WEF systems, the central role of water, also in enabling livelihoods, and the potential for well-meaning policies to have unintended consequences.

As a part of the Zambezi River Basin, Masia et al. (2022) analyze the WEF nexus in the Songwe River Basin (SRB) bordering Tanzania and Malawi where the increasing competition for resources is leading to basin degradation (SRBDP, 2019). The two countries collaborate on a development programme whose main outcome is the construction of a multipurpose reservoir with water storage and hydropower plant capacity of 330 Mm^3 and 180.2 MW respectively (SRBDP, 2018, 2019). The programme is expected to contribute to reducing the number of people currently lacking access to water and electricity (30–50% and 75% of the total basin population, respectively; OECD, 2019), and to accelerate the achievement of SDGs, especially SDGs 2, 6, 7, and 13, thanks to the expected increase in water storage, and consequent food and renewable energy production, demonstrating the central role that water plays. However, the downstream impacts of these interventions are not assessed, but should be taken into account. Increasing water storage is essential to ensure water security (SDG 6), especially during droughts, and to make possible the extension of irrigated land with a consequent benefit in terms of food availability, access, and diversification (SDG 2), human health (e.g., nutrition) and socioeconomic targets (e.g., employment and income generation; SDG 8). The infrastructure is expected to improve livelihoods, human and ecosystem health (although the downstream consequences are not known), alleviate poverty (SDG 1), and mitigate climate change impacts (SDG 13), especially mitigating damages caused by floods and droughts (SRBDP, 2018, 2019; SIWI, 2019). Although the programme has several benefits, some downsides are apparent. Increases in crop production might increase water pollution due to fertilizer and pesticide loads. The rapid expansion of agricultural activities and land use change, if not regulated by policies, might adversely impact WEF resource quantity and quality, ecosystem goods and services provisioning, biodiversity, soil fertility, and human health. Additionally, downstream communities might be negatively affected by the upstream dam-induced shifts in river flows (e.g., Ritcher et al., 2010). The application of the WEF nexus approach is essential in highlighting the critical role that water plays, and the interlinkages between the WEF sectors to identify synergies and trade-offs. The work outcomes provide a means to support decision-making in the basin and track the progress in the SRB toward SDGs (Masia et al., 2022).

From the above discussion and examples, it is clear how water is intimately connected in enabling both energy and food provision, thereby playing a central role in supporting human activities and socioeconomic development. Despite this centrality, recent global data show that c. 4,000 km^3 of water was withdrawn in 2014, with 2,500 km^3 is consumed. This needs to be placed in the context of 'planetary boundaries' (Steffan et al., 2015) which places sustainable global limits or thresholds on various parameters, which if exceeded may lead to serious and potentially irreversible environmental impacts. For water withdrawal, the planetary boundary has been proposed as 4,000 km^3 $yr.^{-1}$, suggesting that withdrawal volumes are very close to the safe boundary. As water demand is expected to increase by 20–30% (Burek et al., 2016; WWAP, 2019), the safe planetary boundary is likely to be exceeded, something also suggested by Sušnik (2018), with unknown consequences on water supply security, water availability for food production, and water availability for energy generation. Considering the key role of water and the potential future of water demand, the next section goes further, suggesting that water is at the very heart of civilization, human development, and progress toward multiple SDGs, and therefore a truly critical and central enabler of nexus systems.

The role of water in enabling civilization, human development, and progress toward the SDGs

Water could be argued to be *the* resource most critical for enabling society, civilization, and human development. This section explores these themes from the viewpoint of the central role of water at three stages of human history, showing that the role of water in energy, food, and development has a long 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 and early Chinese civilization (cf. Adams, 1981; Hassan, 2011; Wilkonson, 2012; Rost, 2017; Wu et al., 2019; Boccaletti, 2021). The ancient Maya in Central America,

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survived in a water-limited environment by their ability to store and manage water. Large centers built reservoirs to guarantee year-round water supply, while smaller settlements were often found at locations with high annual precipitation and near rivers (Lucero, 2002). These water stores supplied drinking water as well as water for crop irrigation to boost yields and provide food surplus. Several long-term drought events compromised water availability, leading to reservoirs emptying and declines in crop yields. Ultimately, this resulted in the downfall of the Maya civilization (Lucero, 2002). This case of the Maya illustrates an example of an overshoot of limits (water availability) and collapse (of the civilization; cf. Diamond, 2011). Shifts to sedentary irrigated agriculture led to detrimental ecological impacts (Holdren and Erlich, 1974). Although absolute water volumes utilized were likely small, agricultural organization and trade led to increasing technological, managerial, and institutional complexity over time (cf. Rost, 2017; Smith, 2020; Boccaletti, 2021). The societal impacts were transformative, starting humanity's path toward urbanization. Water played a central role in this transformation.

ii) The industrial revolution and how water enabled transformational gains in energy and work. The second transformational leap in which water was a key enabler was the industrial revolution, being essential to producing the energy that powered new technology and machines. Especially important was the invention of the steam engine (cf. Hassan, 2011; Smil, 2019), with water wheels and water turbines (e.g., for hydropower) contributing to energy generation and technological advance (e.g., Clavering, 1995; Smil, 2019), with some modern hydropower plants having installed capacities exceeding 20 GW. Water was crucial for large-scale hydropower plant developments that provide electricity to large portions of the global population and industry, facilitating rapid industrial, technical, and human development progress (cf. Severnini, 2014; Boccaletti, 2021). Apart from the role of water in hydroelectric generation, it 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. Early innovations were related to transport applications, though applying the technology to steam-powered electricity generation (requiring increasing volumes of water as input) soon followed (Smil, 2019). The freshwater withdrawal for thermal power generation is significant globally, estimated at 290 km^3 in 2015, with about 18 km^3 of this being consumed (Lohrmann et al., 2019). 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, especially in the form of electricity, to enabling modern society and contributing to broader human development ambitions.

iii) The role of water in enabling human development gains. It is well known that water contributes to human well-being by helping ensure good human health, thereby enabling productive activities (cf. Chenoweth, 2008; Mehta, 2014). It has been shown that lack of access to safe drinking water inhibits health and well-being advances (United Nations, 2010), and that water supply and sanitation infrastructure are preconditions for human development (Arimah, 2017). Despite this awareness, there are still significant global challenges relating to both water supply and sanitation access (WHO and UNICEF, 2017). Using data from over 150 countries for the period covering 2000–2017, Amorocho-Daza (2021) and Amorocho-Daza et al. (2023) quantitatively explore the relationship between human development as measured by the UN Human Development Index (HDI) and water-related variables including access to water supply and sanitation, intra- and inter-seasonal rainfall variability, and water storage. It is shown that access to water supply and sanitation are positively correlated with HDI gains, while increasing seasonal precipitation variability hinders HDI progress. Countries with the highest HDI scores have the greatest levels of supply and sanitation access, and generally lower seasonal variation in precipitation. The relationships found are statistically significant and stable over the 21st century (2000–2017). Although the development of dams and reservoirs often enables agricultural expansion and urban growth (di Baldassarre et al., 2021), water storage variables were shown to have no statistical influence on HDI progress (Amorocho-Daza, 2021; Amorocho-Daza et al., 2023), suggesting that simply storing large volumes of water is insufficient to boost human development opportunities. Rather it is the widespread access to that water and its services via supply and sanitation infrastructure that have much larger human development benefits. This represents an important policy and financing message for human development gains in general, and for helping meeting SDG 6 in particular.

Closely related to this last theme is the role that water plays in ambitions toward meeting the UN SDGs and their respective targets. The SDGs have been shown to form a highly interconnected system in themselves (Pham-Truffert et al., 2020), this being built into their very design (Le Blanc, 2015). From a water standpoint, Pham-Truffert et al. (2020) show that water (SDG 6) represents a 'safe' SDG to achieve, meaning that achieving targets therein would lead to multiple cobenefits in other SDGs without risk of significant trade-offs (Pradhan et al., 2017; Fader et al., 2018). While this is a potentially positive aspect regarding the attainment of SDG 6, it is suggested that SDG 6 is one most at risk of not being achieved (Dawes, 2022), which may lead to widespread cobenefits not being realized. In addition, 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). This central, and multiple, role of water in enabling not just the WEF nexus but attainment of many SDG goals is also highlighted in the analysis of Dawes (2022). Zelinka and Amadei (2019) present a system dynamics approach to model the interactions between SDGs, but do not go as far as to quantitatively assess these relationships. This could be a fruitful future avenue for quantitatively assessing the relative contribution of each SDG to achieving others, as well as for identifying critical feedback relationships within the SDG framework (e.g., Zhang et al., 2022). From a water lens, Bhaduri et al. (2016) highlight how water is linked to many SDGs, some more explicitly than others. For example, groundwater abstraction is linked to food production (SDG 2), energy demand (SDG 7), climate (SDG 13; via emissions from pumping), and land (SDG 15; via potential land transformations as a result of exploiting groundwater). As a result of this water centrality within the SDGs, Bhaduri et al. (2016) go as far as to argue that attaining SDG 6 targets is a precondition to meeting targets in other SDGs, similar to the central thesis of this review. Similarly, Brengtsson and

Shivakoti (2015) highlight the role of water in enabling the achievement of multiple SDGs, but also show how governance of other resources can feedback to influence the water SDG. For example, efforts to meet food production or clean energy generation goals could lead to greater levels of water abstraction. Brengtsson and Shivakoti (2015) go on to stipulate the achievement of any SDG, including SDG 6, is context-specific, with approaches needing to be tailored to each situation. In an African context, Muggaga and Nabaasa (2016) stress the importance of water in reaching many SDG targets on the continent, especially given the vast water resources available. Water across Africa can contribute to agricultural production, energy generation, manufacturing, tourism, health advancement, fisheries, trade, and economic cooperation, in particular being a key leverage point for the achievement of SDGs 1, 2, 3, 14, and 15 (Muggaga and Nabaasa, 2016). This centrality will be critical as Africa is expected to develop rapidly during the next 30–50 years and beyond, with high levels of economic growth currently observed (AfDB et al., 2015).

While water is shown to be central to the successful achievement of many SDGs, others have demonstrated that simultaneous achievement of all 169 SDG targets is not likely to be possible due to inherent trade-offs. Fader et al. (2018) analyzed the water, energy, and food-related SDGs, and show that some targets have little to no interactions with other targets, and are therefore 'safe'. On the other hand, targets in SDG 2 may impinge on other SDG targets, while water was shown to have the greatest number of synergies, reflected in the analysis of Pham-Truffert et al. (2020), once again demonstrating the central, and critical role of water within the SDG framework. In a similar manner, Scherer et al. (2018) assess trade-offs between social and environmental SDGs (including SDG 6), showing that prioritizing social goals can increase environmental impacts, and that water-related impacts are relatively large. All these studies demonstrate that: (a) water is absolutely critical to enabling the achievement of many SDGs, and may even be a precondition before other SDGs can be met; and (b) that due to inherent trade-offs, SDG achievement and their prioritization, must be carefully thought through to help maximize attainment in other SDGs, something that will need tailoring for each country.

The above discussion demonstrates how water has played a key WEF-enabling role through much of human history, how it connects to the ability to achieve SDG goals, and case examples have shown the interconnected nature of the WEF nexus and the role of water therein. The next section uses the unprecedented dry European spring and summer of 2022 to make more concrete the real-world role of water in everyday lives especially when it 'goes wrong', highlighting that studies as those above are more than academic exercises.

The multi-sector impacts of water going 'wrong'

To further underscore the central role that water plays in enabling nexus resources, it is necessary to consider some of the global consequences of 'water going wrong' that occurred throughout 2022. The 2022 drought event in Europe was unprecedented, with suggestions that the continental-wide event could be the most severe for 500 years.[1] The impacts of this drought (i.e., long-term water deficit) event highlight the critical role of water in enabling WEF nexus resource provision, often in ways overlooked when the climate is benevolent. For example, months of extremely dry conditions led to significant reductions in soil moisture throughout much of Europe (Toreti et al., 2022). Low soil moisture, along with water use restrictions in many locations, contributed to agricultural production losses throughout northern, central, and western Europe. Food production in France, Spain, Portugal, and the Netherlands was negatively impacted, among others, with wheat production in southern Europe c. 5% below usual levels (JRC, 2022), with much of Spain, southern France, and part of Germany, Italy, and eastern Europe classified as 'areas of concern' for summer and winter crop production, an impact still being felt in early 2023.[2] Together with the extraordinary outbreak of fires in Europe, which burned over 780,000 ha (data from European Forest Fire Information Service, August 2022; https://effis.jrc.ec.europa.eu/), this highlights the role of water in crop production, serving human consumption needs, as well as the needs of animal feed and crops for biofuels. Water levels in many rivers fell to historical low levels, with water levels on many major EU rivers experiencing extremely low flows (Toreti et al., 2022). This situation directly impacted on shipping and the wider EU economy, (hydro-)power generation, and ecosystems. In terms of shipping, by August 2022 ships on the Rhine were transporting as little as one-sixth of normal capacity to avoid running aground on the river bed (cf. Vinke et al., 2022). In 2018, another year when Rhine levels were low, German industry lost c. €3 billion as not all goods could be delivered by river barge. In 2022, reduced shipping loads led to lower output in German coal-fired power stations due to lack of coal supply to power stations, which is almost entirely by river barge. This in turn had an impact on the German economy.[3] These examples illustrate the wider cascade impacts (Lawrence et al., 2020; Vinke et al., 2022) resulting from severe water shortages. In terms of hydropower generation, Italy, France, and Portugal saw substantial reductions (c. 5,000, 4,000, and 2,200 GWh, respectively; Toreti et al., 2022) as a result of low water levels. Coupled with low water storage in reservoirs, this situation disrupted energy provision and water for irrigation throughout Western and Central Europe. Closely connected to the low water levels is the issue of high water temperatures and the concomitant effects on ecosystems. The link between the WEF nexus and ecosystems has been shown to be underrepresented in the literature, with the 2022 events demonstrating further the crucial need to better integrate ecosystems and their services into nexus studies (Hülsmann et al., 2019; Sušnik and Staddon, 2021). Outside of the EU, a concurrent drought in China threatened hydropower production, food production, inland shipping, and led to direct economic losses of c. €350 million in 1 month alone.[4] These events highlight the criticality of water as a central component in enabling food production, energy/power generation, logistics and supply chains, and maintaining healthy ecosystems functioning. These water-supported roles often go under-appreciated until periods of severe stress, shortage, and resource competition occur, situations that are expected to become more frequent and acute in the future, with increasingly global consequences (Byers et al., 2018; IPCC, 2021;

[1] https://news.sky.com/story/europes-drought-on-course-to-be-worst-for-500-years-european-commission-researcher-warns-12669153 (accessed September 2022).

[2] https://www.theguardian.com/world/2023/feb/17/italy-faces-another-year-severe-drought-little-winter-rain-snow-po-river.

[3] https://www.npr.org/2022/08/17/1117861780/germany-rhine-low-water-level-shipping?t=1661175463673 (accessed September 2022).

[4] https://www.theguardian.com/world/2022/aug/22/china-drought-causes-yangtze-river-to-dry-up-sparking-shortage-of-hydropower (accessed September 2022).

World Economic Forum, 2022). Despite the challenges, recent research has shown that a rapid transition to a net-zero emissions pathway would reduce the physical (e.g., heatwave frequency, lost crop days) and economic (losses) risks associated with climate change, meaning that society would be less vulnerable and more able to deal with increasing resources competition (Drouet et al., 2021).

On the other extreme are large-scale, widespread flood events that also threaten food and energy security. In New Zealand in August 2022, intense rainfall after a period of wet conditions led to widespread flooding, with critical infrastructure coming under severe pressure, and a high occurrence of wastewater overflows, threatening public supply access as well as public health (e.g., Blake et al., 2022). In Pakistan, the flooding was worse, with over 30% of the country inundated, thousands dead and millions displaced (Iqbal et al., 2022). At least one million people were forced into food insecurity due to crop production disruption, and failures in supply chains.[5] A water quality-related impact was that cases of cholera increased due to large areas of stagnant, low-quality water coupled with disrupted fresh drinking water supplies. As of November 2022, large swathes of the country were still underwater, posing a significant local and regional threat to food supply and security. The flooding events serve to demonstrate the central role that water plays in enabling myriad related service and functions including food provision, energy generation, ecosystem service support (van den Heuvel et al., 2020), and contributing to overall human health and well-being.

Discussion: Water in an increasingly connected world

This review article has highlighted the intricately interconnected nature of the water–energy–food (WEF) nexus, and of the centrality of water within the nexus to enabling food and energy provision. The connectedness of nexus sectors, and of the central role of water, is becoming ever more apparent as society becomes increasingly connected (cf. WEF, 2015). Taking this into consideration, there is a greater need than ever for a systems perspective (cf. Sterman, 2002; Capra and Luisi, 2014; Sušnik and Staddon, 2021) that accounts for the interconnections within and between sectors, including the way land is used. This marks a departure from prevailing silo-thinking, and recognizes that actions (e.g., implementation of policy objectives) are rarely contained within the sector for which they were intended (Purwanto et al., 2019). For example, objectives related to food self-sufficiency (i.e., land use changes) will likely impact on water quality, water quantity, ecosystems, biodiversity, and potentially on green energy objectives. Often, objectives between sectors may be synergistic, helping each other to meet their goals (Blicharska et al., in review), but in some cases, the opposite may be true, with trade-offs meaning that certain objectives might be met at the expense of others (e.g., Munaretto et al., 2017), something also apparent in the SDG targets.

It is worth noting that the WEF nexus and the myriad relationships that constitute it, operates across a vast range of spatial scales from households up to global. Different scales may interact and impact on each other. A review of the spatial scales in the WEF nexus, as well as their interactions, is given in Sušnik et al. (2022a). Difference in temporal scaling also exists, though this aspect is much less covered in nexus research. At present, it is common to focus on single-scale case studies, for example at household (Hussein et al., 2017), river basin (Masia et al., 2022), regional (Wang et al., 2023), national (Sušnik et al., 2021), or global (Meadows et al., 1972) level. Much less common is representing and dealing with multi-scalar interaction in quantitative modeling studies. Interactions between scales have however been extensively assessed in policy coherence studies across the WEF nexus (e.g., Munaretto et al., 2017, 2018).

When attempting to model WEF nexus interaction and system trends, a wide variety of approaches are available, some of which are outlined in Endo et al. (2015) and Sušnik et al. (2022b). Some appropriate methodological approaches include conceptual mapping and casual loop diagrams, system dynamics modeling, agent-based modeling, (multi-region) input–output modeling, life-cycle assessment, cost–benefit analysis, and integrated assessment modeling. Each approach has its own advantages and drawbacks, and the method(s) chosen should be those best suited to the issues being addressed, the desired outcomes of the study, and the capabilities of the approach to deal with specific study requirements. There is no one-size-fits-all methodological approach that can study 'the nexus' as an entity. This is largely due to the huge diversity in study regions, issues, scales, challenges, and requirements of local stakeholders. Therefore, methods must be chosen tailored to the circumstance.

Although substantial progress has been made in understanding the WEF nexus over the past decade, much remains to be done, especially in relation to the ongoing challenge in integrating the role of, and impact upon, ecosystems and their services in nexus assessments (Hülsmann et al., 2019; van den Heuvel et al., 2020), and frontier research seeking to explore the links between WEF nexus resources security and accessibility and human health consequences. The role of water in supporting and enabling ecosystem services is gaining prominence, but still largely under-represented in nexus assessments (Sušnik and Staddon, 2021). Perhaps one reason for the difficulty is a lack of consensus on which terminology to use (ecosystems, ecosystem services, biodiversity, etc.), as well as the extraordinary diversity in ecosystems and their services around the world (Keith et al., 2020). This diversity largely precludes a single overarching methodological approach as to their valuation (monetary or not). For example, how can southern African Savannah be compared to northern European grasslands, or to equatorial rainforest? How can these ecosystems and their services be equally and fairly compared and valued? How can resource exploitation impacts on ecosystems be assessed, and indeed are the impacts even the same across ecosystems and their services? In one location, water temperature may be a critical variable as a proxy for the health and functioning of an ecosystem, whereas in another it may be above-ground biomass or soil-based carbon. This is saying nothing about the intricacies of aquatic and oceanic ecosystems. This leads to the comment in Sušnik and Staddon (2021) that ecosystems lack a common 'currency', especially for nonmaterial benefits such as cultural or esthetic services, further hampering their inclusion in nexus assessments (Farber et al., 2002; Small et al., 2017). Recently, tools and models such as InVEST (Tallis and Polasky, 2009) have been developed to help assess and value ecosystem services. Integrating InVEST concepts and modeling in nexus assessments could be a useful way forward in the WEF nexus field, which has been attempted in recent studies (Ding et al., 2023).

As this article has demonstrated, water is at the heart of enabling progress in modern food and energy sectors. This strong relationship is argued to stretch back far in time, with the ever-more sophisticated exploitation of water being crucial to the development of agriculture, settlements, large-scale and efficient energy

[5] https://reliefweb.int/disaster/fl-2022-000254-pak (accessed September 2022).

generation, poverty eradication, economic growth, and ultimately to enabling modern society. It is shown that water plays an important role in human development gains, and that access to water-related services appears to be a critical driver in this regard. Recognizing this centrality and the impact that water plays in enabling everyday life, is a key part of the systems thinking perspective. Following the unprecedented 2022 events, it is likely that the wider role of water in enabling society through a nexus lens will be increasingly recognized and accounted for in policy-making and resources management decisions. As such, water may well receive an even greater level of 'centrality' in the nexus.

At the same time, it will be crucial not to, somewhat ironically, fall into the trap of reverting to a 'water-centric' worldview. Despite the role of water, following the philosophy of the nexus approach, 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 (cf. Capra and Luisi, 2014). In this way, integrated resources management, planning, and security are supported, and future threats arising from rapidly growing resource demand within the interconnected WEF nexus can be anticipated and mitigated in a systemic way, minimizing detrimental trade-offs. Likewise, synergies can be leveraged, enhancing the effectiveness of policy actions across nexus resources, and possibly pointing to new ways for living in a more sustainable way. Ultimately, the central role of water in enabling the WEF nexus is here to stay, and managing it appropriately in a 'thirstier' world will only grow in importance to satisfy societal progress.

Implications for water management practice

This review has shown extensively and explicitly how water is central in enabling the food and energy provisioning sectors, how it is essential in many modern human societal developments including human development, and how it has a long history in enabling human progress. At the same time, it is cautioned not to revert back to a water-centric view of the world, returning to a fragmented and isolationist academic and practical landscape. This is important for water management practice. Water managers everywhere should be aware of the intimate connections that their sector has with other sectors of the economy, and vice versa. For example, as shown here, it should be realized that water plays a central role in energy generation (e.g., water volumes needed for thermal power generation) and in food production (for irrigation particularly at certain times of the year). Water managers should be acutely familiar with the local situation, tailoring water planning and management to ensure that all sectors are adequately served. Likewise, the reverse is true, with food production, land utilization, and the energy sector impacting on the water sector, in terms of demand patterns and quality impacts. For example, energy generation shortages may lead to a breakdown in water supply and/or treatment. Such feedback connections must be recognized and planned for. In emerging economies, the link between extending water supply and sanitation services and the benefits to human health and wider socioeconomic considerations should be considered when planning investment and maintenance in order to leverage potential benefits. Engaging in cross-sectoral dialog to 'map' and understand intersectoral linkages can help in this regard, with it being necessary to involve stakeholders, planners, and managers across resource sectors and disciplines to codevelop such resource-linkage maps. In doing so, potential trade-offs in policy or planning goals can be identified and avoided, while synergistic actions can be exploited to boost impact and increase efficiency in terms of resources utilization, of financial commitment, and in terms of policy effectiveness across the economy.

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