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OPINION PAPER



## Water quality: the missing dimension of water in the water–energy–food nexus

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### ABSTRACT

The role of water quality, particularly its impact on health, environment and wider well-being, are rarely acknowledged in the water–energy–food (WEF) nexus. Here we demonstrate the necessity to include water quality within the water dimension of the WEF nexus to address complex and multi-disciplinary challenges facing humanity. Firstly, we demonstrate the impact of water quality on the energy and food dimensions of the WEF nexus and vice versa at multiple scales, from households to cities, regions and transboundary basins. Secondly, we use examples to demonstrate how including water quality would have augmented and improved the WEF analysis and its application. Finally, we encourage hydrological scientists to promote relevant water quality research as addressing WEF nexus challenges. To make tangible progress, we propose that analysis of water quality interactions focuses initially on WEF nexus “hotspots,” such as cities, semi-arid areas, and areas dependent on groundwater or climate change-threatened meltwater.

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## 1 Introduction

The water–energy–food (WEF) nexus is a framework increasingly used by researchers and promoted for policymaking to address complex grand challenges facing humanity that require a multi-disciplinary approach (Liu *et al.* 2017, McGrane *et al.* 2019). An example is the United Nations Sustainable Development Goals (SDGs; United Nations 2015) which include zero hunger (SDG 2), good health and well-being (SDG 3), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), sustainable cities and communities (SDG 11), combating climate change and its impacts (SDG 13) and life below water (SDG 14). All these goals are underpinned individually, and also interlinked by, water (UN-Water 2016, United Nations 2018, Connor *et al.* 2020). Detailed analyses of water quality interlinkages with the SDGs (Alcamo 2019) and of the synergies among SDGs 2, 6 and 7 (Fader *et al.* 2018) have demonstrated how cross-sectoral efforts to improve water quality can bring mutual benefits in addressing other SDG targets. However, the synergies among goals relating to economic, energy, food and water security, and the essential role of water quality in these, are less prominent in national policies and laws that principally drive water quality management.

National and regional policies and laws relating to water management rarely mention the WEF nexus specifically, such as the EU Water Framework Directive (WFD; Venghaus and Hake 2018). Nevertheless, interdependencies between water and other sectors are considered in some key policy instruments. For example, to improve the ecological status of water bodies (which

includes water quality) the WFD requires the establishment and implementation of River Basin Management Plans and Programmes of Measures over a 6-year planning cycle (EU Directive on Water Policy 2000). To ensure compliance with the US Federal Water Pollution Control Act (often referred to as the Clean Water Act, CWA; US Government 1972), the US Environmental Protection Agency (EPA) has established various programmes or regulations, such as the National Pollutant Discharge Elimination System to control point sources discharging pollutants and the CWA Section 319 Program to prevent nonpoint-source pollution from agricultural and residential areas, livestock and husbandry. In China, the “3 Red Lines” water policies, implemented in 2012, include a target to reduce industrial water use such as in energy generation, and the Water Pollution Prevention and Control Action Plan (“10-Point Water Plan,” April 2015) aims to improve surface and groundwater quality (Qin *et al.* 2015), including by ecological protection and controlling agricultural nonpoint-source pollution (Han *et al.* 2016). In India, the National Water Policy (Government of India 2012) recognizes the need for integrated water resources management to meet different water needs, particularly domestic, agricultural and ecological, and the draft National Water Framework Bill (Government of India 2016) specifically mentions wastewater reuse and the consideration of water efficiency and energy efficiency in agricultural crop production. Both water quality and the WEF nexus are recurrent themes within these and other policy frameworks, yet they are rarely integrated explicitly with each other.

Water quality is defined as “the physical, chemical, biological and organoleptic properties of water” (WMO 2012), which includes water temperature. Here we also consider the processes that control these properties, operating over time and space. When examining the interaction of water with the other dimensions of the WEF nexus, the focus is often on water quantity (van Vliet *et al.* 2017). Yet food and energy production need water of a suitable quality as well as in sufficient quantity. Conversely, energy and food production can damage water quality. In this paper, we consider “food” to encompass food produced by agriculture as well as by aquaculture and fisheries in rivers, lakes, and freshwater-influenced estuaries and coastal zones. Although fish can be considered both a food and a component of water quality within ecological assessment schemes, here we highlight food production and security aspects of agriculture, aquaculture and fisheries, because (1) they are directly affected by water quality and (2) effects of water quality on human health through bioaccumulation in the food chain are primarily expressed in these two pathways.

The role of water quality, and in particular water quality aspects of health, environment and wider well-being, are rarely acknowledged specifically in discussions of the WEF nexus (Varis and Keskinen 2018). However, the adverse effects of poor water quality are increasingly well documented worldwide. Inadequate drinking water caused an estimated 485,000 deaths due to diarrhoea in low- and middle-income countries in 2016 (Prüss-Üstün *et al.* 2019). Gross domestic product (GDP) growth is reduced by a third in regions downstream of heavily polluted rivers, and the use of saline water for crop watering results in a reduction in yield equivalent to what would feed 170 million people each year (Damania *et al.* 2019). Contributions from the hydrological sciences to addressing WEF challenges include hydrological tools and models (Liu *et al.* 2017, Scanlon *et al.* 2017, Cudennec *et al.* 2018) and combined socio-hydrologic modelling approaches (e.g. van Emmerik *et al.* 2014) to operationalizing the WEF nexus, but do not explicitly encompass “water quality.” Greater contributions from the hydrological sciences are anticipated through ongoing initiatives led by the International Association of Hydrological Sciences, notably the “Panta Rhei – Everything Flows” Scientific Decade 2013–2022 (Montanari *et al.* 2013, McMillan *et al.* 2016) and the identification of 23 “Unsolved Problems in Hydrology” (UPH) (Blöschl *et al.* 2019), which include water quality and wider WEF nexus issues.

Even though water quality has been included in the conceptualization of WEF interlinkages in three large Asian drainage basins (Keskinen *et al.* 2016), attempts to describe the issues quantitatively were limited to water quantity indicators. This highlights a very important reason for the lack of attention to water quality, i.e. that appropriate surface and groundwater global water quality datasets are not yet available to support such assessments (UNEP 2016). A further reason for the lack of attention to water quality in the WEF nexus is that many different conceptualizations of the nexus exist, including the number of sectors considered in it, the scale of application, and the aim of using a nexus framework (Keskinen *et al.* 2016). Within different conceptualizations of the WEF nexus, water quality is often used interchangeably with considerations of ecosystems, and human and ecosystem health. Nevertheless, United Nations Economic Commission for Europe (UNECE) uses a water–food–energy–

ecosystems nexus to analyse transboundary issues, which does include consideration of water quality (de Strasser *et al.* 2016, UNECE 2018).

In this paper, we aim to demonstrate how explicit inclusion of water quality in the water dimension of the WEF nexus enhances the value of the WEF approach for policymaking and helps advance water quality research. This is particularly important for low- and middle-income countries such as those in Africa, Asia and Latin America, which are often disproportionately affected by pressures on the WEF nexus (Schlör *et al.* 2018). It will also become increasingly urgent under global change, including climate change, accelerated extreme events (Diftenbaugh 2020) and increased demands for water, energy and food (Ceola *et al.* 2016, Yillia 2016).

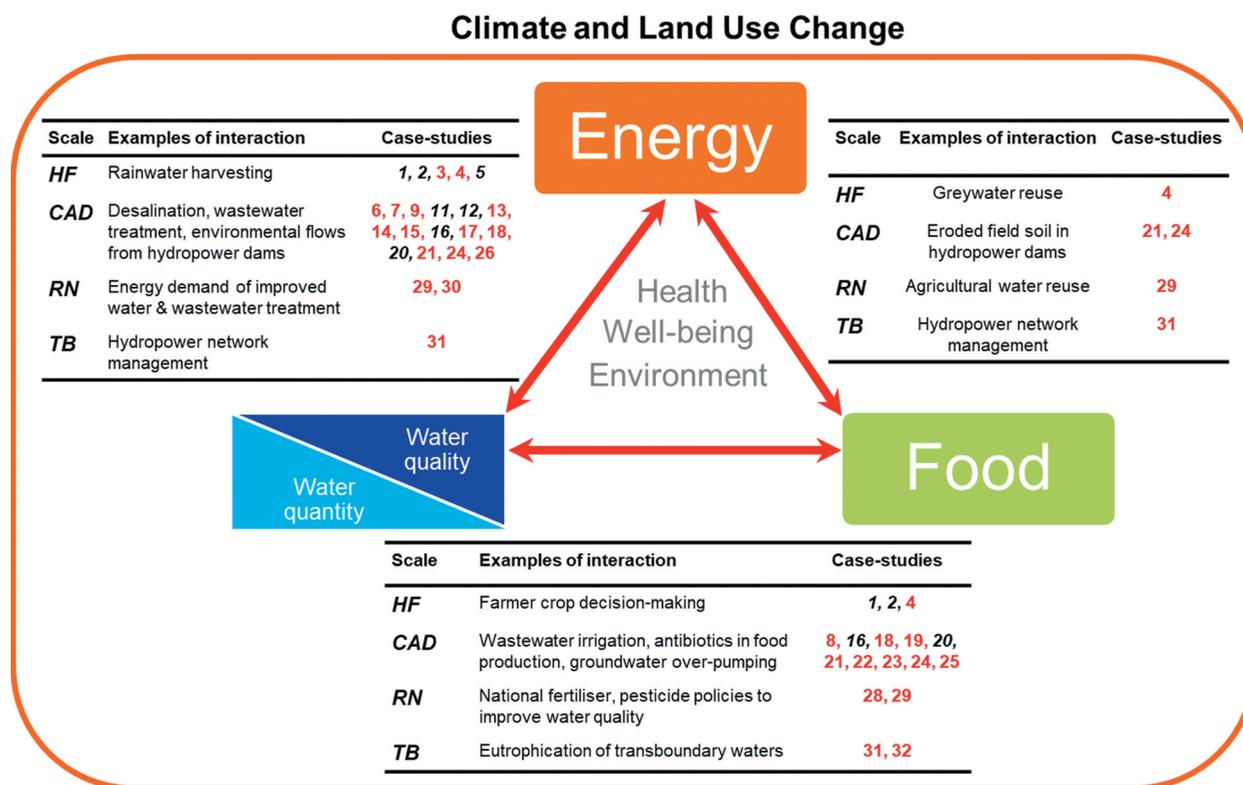
## 2 Identification of water quality as a key component of the different dimensions of the WEF nexus

In this section we discuss examples of water quality issues with respect to energy, food production, water quantity and tripartite WEF interactions. Due to the breadth and depth of water quality research in many areas – such as biogeochemical cycling, eco-hydrology and limnology – we do not attempt to include all water quality-related research within the current analysis, but note the availability and relevance of this foundational literature to support the integration of water quality into WEF research. Informed by an initial review of published papers (described in the Supplementary Material and summarized in Table S1), we identified examples of water quality interactions with the WEF nexus dimensions and classified these by spatial scale (Fig. 1). This exercise revealed that water quality research was only related explicitly to the WEF framework nexus in a few themes (numbers in black italic font in Fig. 1). We therefore refer to a large number of existing studies that are relevant, but do not make this connection explicit, to demonstrate how water quality is embedded in all three dimensions of the WEF framework. First, water quality aspects of each WEF nexus dimension are examined sequentially in three sub-sections (water quality–energy, water quality–food, water quality–water quantity). Within each sub-section, we first discuss how that WEF dimension affects water quality (e.g. how energy production affects water quality) and then how water quality affects that dimension (e.g. how water quality affects energy production). Next, examples are presented of more complex water quality interactions with all three dimensions of the WEF nexus. The section concludes by highlighting water quality–WEF nexus interactions within and across spatial scales. The examples selected from the literature rarely mention WEF explicitly, but they demonstrate the significant impact of water quality included within the “water” dimension on the energy, food and water dimensions of the WEF nexus and vice versa.

### 2.1 Water quality and energy

#### 2.1.1 Energy impacts on water quality

All forms of energy production have impacts on water quality (WWAP 2014). Water quality can be affected at every step in the extraction, refining and combustion of fossil fuels, including shale gas development using hydraulic fracking, through both regular



**Figure 1.** Overview of some themes that are relevant to water quality issues within the water–energy–food (WEF) framework. Numbers refer to case-study themes in Table S1. Themes in which the WEF framework is mentioned (**black italic font**) are distinguished from themes where it is not explicitly mentioned (**red font**). Studies are classified by scale in tables along the WEF dimensions using spatial scale definitions for hydrology which are loosely based on the four scales identified in Blöschl and Sivapalan (1995). “HF,” “CAD,” “RN” and “TB” refer to the “household/farm field plot,” “city/aquifer/drainage basin,” “region/nation” and “transboundary” scales, respectively. The figure format is based on Fig. 1 in Liu *et al.* (2017), with the orange envelope around the WEF nexus indicating that WEF interactions occur within (and also influence) climate and land-use change.

operations and accidental releases, such as leaks from surface underground storage tanks. Approximately 15–18 billion m<sup>3</sup> of freshwater resources worldwide are affected by fossil fuel production every year (Allen *et al.* 2012), with significant implications for ecosystems and communities dependent on this water. For example, national demand for coal in the USA has been met partly by mountaintop mining with valley fills in Appalachian Kentucky, resulting in contamination of domestic supply wells and selenium concentrations exceeding the threshold for toxic bioaccumulation in more than 90% of streams surveyed (Table S1 #9; Palmer *et al.* 2010). Atmospheric emissions from thermal power plants can include mercury, sulphur and nitrogen oxides which, when transported and deposited across a range of scales, may impair water quality and threaten aquatic ecosystems and human health (Peterson *et al.* 2007). Several pathways of surface water contamination are associated with unconventional shale gas development and hydraulic fracturing (Table S1 #9; Vengosh *et al.* 2014). They involve flowback fluids (fluids returned to the surface after hydraulic fracturing) and produced waters (fluids extracted during production together with the natural gas), which are typically hypersaline and contain elevated concentrations of barium, strontium, radioactive radium and total dissolved organic carbon. Examples of deteriorating surface water quality downstream of treated wastewater disposal from shale gas operations include: increased concentrations of total trihalomethanes (THMs), especially brominated THMs, in municipal drinking water, which might compromise disinfection processes (States *et al.* 2013); and potential environmental risks of radium bioaccumulation in

downstream sediments in which <sup>226</sup>Ra concentrations may be ~200 times greater than background (Warner *et al.* 2013).

While other sources of energy, such as hydropower, solar (both photovoltaic and concentrating solar power plants), or wind, have significantly lower greenhouse gas emissions than fossil fuel power plants, they are not without consequences for the environment and water quality. Aside from manufacturing of materials and disposal of old units, maintenance and operation of energy production units can also impact water quality (e.g. application of pesticides and cleaning agents). Their very existence impacts on the land use and thermal balance in the local area. For example, wind farm developments may necessitate forest felling, resulting in a reduction in downstream river water quality due to increased soluble reactive phosphorus concentrations (Heal *et al.* 2020).

Hydropower reservoirs completely change the characteristics of water bodies from fast-flowing to mostly stagnant waters upstream of dams, and their storage and release of water changes the hydrological regime and sediment and nutrient supply, and hinders fish movement. The principal effects on water quality are an altered thermal regime; decreased dissolved oxygen but increased concentrations of the reduced forms of iron and hydrogen sulphide, limiting the capacity for pollutant breakdown; altered availability of the nutrients phosphorus, nitrogen and silicon; and habitat alteration (Table S1 #10; Winton *et al.* 2019). Water quality and environmental effects can be damaging and cumulative in river networks, particularly for biodiversity, which underpins

fisheries in rivers, lakes and freshwater-influenced estuaries and coastal zones and livelihoods in many low- and middle-income countries. The additional ~450 dams planned for the Amazon, Mekong and Congo river basins, which together contain one-third of the world's freshwater species, pose a threat to freshwater fish diversity and migration and thus to communities reliant on wild fish (Winemiller *et al.* 2016).

A number of energy–water quality interactions may be exacerbated by climate change and measures to mitigate it. For example, warmer temperatures due to climate change can exacerbate water temperatures increased by cooling waters from thermoelectric plants and impoundment of water for hydropower production (Table S1 #26; Lugg and Copeland 2014) and lead to biological impairments (Stewart *et al.* 2013). The recent increase in large hydropower dams planned principally in low- and middle-income countries is partly attributed to the Paris Agreement of December 2015, with the aim of supporting low greenhouse gas emissions (Hermoso 2017). Increased forestry operations to produce biomass as a substitute for fossil fuels can amplify the transfer of mercury from soil to water, enhancing mercury bioaccumulation in food webs (Eklöf *et al.* 2016).

Another reported impact on water quality of energy policies is the effect of promoting biomass production on soil erosion and nonpoint-source pollution. For example, if the US congressional biofuel production mandate is met without enacting nutrient management measures, a 45% increase in total phosphorus loading in the Upper Mississippi River basin is projected to occur, resulting in declining river water quality and an increase in size of the Gulf of Mexico hypoxic zone (Table S1 #20; Demissie *et al.* 2012). Conversely, in a study focusing on nitrate, which behaves very differently from phosphorus, crop choice was found to have positive benefits for water quality. For example, modelling of a watershed in Illinois, USA, indicated that adoption of second-generation biofuel crops (e.g. *Miscanthus*) over corn and soybean would help reduce stream nitrate load, although irrigation water demand was predicted to increase (Table S1 #2; Ng *et al.* 2011). However, the local water quality improvement arising from replacing food-related crops with biofuel crops could be offset by increased food production and associated degradation in water quality in other regions, particularly where freshwater resources are limited and rainfall is insufficient for rainfed crops (Healy *et al.* 2015).

### 2.1.2 Water quality impacts on energy

Water quality, or the need to meet certain minimum water quality requirements, also affects the production of and demand for energy. Water temperature can act as a constraint on power production, with elevated water temperatures resulting in reduced power plant efficiency and shutdowns when water temperatures approach threshold values for environmental regulation (Miara *et al.* 2013). Measures taken to reduce the negative impacts of hydropower dams on fish, such as dam removals, the installation of fish passages, and turbine shutdowns during fish migration periods, result in lower electricity generation (Song *et al.* 2019). Partly because of more stringent water quality regulations for drinking water

and wastewater treatment, the total electricity demand for water and wastewater treatment in the USA increased by more than 50% between 1996 and 2013 (Table S1 #30; EPRI and Water Research Foundation 2013).

Water scarcity in arid, coastal and island locations often necessitates the use of lower quality water sources, such as wastewater and saline water, requiring more extensive treatment or desalination. Desalination not only has high energy requirements to meet water quality use standards, but also produces hypersaline brine that can have negative environmental impacts if not disposed of properly. Currently, desalinated water production for human use totals ~100 million m<sup>3</sup> day<sup>-1</sup> worldwide and generates ~140 million m<sup>3</sup> day<sup>-1</sup> of brine (Jones *et al.* 2019).

The drive for water-sensitive practices in cities may also lead to increased concentrations of sediment, nutrients and organic matter in sewers due to water efficiency measures, resulting in higher treatment costs (Table S1 #7; Murali *et al.* 2019). However, cost–benefit analyses for 13 wastewater treatment plants in Spain showed that the higher energy costs of treating wastewater can be economically viable when external benefits (e.g. reduced nitrogen and phosphorus pollution of receiving waters) are considered (Table S1 #15; Molinos-Senante *et al.* 2011).

## 2.2 Water quality and food

### 2.2.1 Food impacts on water quality

Since agriculture accounts for the majority of water withdrawals worldwide (70%, FAO 2003), it is not surprising that food production in agriculture and aquaculture has major impacts on all aspects of water quality, including the transfer of emerging contaminants. As the global demand for food (including fish protein from aquaculture) continues to increase at an unprecedented pace, there is significant pressure on farmers to intensify production, resulting in continued growth in demand for fertilizers (FAO 2017) and antimicrobials in livestock and aquaculture systems (Van Boeckel *et al.* 2015). Increased antimicrobial use, including antibiotics, in these sectors results in rising concentrations in surface waters and groundwater due to excretion and manure application (Charuaud *et al.* 2019), contributing to the spread of antimicrobial resistance and human health impacts (Table S1 #22, Baquero *et al.* 2008). Increasing use of plastic mulch films in many regions of the world as an agricultural practice to enhance crop yield, quality and water-use efficiency, amongst other benefits, also increases concentrations of micro(nano) plastics in agricultural runoff which additionally transport adsorbed micropollutants, such as pesticides and Potentially Toxic Elements (PTEs), into surface waters and groundwaters (Steinmetz *et al.* 2016). For example, runoff from tomato plots covered with polyethylene film contained 3 times the sediment concentration and 19, 6, and 9 times the total load of the pesticides chlorothalonil and alpha- and beta-endosulphan, respectively, compared to a vegetative-mulched control (Rice *et al.* 2001).

Meeting the water quantity demands of food production in agriculture and aquaculture is frequently associated with deteriorating water quality, particularly salinization. Over-

pumping of groundwater for crop irrigation and mismanagement of irrigation water often has undesirable impacts on potable water supplies and crop yield if water and soil salinization occurs, and on freshwater ecosystems due to drying up of rivers (Table S1 #23; Qureshi *et al.* 2010, Jayasekera *et al.* 2011, Currell *et al.* 2012, Singh 2016, 2018, Libutti *et al.* 2018). However, in some situations the sources of contaminants in groundwater are geological, e.g. arsenic and fluoride in aquifers of the Indo-Gangetic Basin, which can pose a greater water quality threat than over-pumping to groundwater use (MacDonald *et al.* 2016). Use of saline water in aquaculture can have similar impacts; rapid expansion of shrimp farming using saline water in Bangladesh led to an increase in average soil salinity by 6–15 times from 1984 to 2014 (Table S1 #24; Islam and Tabeta 2019). In the same study, yields of other crops and livestock were found to have decreased significantly due to salinity intrusion caused by shrimp farming.

Food–water quality interactions also occur through the greywater component of water “footprinting” (defined in this use as the amount of water needed to dilute pollution; Liu *et al.* 2019) and virtual water trade. The few studies that have explored this topic suggest that food trade may contribute to reducing the global greywater footprint (i.e. reducing total water pollution worldwide) because major food-exporting countries had lower pollutant loss intensity than food importers did (Liu *et al.* 2019).

### 2.2.2 Water quality impacts on food

The use of water of inappropriate quality in crop agriculture is the principal way in which water quality impacts food quality and security, since irrigation with contaminated water reduces crop yields and poses a risk to human health. However, there are also opportunities for wastewater reuse in crop production (when done properly) to enhance yields and reduce pollution of aquatic ecosystems, particularly in areas facing an acute water crisis. Recovery of phosphorus from wastewater can have a strong positive impact on water quality and (reduced) nutrient loads, and can substitute for manufactured mineral fertilizers in crop production (Table S1 #14; Schoumans *et al.* 2015). Due to the sheer volumes involved, wastewater utilization is crucial for meeting the irrigation and fertilizer requirements of food crops since it contains many nutrients, but the practice also raises environmental and public health concerns (Table S1 #18; Hanjra *et al.* 2012). The reduction of the water footprint of crop production is a clear benefit, but there are potential risks to health and environment, that require adequate policies.

In addition to PTEs such as chromium, cadmium, copper, arsenic and zinc, effluents from wastewater treatment plants contain micropollutants, including *o*-phenylphenol, chlor-dane, polychlorinated biphenyls, atrazine and dioxins, which are endocrine disruptors that can be transferred to soil and subsequently to aquatic environments via wastewater irrigation. Both treated and untreated wastewater contain concentrations of microplastics in ranges of 0–125 000 and 1000–627 000 items  $m^{-3}$  that could result in the estimated application of  $2 \times 10^6$ – $10^9$   $ha^{-1}$  plastic items per cropping season to wastewater-irrigated cabbage and maize crops (Bläsing and Amelung 2018). Although uptake of microplastics into the

roots and translocation to shoots of edible plants has been demonstrated, the risk to human health of ingestion of plastics from this exposure pathway is not yet known (Qi *et al.* 2020). Wastewater is also an important source of antibiotic-resistant bacteria (ARBs) and antibiotic-resistant genes (ARGs), which have become a serious public health concern worldwide (Berglund 2015). A high diversity of ARGs is reported in municipal wastewater-treated effluent that can serve as a potential hotspot for horizontal gene transfer and selection of ARBs (e.g. Rizzo *et al.* 2013, Agga *et al.* 2015). Reuse of wastewater in agricultural irrigation can increase soil concentrations of antibiotics and ARGs. For example, irrigation with untreated wastewater has resulted in soil accumulation of pharmaceuticals and sulphonamide resistance genes in the Mezquital Valley, central Mexico (Table S1 #18; Dalkmann *et al.* 2012). Contamination of food plants with pathogens can occur through surface contact with contaminated irrigation water, livestock and wildlife faeces, or soil during harvest, posing a health risk if the plant is not properly washed (Allard *et al.* 2019). Although uptake of pathogens from irrigation water into plant internal tissues has been demonstrated in greenhouse studies (Solomon *et al.* 2002), uptake of ARGs and faecal pathogens was not evident in plants grown in soils in central Mexico irrigated with untreated wastewater (Table S1 #18; Broszat and Grohmann 2018). The risk to human health from pharmaceutical and personal care products (PPCPs) consumed in the edible plant tissues from crops that were irrigated with wastewater has been suggested to be minimal, although the risk from mixtures of PPCPs requires further assessment (Prosser and Sibley 2015).

A further, more indirect, impact of water quality on crop production may occur when environmental flows set to improve water quality result in lower yields through reduced irrigation water allocations. This is exemplified in the Murray–Darling Basin, Australia, which provides 40% of Australia’s agricultural production by value and almost all of Australia’s rice production. In this case, proposed reductions in the average annual water use to allow more environmental flows were projected to cause annual agricultural production to fall by 13–17% (Table S1 #25; Leblanc *et al.* 2012).

## 2.3 Water quality and water quantity

Although we have so far highlighted water quality interactions with the energy and food dimensions of the WEF nexus, we discuss below some examples of the interaction between water quality and water quantity to demonstrate that they are inextricably coupled (Nilsson and Renöfält 2008).

### 2.3.1 Water quantity impacts on water quality

Dams constructed on river systems for the purpose of water abstraction have similar impacts on downstream water quality and river health to those of hydropower dams, already discussed in Section 2.1.1. Urban water management is another example of how management for water quantity impacts water quality. In many parts of the world in the 20<sup>th</sup> century, urban water management initially focused on flood risk reduction within cities through combined or separately sewered piped

systems, which managed flood risk by transporting stormwater runoff rapidly downstream, but resulted in water quality deterioration through combined sewer overflows or washoff of pollutants from urban surfaces. In the early 21<sup>st</sup> century, non-point-source stormwater runoff was identified as the leading source of water pollution in the USA (Lee *et al.* 2007). The more recent adoption of distributed source-control approaches to urban flood risk reduction in many parts of the world under various names (including best management practices – BMPs, low-impact development – LID, water-sensitive urban design – WSUD, sustainable urban drainage systems – SUDS, and blue-green infrastructure – BGI) has provided co-benefits in improving water quality as well as water savings (Barbosa *et al.* 2012, Ossa-Moreno *et al.* 2017, Alves *et al.* 2019).

### 2.3.2 Water quality impacts on water quantity

The quality of water also defines the quantity of water available for a particular use, including potable water supply, toilet flushing, car washing, fire extinguishing and managed aquifer recharge. For example, elevated nitrate concentrations in Vermilion River in Illinois, USA, limit the usability of river water for drinking water supply for the city of Pontiac, requiring the use of an off-stream reservoir blending system (Hecht *et al.* 2014). The growing threat of cyanobacteria dominance in rivers and reservoirs can also limit the use of water that would otherwise be available (He *et al.* 2016). Ever more stringent water quality regulations in many countries are also impacting water quantity, both in constraining the availability of water of sufficient quality and in increasing the demand for water to dilute contaminated flows and/or provide environmental flows (Pitcock and Lankford 2010). Thus, increasingly, water resource management options are being investigated that resolve both water pollution and water scarcity issues. For example, managed aquifer recharge with treated wastewater and urban river water has been demonstrated as a feasible way to address growing water demands and the lack of treatment of wastewater in cities such as Addis Ababa, Ethiopia (Table S1 #17; Abiye *et al.* 2009).

## 2.4 Water quality and tripartite water–energy–food interactions

Water quality can be embedded in complex tripartite interactions involving all three dimensions of the WEF nexus, as demonstrated at a range of spatial scales in the case studies presented below.

Lightly polluted water (e.g. from showers, baths and hand-basins, also referred to as “greywater”) can offer another unconventional option for non-potable water reuse at the household/community scale (Table S1 #4; Boyjoo *et al.* 2013) and is suitable for on-site treatment, reducing demands on water resources and energy requirements of wastewater treatment systems. It is important to develop low-energy and low-maintenance greywater treatment systems that provide critical amenities and micro-climate benefits to cities facing water crises (Wong and Brown 2009, Connor *et al.* 2020). Biofiltration systems, such as green walls, which require only

a small land area, potentially represent a low-cost, low-maintenance on-site greywater treatment approach for use in dense urban areas (Pradhan *et al.* 2019). A number of studies have demonstrated the effectiveness of green walls for greywater treatment (Table S1 #4, e.g. Masi *et al.* 2016), with the choice of plants (Table S1 #4; Fowdar *et al.* 2017), growing media and maintenance shown to be important considerations for optimal performance. Despite the reported contamination of greywater, health risks from bacterial pathogens in greywater are negligible where treatment recommendations are followed (Table S1 #4; Benami *et al.* 2016). Furthermore, studies in Australia and Israel investigating whether greywater use increases the risk of gastrointestinal illness identified no significant differences in risk between greywater-exposed and control groups (Table S1 #4; Busgang *et al.* 2015).

At the larger drainage basin and regional/national scales, activities targeted to boost one or more dimensions of the WEF nexus and improve livelihoods can have negative consequences for the other dimensions, including water quality deterioration. For example, in the semi-arid area of Pernambuco, Brazil, tilapia fish farming has been encouraged in the Itacuruba reservoir dammed for hydropower production, to meet the growing demand for fish protein in Brazil and improve the economic situation of local people affected by the dam construction (Table S1 #24; Marques *et al.* 2018). However, phosphorus-containing effluent from intensive tilapia cage fish farms in the reservoir poses a risk to the already scarce water resources through eutrophication of the dam waters. In Egypt, the country’s water availability has been increased by 20% by reusing agricultural drainage water, but only by increased energy demand for large pumping stations and small diesel pumps to return water from drainage ditches to irrigation canals. Moreover, water availability has been achieved at the expense of water quality deterioration in the country’s irrigation network due to the increased concentration of salinity and pollutants in drainage water (Table S1 #29; Barnes 2014).

Water quality can also be the vector of conflicting interactions between the individual dimensions of the WEF nexus in drainage basins within countries, and in transboundary basins. For example, reservoirs constructed in the Upper Mahaweli Catchment, Sri Lanka, generate ~27% of the country’s electricity through hydropower and provide irrigation water for 3000 km<sup>2</sup> of agricultural land (Table S1 #21; Diyabalanage *et al.* 2017). However, high soil erosion rates in the catchment (up to 700 t km<sup>-2</sup> y<sup>-1</sup>, 100 times greater than background soil production rates) attributed to intensive cultivation of crops on steep land have caused rapid sedimentation within the reservoirs and reduced water storage capacity to 56% over 17 years after impoundment in one reservoir and to 72% over 3 years in another (Hewawasam 2010). At the transboundary scale, it is estimated that the construction of the 11 proposed dams on the main stem of the Mekong River, primarily for hydropower energy production but also for increased irrigation and flood control, would result in a 75% reduction in the nutrient loading that supports the productivity of floodplain agriculture and fisheries downstream (Table S1 #31; ICM 2010). A 21–42% reduction in fisheries production is projected, which could cause nutritional deficiencies in

an additional 2–8 million people in the Lower Mekong Delta by 2030 (Golden *et al.* 2019).

### 2.5 Scale is a key consideration in water quality interactions in the WEF nexus

As has become apparent from the examples discussed above and summarized in Table S1, water quality interactions within the WEF nexus play out across a range of spatial scales. Not only do water quality–WEF nexus interactions occur from the very local (individual households and fields) level to international transboundary drainage basins, but complications occur because the impacts of these interactions may cross scales. Activities at the household/farm scale can affect WEF–water quality interactions at larger scales. For example, farmer decisions to replace food crops with biofuel crops are predicted to improve water quality locally, but displace intensive food crop production and associated water quality deterioration to other locations (Table S1 #2; Zhong *et al.* 2018). Conversely, national WEF-related policies can cause localized water quality impacts, as exemplified by national demand for coal in the USA resulting in significant surface and groundwater quality impairment in Appalachian Kentucky (Scott *et al.* 2011). Furthermore, there can be transboundary physical effects propagated from upstream to downstream, e.g. when management of hydropower dams impacts downstream water quality and river health, or virtual water embedded in commodities consumed in one country impact on water availability and quality in other countries (O’Bannon *et al.* 2014, Liu *et al.* 2019). The multi-scale and cross-scale nature of water quality–WEF interactions suggests that different data and analysis approaches are needed for different scales.

## 3 Perspective and outlook to better integrate water quality research into WEF issues

### 3.1 Including water quality in the WEF nexus helps to achieve SDG targets

Applying a water quality lens to the WEF nexus can help to identify appropriate solutions required to achieve the SDG targets. Environmental problems associated with poor water quality generally lead to other social and economic issues (Ghodsvali *et al.* 2019), driving complex feedbacks between social cohesion, land and water resource management and environmental conditions (Thanh *et al.* 2020). The myriad of water quality issues, and diversity of pollutants, leads to highly site-specific manifestations of these feedbacks, making them difficult to generalize. Here, two of the most prominent water quality issues to the WEF nexus are discussed: eutrophication and sediments. We focus on these for the sake of brevity, noting that similar reasoning can be applied to *other important water issues such as salinization, micropollutants and hazardous substances, plastics, pathogens and antimicrobial resistance, and aquatic ecosystem health* more broadly.

Eutrophication is a particularly instructive issue to analyse in this context as it spans several WEF nexus axes, is relevant across multiple SDGs, and in many cases is multi-scale and cross-boundary (Biermann *et al.* 2016, Le Moal *et al.* 2019).

Existing annual fluxes of nitrogen and phosphorus already exceed the “planetary boundary” values estimated to define “a safe operating space for humanity” (Steffen *et al.* 2015). A primary driver has been the food production system based on crop and livestock agriculture that releases organic and inorganic nutrients into aquatic and terrestrial ecosystems. Answering the call to end world hunger (SDG 2) through increasing agricultural food productivity will amplify eutrophication pressures if mitigation approaches are not adopted. Within cities, urban stormwater drainage practices and inadequate sanitation and wastewater treatment also significantly contribute to eutrophication, most notably in low- and middle-income countries. On the other side of the WEF nexus, controlling and reducing these nutrient releases into the environment consume energy. Construction, maintenance and operation of conventional centralized wastewater treatment systems contribute to achieving SDG Target 6.3 (improved water quality), but lead to increasing energy demand. The increasing adoption of blue–green infrastructure, such as reducing wastewater at source, designing facilities to generate their own energy, and decentralized treatment technologies, such as constructed wetlands (Alcamo 2019), is helping to alleviate this increased energy demand.

Another water quality issue recognized at a global level, and as a defining feature of the Anthropocene, is altered river sediment regimes (Syvitski and Kettner 2011). Human activities have resulted in an estimated 160% increase in land–ocean sediment flux, whilst reservoirs trap 66% of the sediment flux within river systems (Walling 2008). Accelerated soil erosion has been linked to human activities, primarily agriculture, although other causes can be locally important (e.g. deforestation or construction). The loss of nutrient-rich topsoil through erosion reduces agricultural productivity, thereby increasing demands for resources to sustain food production (FAO 1996). Dams, many of which are used for hydropower production or water supply for drinking or irrigation, also upset the river sediment balance. Sediments are deposited in reservoirs due to the long residence time and low velocities encountered behind dams, slowly diminishing the capacity of the reservoir and reducing water security. While sediment management in reservoir systems is possible (Annandale *et al.* 2003), it can be difficult in practice and requires energy (Coker *et al.* 2009). In addition, flows from reservoirs may become sediment-starved (Kondolf 1997), leading to increased channel erosion or beach erosion and a loss of productive agricultural land or fisheries downstream of dams (Owusu *et al.* 2017). Unfortunately, downstream effects of dams (as also discussed above in Sections 2.1.1 and 2.4) are not always fully considered during the evaluation of dam proposals. Accordingly, river sediment regimes should be considered in devising appropriate solutions to several SDGs, such as zero hunger (SDG 2), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), combating climate change and its impacts (SDG 13) and life below water (SDG 14).

Although our recommendation is that water quality should become intrinsic to all WEF studies, we recognize that this is seriously hindered by the limited availability of suitable water quality data in many situations (discussed in Section 2.3.2).

This is especially a problem at smaller scales where management efforts are often targeted, since national, regional or global estimates from statistical analyses, remote sensing or coarse-scale hydrological models must be relied upon for setting policy at larger scales. Therefore, for the scientific community to make tangible and rapid progress towards achieving the SDGs, we propose that efforts to collect water quality data and analyse water quality interactions with WEF should initially target nexus “hotspots” where WEF-related stresses are most severe and are anticipated to grow most rapidly. Such hotspots have been identified as (1) urban areas (e.g. Grimm *et al.* 2008); (2) areas of intensive groundwater use for agricultural food and energy production (e.g. the North China Plain – Zheng *et al.* 2010); (3) semi-arid and arid areas where climate change and the use of scarce water resources threaten water quality (e.g. the Mediterranean region, where nexus projects are already planned – Global Water Partnership – Mediterranean 2019; Egypt – Abdel-Dayem 2011; Australia – Davis *et al.* 2015; and Texas, USA – Daher *et al.* 2019, Mohtar and Daher 2019); and (4) other areas particularly vulnerable to climate change, such as drainage basins heavily dependent on meltwater from snow and glaciers (Huss *et al.* 2017). Explicit inclusion of water quality in the WEF nexus is also essential for addressing transboundary issues, for which UNECE has proposed a water–food–energy–ecosystems nexus methodology (de Strasser *et al.* 2016, UNECE 2018).

### 3.2 The need for coordinated and open water quality datasets

In order to better integrate water quality research within WEF issues, there is a clear need for water quality data suited to addressing nexus challenges (Scanlon *et al.* 2017, Cudennec *et al.* 2020). Relevant water quality monitoring is required to reflect changing environmental, climate and anthropic conditions, including emerging contaminants. In water quality–WEF interactions related to human and ecosystem health, this monitoring must be rapid and reliable, for example to ensure the safety of food crops irrigated with recycled wastewater. However, despite several efforts to compile water quality data at a global scale (e.g. GEMStat (<https://gemstat.org/>), the Global River Chemistry Database (GLORICH, Hartmann *et al.* 2014), and the Water Quality Database of the Global Open Data Index (<https://index.okfn.org/dataset/water/>), water quality data are sparse in many parts of the world where the pressures are the greatest. One of the aims of the newly established World Water Quality Alliance coordinated by United Nations Environment Programme (UNEP), within the framework of UN Water, is to build upon the Global Environment Monitoring System for Water (GEMS/Water) that includes water quality measurements in groundwater, rivers, lakes and reservoirs, and wetlands, to improve the availability of data that is fit for the purpose for water quality assessment (UNEP 2016). Opportunities for this may be enhanced by increasing the use of remote sensing for some parameters (e.g. chlorophyll-*a* to indicate eutrophication in lakes and large rivers; Alikas *et al.* 2015), and water quality monitoring using affordable and wireless sensors and smart phones, including by citizen scientists (e.g. Liao *et al.* 2020); although this approach

is not without challenges (Buytaert *et al.* 2014). Large-scale models can be augmented to include water quality components to harvest the information from monitored basins for estimating water quality in ungauged catchments as estimates of long-term values (e.g. Cohen *et al.* 2013) or at a finer temporal resolution using hydrodynamic models (e.g. Bartosova *et al.* 2019).

In addition to data describing ambient water quality, the quality of municipal and industrial wastewater effluents, agricultural return flows with irrigation water sources and types, drinking water sources, wet atmospheric deposition, and urban stormwater require specific attention to generate additional information critical to understanding water quality issues within the WEF nexus. New indices and analyses are also needed to fully harness the rich data provided by ever-increasing water quality monitoring (Hipsey *et al.* 2015). These include the development of holistic water quality and river/lake/groundwater health indicators supported by enhanced remote sensing capabilities, novel *in situ* water quality sensors, and the necessary hydro-informatics approaches associated with data analytics (Tauro *et al.* 2018). Many new indicators are being developed to assess progress towards multi-faceted and interlinked challenges, such as the SDG indicators, water footprinting and virtual water, or the quantification of ecosystem services. A challenge for hydrologists is to articulate conventional water quality assessments with these new WEF-related use requirements.

### 3.3 Moving beyond case studies: research needs for including water quality within WEF nexus analyses

We have used a number of examples to demonstrate how including water quality within the WEF context would have augmented and improved the analysis and its application. The case studies demonstrate that the WEF nexus cuts across scales (household/field, drainage basin, region, and impacts at a distance through trade and transportation), is highly transdisciplinary and displays dynamics that can evolve over time. There is no doubt this complexity will continue to create seemingly endless opportunities for studies into local issues and solutions, but the pressing challenge is to develop generalized conceptualization and analysis frameworks that allow us to transcend the anecdotal. Indeed, this challenge is reflected in the recent compilation of “Unsolved Problems in Hydrology” (Blöschl *et al.* 2019).

The need for more integrated WEF nexus analyses is increasingly pressing, with growth in demands for water, energy and food. Methods for identifying an optimum solution space in the nexus – that also consider water quality constraints – are necessary to understand the trade-offs and synergies that exist in the system. Prior approaches to this problem for allocation of water quantity in drainage basins to multiple users include multi-objective optimization models (Roobahani *et al.* 2014), analytical methods such as bankruptcy rules (Mianabadi *et al.* 2014) and game theory (Madani 2010). The goals are to maximize the net benefit or production of water allocated to agriculture (food), domestic and industrial users (water supply) and hydropower (energy), whilst minimizing water shortage, sewage drainage and the

amounts of polluted water (Liu *et al.* 2012). Game theory provides a framework for the study of the strategic behaviours of individual decision makers with which to develop more broadly acceptable solutions (Madani 2010), and has been integrated into a general systems analysis for water resources exploring solutions with both cooperative and non-cooperative actors (Wei *et al.* 2010, Madani and Hooshyar 2014, Roozbahani *et al.* 2014). Further research is required to develop these methods for diverse application contexts and to extend their ability to account for the changing drivers of water, energy and food, such as population and economic growth, urbanization, improvements in living standards, and changes in diets and consumption patterns (Yillia 2016).

A further practical challenge remains in identifying suitable metrics for summarizing the water quality attributes that drive change; for example, how we quantify aquatic system “health.” Risk assessment methods represent one approach to quantify in a tangible way the impacts of water quality within the WEF nexus, translating diverse water quality data to human health or ecological risks. These methods relate the quantity of the water quality substance of interest, its characteristics, and its use to a quantifiable dimensionless risk that can be evaluated alongside economic indicators for impact assessment and comparison of alternatives across substances. For example, the US EPA recommends four steps to assess health risks (US EPA 2014): (1) exposure assessment that quantifies pathways, duration, frequency and other factors of exposure; (2) hazard identification that specifies the type of impact that can be associated with the substance (e.g. cancer, birth defects); (3) dose–response assessment that defines a relationship between the exposure dose and the probability of the hazard; and (4) risk characterization that quantifies the magnitude and uncertainty of risk. These general steps are also applicable to assessing ecological risks. The risk-based assessments can evaluate impacts of different water quality substances and express the impacts in a comparable way, although significant information about the substances needs to be available for such quantifications.

The WEF nexus is not static, and needs to consider the changing nature of global change drivers, which affect demands for water, energy and food, individually as well as their interactions. The effects of climate change in particular increase the relevance of water quality in shaping key WEF nexus issues. For example, the decade-long drought in California in 2007–2016 caused an increasing reliance on groundwater resources for irrigation. The intense pumping of groundwater in the Central Valley to sustain crop yields resulted in seawater intrusion into aquifers near the coastal zone, thus reducing the quality and availability of potable water resources (Goebel *et al.* 2017). Climate change will also contribute to increased cyanobacterial dominance in polluted waterways (Carey *et al.* 2012), further challenging water supply systems and river health, with implications for water quantity, treatment costs and reuse. Further, increasing water temperatures due to climate change are projected to impact freshwater fish populations, though the impacts can be spatially variable due to the nonlinear relationships between fish survival and water temperature and their interaction with water management activities, such as reservoir operation (Zhang *et al.* 2019). Whilst climate change and other global drivers for food and energy tend to intensify water quality-

related problems, there is also evidence that this can drive innovation, resulting in increased overall resilience of the nexus to stressors (e.g. Low *et al.* 2015). Identifying opportunities to integrate WEF analyses with research on new and emerging water quality management technologies can assist decision makers to undertake cost–benefit calculations and identify economically viable solutions.

The non-stationarity in global, regional and local drivers of water, energy and food sectors, plus the myriad of complex feedbacks linking communities with their environment, requires continued advancement in integrated earth–human system modelling frameworks (e.g. Elshafei *et al.* 2014, Di Baldassarre *et al.* 2019). The need for WEF nexus analysis of multi-disciplinary, multi-scale and multi-model frameworks integrating physical, chemical, ecological and socio-economic processes and feedbacks has already been identified (Liu *et al.* 2017), with examples increasingly emerging (Howells *et al.* 2013, van Emmerik *et al.* 2014, Zhang *et al.* 2019, 2020). Great opportunities exist to expand these earth–human system modelling frameworks to more coherently include water quality dynamics and feedbacks. In parallel, there have been advances in local- and regional- to global-scale water quality modelling (Hofstra *et al.* 2019, Hipsey *et al.* 2020). Efforts to improve integration of these modelling approaches to account for energy and food drivers will allow for more comprehensive tools able to operate over a range of scales relevant to decision-making within the nexus.

The complex external drivers and internal processes within these models also create challenges for addressing uncertainty, such as in model inputs, structures and validating datasets, which will further grow given the myriad of future potential scenarios and plausible trajectories (Maier *et al.* 2016). Convincing relevant stakeholders of the utility of WEF analyses and model predictions requires transparent communication of the risks and uncertainties in the recommended solutions that aim to balance competing interests. New practical approaches dealing with the treatment of uncertainty relating to water quality within the various axes of the WEF nexus will help facilitate the uptake of these analyses by decision makers.

## 4 Conclusions

Through discussion of a number of examples, we have highlighted the significant impact of water quality on the energy, food and water dimensions of the WEF nexus and vice versa. We advocate that including water quality explicitly will increase the ability of the WEF framework to generate integrated policies and management approaches, not only for water quality improvement, but most importantly for balancing and meeting demands for water, energy, food and ecosystem needs. Including water quality adds themes of health, well-being and environment that are not often explicitly covered within the nexus, and helps to address some of the power and social inequalities in the WEF nexus conceptualization (Wiegleb and Bruns 2018).

Ultimately, societal needs have driven the development of hydrological science (Sivapalan and Blöschl 2017) and, given the importance of water quality in the Sustainable Development Goals (SDG 6 in particular), addressing this need may be an overlooked opportunity for the hydrological

sciences community. For example, meeting the SDG Targets 6.3 (improve water quality) and 6.5 (implement integrated water resource management) requires the understanding of pollution sources and mobilization through hydrological pathways into rivers, lakes and aquifers that the hydrological sciences can provide. Given that only ~30% of the journal papers cited in this paper are in the “Water Resources” journal subject category of Web of Science, we conclude that water quality–WEF studies in water-related journals are under-represented and suggest that hydrological scientists could do more to ensure that their research contributes to addressing complex nexus challenges. So that water quality does not remain an overlooked component of the WEF nexus, we encourage hydrological scientists to label and promote relevant water quality research as addressing WEF nexus challenges during both the research design and publication stages.

We have demonstrated that water quality within the WEF nexus cuts across scales (households and fields, cities, drainage basins, regions, transboundary and large distances through trade and transportation). This scale-independence demonstrates the generic appeal of the WEF nexus approach and its flexibility when put into practice for generating innovative and impactful measures to improve water quality for addressing grand challenges in different settings. Nevertheless, the generic approach to considering the role of water quality in the WEF nexus taken here should be implemented within specific country or drainage basin contexts so that resource constraints and other local conditions are considered, such as cultural practices and ecosystem services relating to water.

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