LETTER • OPEN ACCESS

Trade-offs between water needs for food, utilities, and the environment—a nexus quantification at different scales

View the article online for updates and enhancements.

ENVIRONMENTAL RESEARCH
LETTERS

LETTER

Trade-offs between water needs for food, utilities, and the environment—a nexus quantification at different scales

Lotte de Vos[1,2] , Hester Biemans[1] , Jonathan C Doelman[2,3] , Elke Stehfest[2] and Detlef P van Vuuren[2,3]

[1] Wageningen Environmental Research, Wageningen University & Research, Wageningen, The Netherlands
[2] PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands
[3] Copernicus Institute for Sustainable Development, Utrecht University, Utrecht, The Netherlands

E-mail: Lotte.devos@pbl.nl

Abstract

With a growing population and a changing climate, competition for water resources in the water-energy-food (WEF) nexus is expected to increase. In this study, competing water demands between food production, freshwater ecosystems and utilities (energy, industries and households) are quantified. The potential trade-offs and related impacts are elaborated for different SSP scenarios with the integrated assessment model IMAGE, which includes the global vegetation and hydrology model Lund-Potsdam-Jena managed Land (LPJmL). Results for the 2045–2054 period are evaluated at the global scale and for a selection of 14 hotspot basins and coastal zones. On the global scale, we estimate that an additional 1.7 billion people could potentially face severe water shortage for electricity, industries and households if food production and environmental flows would be prioritized. Zooming in on the hotspots, this translates to up to 70% of the local population. Results furthermore show that up to 33% of river length in the hotspots risks not meeting environmental targets when prioritizing other water demands in the nexus. For local food production, up to 41% might be lost due to competing water demands. The potential trade-offs quantified in this study highlight the competition for resources in the WEF nexus, for which impacts are most notably felt at local scales. This emphasizes the need to simultaneously consider different dimensions of the nexus when developing scenarios that aim to achieve multiple sustainability targets.

1. Introduction

Global targets for food production, energy supply, sanitation and biodiversity all rely on the availability of freshwater resources. These resources, however, suffer from increasing pressures caused by human activities, such as land cover change, irrigation, urbanization and industrialization (Gleick and Palaniappan 2010, Vörösmarty *et al* 2010). The biodiversity in rivers, lakes and wetlands is rapidly declining, with an average decrease of species population size of 84% since 1970 (WWF 2020). At the same time, local issues related to water scarcity may increase as an effect of climate change (Mekonnen and Hoekstra 2016). Over the past few decades, increasing awareness of the limits to freshwater availability has led to global water resources assessments

that account for water availability and use (Bierkens 2015). To support these assessments, several studies have projected how future water demands in the water-energy-food (WEF) nexus might develop (Grafton *et al* 2017, Bijl *et al* 2018). Eventually, an important goal is to identify solution pathways that remain within 'planetary boundaries', while still meeting societal demands (Rockström *et al* 2009, Gerten *et al* 2013, Jägermeyr *et al* 2017).

Scenario studies using Integrated Assessment Models (IAMs) can be used to explore how the water, food and energy systems may develop in the future, the relevant synergies and trade-offs between these systems and possible response strategies to shortages. Several studies have already quantified the impact of human water withdrawals on parts of the natural system. Studies by Hanasaki *et al* (2013) and

Wada *et al* (2016) focussed on the impact of sectoral water demands on future water scarcity, concluding that socio-economic changes will have larger impact on water availability than climate change. Other studies have investigated the competition between agricultural and non-agricultural use on a global scale, which is expected to increase especially in areas where there already is scarcity (Bijl *et al* 2018, Rosa *et al* 2018b). At the same time, more studies are including trade-offs between societal demands and freshwater ecosystems. It has been recognized that disruption of flow due to human water withdrawals is an important cause of the degradation of aquatic ecosystems and its biodiversity (Döll *et al* 2009, Poff and Zimmerman 2010, Darwall *et al* 2018). Several global studies have accounted for this by reserving a percentage of the natural flow for the environment. For example, Jägermeyr *et al* (2017) demonstrate that 40% of current irrigation withdrawals occurs at the expense of these environmental flows. The study however indicates that an improvement of water management could help meeting future demands without compromising the environment. Other studies have shown that a global redistribution of crops could enable sustainable agriculture in the future (Davis *et al* 2017, Pastor *et al* 2019). However, to design solution pathways there is a need for an integrative approach that considers synergies and trade-offs in the global WEF nexus (Scanlon *et al* 2017, Albrecht *et al* 2018, Johnson *et al* 2019, Van Vuuren *et al* 2019).

Even though interdependencies in the WEF nexus are increasingly recognized (D'Odorico *et al* 2018), few scenario studies consider the consequences of the trade-offs between water for food production, industrial and residential use, and environmental flows. In contrast, they mostly look at single impact relationships. In this study we go beyond the current state-of-the-art by showing where conflicts between all these uses occur and we quantify the consequences for the different sectors. We translate competing water demands in the WEF nexus to impact indicators relating to food production, water consumption for utilities in the form of electricity, industries and households (EIHs) and environmental flows. By treating each element in the nexus as equally important, the study provides a new framework to gain insight that is crucial for the development of solution strategies. The study uses the IAM IMAGE, which combines regional policy modelling with a relatively detailed description of biophysical dynamics. It is the only IAM that includes grid-scale hydrology and crop production. The model includes key connections between industrial demands and water use, as well as the relation between water availability and land use. Through this, the framework is suitable for evaluation of water related nexus connections at different spatial scales. The impacts of competing water demands are evaluated in three parts: (a) the global implications of environmental flow regulation on a baseline scenario, (b) an analysis of nexus competition in a selection of hotspot basins and coastal zones and (c) a scenario sensitivity analyses using different scenarios for socio-economic development and climate pathways.

2. Methods

2.1. IMAGE model framework

The IAM IMAGE (Stehfest *et al* 2014) consists of a suite of coupled modules that describe different elements of the global environment. It combines regional scale agro-economic, energy and climate policy modelling with grid-scale land-use, dynamic vegetation and hydrological modelling. Different scenarios of socioeconomic development and climate mitigation can be used to simulate potential effects of humans on the natural system. The socioeconomic components are modelled on a regional scale (26 regions), while the environmental components are modelled on a geographic grid (5 and 30 arc-minute grid cells). Interaction between the models takes place through upscaling and downscaling algorithms. In the description, we focus on the water-related aspects (see SI figure 1 available online at stacks.iop.org/ERL/16/115003/mmedia for a schematic overview of the relevant model components). The TIMER module simulates energy supply and demand. Future climate is projected by the MAGICC module (Meinshausen *et al* 2011), a simple climate model where global mean temperature is calculated on the basis of the emission trajectory. Daily and spatially explicit precipitation and temperature patterns are acquired through patterns scaling with the bias corrected output of the IPSL general circulation model from the ISI-MIP project (Hempel *et al* 2013). To simulate interannual variation of temperature and precipitation in the future, the historical variability from the CRU 2.0 monthly climatology (New *et al* 2000) is imposed on projected mean values (Müller *et al* 2016). Agricultural demand, production and trade are simulated in the global economic model MAGNET (Woltjer and Kuiper 2014). Agricultural land use is then allocated to the grid level based on suitability in the Land Management module of IMAGE. It is informed by potential crop yields calculated in the global vegetation and hydrology model LPJmL (section 2.2). A detailed description of all parameters exchanged between the various IMAGE sub-models is available (Stehfest *et al* 2014).

2.1.1. LPJmL

As an integral part of IMAGE, the global hydrology and vegetation model LPJmL (Bondeau *et al* 2007) is used to simulate water and vegetation dynamics including water availability, crop yields, grassland productivity and carbon cycles (see Müller *et al*

(2016) on IMAGE-LPJmL coupling). The model is based on the concept of multiple plant functional types (PFTs) that are categorized according to biophysical characteristics. Both natural vegetation and crop PFTs are represented. Crop yields and the relating carbon dynamics are influenced by water availability. This information is provided to IMAGE and influences the simulated land use change in terms of area requirements and location of future crop production, and allocation of irrigated areas.

The LPJmL model accounts for both 'blue' water (water from rivers, lakes, aquifers and dams) and 'green' water (precipitation used by plants directly). Precipitation or water supplied by irrigation is partitioned into soil moisture, transpiration, evaporation, interception and runoff. The model includes a river routing module that calculates river discharge, accounting for human water withdrawals and with lakes and reservoirs as additional water stores. Reservoirs with assigned functions (irrigation or other) are included from the GRanD database (Lehner *et al* 2011). For a detailed description of the water fluxes see Stehfest *et al* (2014). Hydrology and crop growth in LPJmL are calculated on 30 arc-minute grid cells and at daily resolution and exchanged with IMAGE on a yearly basis.

2.1.2. Water withdrawal and consumption demands

Agriculture accounts for approximately 70% of all water withdrawals, with irrigation as the largest contributor (FAO 2016). The remaining 30% is dominated by withdrawals for households (about 11%) and industries and electricity (together around 19%). In IMAGE, water withdrawals for irrigation and water withdrawals for EIHs are represented separately. They are fulfilled in LPJmL using freshwater resources ('blue' water), and are constrained by water availability on the grid level (including neighbouring cells and reservoirs). Non-agricultural withdrawals have priority over agricultural withdrawals but it is assumed that they use only surface water from rivers, while irrigation can also make use of the sustainable groundwater storage and of nearby reservoirs (Biemans *et al* 2011). All withdrawals consist of two components, namely the water that is consumed (made unavailable for other purposes), e.g. through evaporation and transpiration, and the water that is not consumed but flows back into the river system. The latter is available for water demands in downstream cells. As a result, a distinction can be made between water withdrawals and water consumption[4].

---

[4] Water withdrawals entails the total volume of water that is withdrawn from freshwater resources for societal use. Water consumption is the volume of water that is actually consumed (e.g. through evaporation and transpiration), i.e. the water withdrawals minus the return flows. The term water demand, used to describe the volume of water that is needed to fulfill the demands in each sector,

2.1.2.1. Irrigation water demands

Irrigated area projections are based on the FAO Agricultural Outlook (Alexandratos and Bruinsma 2012) with region specific assumptions on growth rates. The allocation at grid level is informed by proximity to existing irrigation, potential production increase and water availability (Doelman *et al* 2018). Irrigation water demands are calculated in LPJmL, which accounts for 12 crop functional types (both irrigated and rainfed). The water demands are determined per crop type and depend on soil moisture deficits and atmospheric demand for transpiration (Bondeau *et al* 2007). Total withdrawal demands are higher than crop water demand due to inefficiencies in the irrigation systems, including losses through evaporation, interception and conveyance (Jägermeyr *et al* 2015). This is included by means of assumptions on irrigation efficiency, which are system (surface, sprinkler, drip) specific and allocated per country (SI figure 14). Water that is not consumed through transpiration or evaporation is returned to runoff and available for downstream cells (Rost *et al* 2008, Jägermeyr *et al* 2015).

2.1.2.2. Water demands for energy, industries and households

Other water withdrawals in IMAGE comprise the withdrawals for EIHs. They are calculated separately in the TIMER module, each influenced by different driving forces. The water demand for electricity production is based on Macknick *et al* (2011), and transformed to water demands per unit of excess heat. Other driving forces are the industry value added and the population size. Future demands are based on historical withdrawals from AQUASTAT (FAO 2016) combined with assumptions on water use efficiency. For a detailed description of the separate modules see Bijl *et al* (2016). Corresponding to the TIMER resolution the demands are computed for 26 regions, on a yearly timestep. They are subsequently downscaled to a half degree resolution grid using the population distribution, and provided as input to LPJmL. The non-agricultural demands remain constant throughout a year.

2.1.3. Water demands for freshwater ecosystems

In this study, the water demands for freshwater ecosystems are expressed through environmental flow requirements (EFRs). They are calculated in LPJmL, and are represented by a minimum discharge requirement for each grid cell. Ideally, environmental flows are defined as the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems (IRF—International

---

applies to both the withdrawal and consumption demands, as well as the demands for freshwater ecosystems (EFRs). Unlike the other water demands, EFRs are not withdrawn from freshwater resources but remain in the river system to sustain environmental flows.

River Foundation 2007). However, this would depend on many local factors like discharge, nutrients, temperature and ecological status, which has led most global studies to neglect them entirely. Several studies have therefore used a discharge requirement as proxy value to determine EFRs (Gerten *et al* 2011, Richter *et al* 2012, Pastor *et al* 2019). We implemented the variable monthly flow (VMF) method developed by Pastor *et al* (2014). This method is based on mean monthly flows (MMFs), i.e. the 30 year mean river flows without human land use, water infrastructure and water withdrawals. The historic CRU 2.0 monthly climatology is used to determine this pristine flow (1961–1990). During the low-flow season, 60% of the MMF is reserved for ecosystems. During an intermediate flow period this is 45%, and during the high-flow season only 30% of the MMF is reserved. The MMFs are classified based on their relation to the mean annual flow (MAF): High flow months if the MMF is greater than 80% of the MAF, low flow months if the MMF is less than 40% of MAF, and intermediate is everything in between.

2.2. Quantification of trade-offs

Trade-offs in the WEF nexus are translated to impacts on (a) transgression of environmental flows, (b) communities supplied with water for EIHs and (c) food production (table 1).

Impacts on transgressions of environmental flows are quantified through the percentage of river length that meets the environmental flow requirements under the simulated future, as also suggested by Gleeson *et al* (2020). All transgressions smaller than 0.01 hm^3 d^{-1} are neglected, however all other transgressions are considered as equally important. For river length, all cells where the MAF is higher than 5 hm^3 d^{-1} are considered.

Impacts on communities supplied with water for EIH is represented by the number of people living in areas that are at severe risk of water shortage. Severe risk of water shortage for EIH is expressed as the situation when the yearly ratio between the consumption demand and the actual consumption for EIH is higher than 2, which is similar to the definition used by Mekonnen and Hoekstra (2016). In our definition, irrigation withdrawals are not included, and the focus is on actual consumption for EIH instead of water availability.

To assess the impact of water competition on food, changes in crop production on agricultural land are calculated. The results are constrained to impacts from water availability, changes in land use are not considered. Land use allocation comes from the baseline scenario (see section 2.2.1). Total production entails all rainfed and irrigated crops, including food and feed, and is calculated in tonnes of fresh matter.

Table 1. Impact indicators that quantify the trade-offs in the Water-Energy-Food nexus.

Impact indicator	Method
Percentage of river length that meets environmental flow requirements	Total river length is determined as cells where the yearly average natural flow is higher than 5 hm^3 d^{-1}. Transgressions smaller than 0.01 hm^3 d^{-1} are not considered.
Number of people at severe risk of water shortage	People living in areas where consumption demand for EIH/actual consumption for EIH >2
Food production	Change in total production on agricultural land (rainfed and irrigated), in tonnes of fresh matter

The impact indicators are used to quantify the trade-offs in three steps, namely (a) the global implications of sustaining environmental flows in a baseline SSP2 scenario, (b) competition in the WEF nexus for 14 hotspot basins and coastal zones and (c) a scenario sensitivity analysis using different SSPs, including a climate mitigation scenario aiming for the long-term target of 2 °C. All results are presented as yearly averages for the period of 2045–2054.

2.2.1. Global implications of sustaining environmental flows on the baseline SSP2 scenario

The SSP2 scenario used in this study is part of a larger scenario framework that is designed to deal with the uncertainty of climate change and its key drivers. Each SSP (Shared Socioeconomic Pathways) is based on a narrative describing a pathway of socioeconomic development, and is provided with quantitative scenario drivers (e.g. population, economic growth, land use, technology development) (O'Neill *et al* 2017, Riahi *et al* 2017, Van Vuuren *et al* 2017). Table 2 presents the SSP2 storyline assumptions that are related to the WEF nexus. The water demands for EIHs follow the storyline described in Bijl *et al* (2016).

The baseline SSP2 scenario considers water withdrawals for irrigation and for EIH. However, there is no restriction policy to protect EFRs. We created a variation of the SSP2 baseline scenario, the SSP2-EFR scenario, where EFRs need to be fulfilled before water withdrawals are allowed (table 3). By comparing these scenarios, the impacts of implementing EFR policy in the baseline SSP2 scenario are quantified for all three dimensions in the nexus.

2.2.2. Hotspots of water competition

For a selection of hotspots, we quantify the deficits per sector that could be caused by prioritizing the other sectors in the nexus. These deficits are expressed in terms of the impact indicators. They are determined

Table 2. Characteristics and assumptions of the SSP2 baseline (details see text).

	SSP2 assumptions
Description	Social, economic and technological trends do not shift markedly from historical patterns. Medium challenges to mitigation and adaptation
Climate projection	~RCP6.0
Population in 2050	9.2 billion
GDP (2005 US$ per capita 2050)	25 000
Industry value added per capita in 2050	6930 IVA$
Electricity production in 2050	Around 190 EJ yr^{-1}
Electricity technologies	Mostly coal (transitioning to combined cycle), some natural gas, hydropower and nuclear
Wet tower water efficiency	Towards 28% (withdrawal) and 25% (consumption) less water use in 2040
Municipal water efficiency	Save 0.48% per year (withdrawal) and 0.49% (consumption)
Industrial water efficiency	Save 0.55–2.48% per year (withdrawal) and 0.5% (consumption)
Irrigated area	Irrigated harvested area increases follow FAO agricultural outlook

Table 3. Scenario specification.

Scenario	Description
SSP2 baseline	Water withdrawals for irrigation and for EIH, no implementation of EFR policy. Water allocation prioritization: (1) EIH (2) irrigation
SSP2-EFR	SSP2 scenario with implementation of EFR policy: Water withdrawals for irrigation and for EIH are only allowed if EFRs are met. Water allocation prioritization: (1) EFR (2) EIH (3) irrigation

by comparing simulations in which the sectors compete, to simulations with unconstrained supply for one of the use categories (constrained by water availability but unconstrained by other sector demands). As such, potential trade-offs PT for each sector i are calculated as

$$\text{PT}_i = \text{SupplyUnc}_i \text{-} \text{SupplyComp}_i$$

in which SupplyUnc$_i$ is the unconstrained supply and SupplyComp$_i$ is the competed supply. To estimate

Table 4. Model runs used to determine the potential trade-offs for each indicator. Potential trade-offs are calculated as SupplyUnc—SupplyComp.

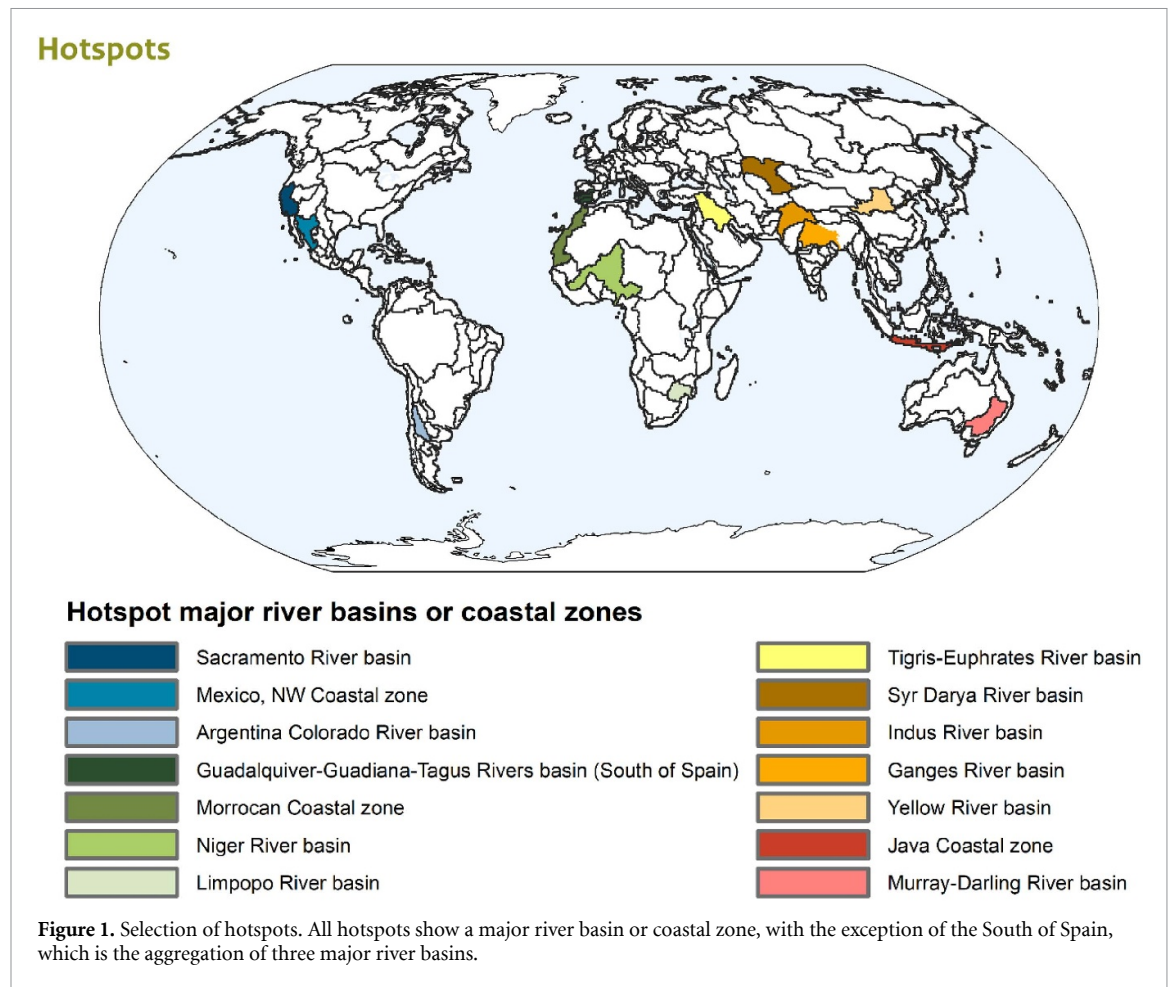| Impact indicator	SupplyUnc	SupplyComp
Percentage of river length that meets environmental flow requirements	SSP2 scenario without water supply for EIH and irrigation.	SSP2 scenario without implementation of EFR policy: Water allocation prioritization: (1) EIH (2) irrigation
Number of people at severe risk of water shortage	SSP2 scenario with only supply for EIH, no water supply for irrigation and no EFR policy.	SSP2 scenario with implementation of EFR policy: Water allocation prioritization: (1) EFR (2) EIH (3) irrigation
Food production	SSP2 scenario with only supply for irrigation, no water supply for EIH and no EFR policy.	SSP2 scenario with implementation of EFR policy: Water allocation prioritization: (1) EFR (2) EIH (3) irrigation

the unconstrained supply (SupplyUnc), stylized runs are performed in which the water demand of only one sector is fulfilled. The competed supply (SupplyComp) for food production and water consumption for EIH is derived from the SSP2 scenario with demands for all three sectors (table 4). This is the same as the SSP2-EFR scenario (section 2.2.1), where EFRs are prioritized over other water demands. The competed supply (SupplyComp) for EFRs is calculated in the baseline SSP2 scenario without EFR prioritization. Additionally, the contribution per sector has been determined. For this, additional runs are performed, where only two sectors are competing.

The results are presented for 14 hotspots. Hotspots are major basins or coastal zones that show high nexus impact in at least one of the three sectors (figure 1).

2.2.3. Part 3: scenario sensitivity analyses
In addition to the SSP2 analysis of the hotspots, a scenario sensitivity analysis is performed with the SSP1 and SSP3 baseline scenarios, and a SSP2 mitigation scenario that limits global warming to 2 °C. Together SSP1-3 encompass the range from high to low human impact on the environment. Their complete storylines are described in O'Neill *et al* (2017). The baseline of SSP3 corresponds to forcing targets similar to SSP2 (RCP6.0), the baseline of SSP1 to RCP4.5, and the SSP2 mitigation scenario to RCP2.6. For an overview of all four scenarios (SSP1,2,3 and SSP2 mitigation) the reader is referred to SI section 1 and SI table 1.

Figure 1. Selection of hotspots. All hotspots show a major river basin or coastal zone, with the exception of the South of Spain, which is the aggregation of three major river basins.

3. Results

3.1. Global results SSP2 baseline and SSP2-EFR scenario

In SSP2, global water demands are expected to increase (SI figure 2). This is predominantly driven by population growth, which leads to higher water demands for EIH. Global irrigation water demands do not increase significantly, because the limited expansion in irrigated area is offset by an increased water use efficiency of crops caused by CO_2 fertilization. For the 2045–2055 period, the results show withdrawal demands for EIH of 2033 km^3 yr^{-1}. In the SSP2 baseline scenario without EFR policy, actual withdrawals for EIH are projected to be 1954 km^3 yr^{-1} (a 78 km^3 yr^{-1} deficit). For irrigation, the baseline results show actual withdrawals of 1959 km^3 yr^{-1}, bringing total water withdrawals to 3914 km^3 yr^{-1}. Total water consumption is much lower, with 1518 km^3 yr^{-1}. Of this water consumption, 447 km^3 yr^{-1} is intended for EIH and 1071 km^3 yr^{-1} for irrigation.

The baseline results furthermore show high transgressions of EFRs in the larger rivers of Southeast Australia, the Middle Eastern region and South, East and Central Asia (SI figure 3(a)). The Indus River stands out with transgressions reaching up to 33 km^3 yr^{-1} in certain river stretches. Other rivers with severe violations of EFRs are the Ganges (average deficits up to 22 km^3 yr^{-1}), the Yellow River (13 km^3 yr^{-1}) and the Arvan Rud downstream in the Tigris-Euphrates basin (18 km^3 yr^{-1}).

In the SSP2-EFR scenario, in which EFRs are protected, withdrawals for EIH decrease with 19.3%, and irrigation withdrawals decrease by 30.3% (table 5). As a result, many locations show an improvement in terms of EFRs. For example, maximum transgressions substantially decrease for the Indus (to 6.1 km^3 yr^{-1}), the Ganges (to 3.3 km^3 yr^{-1}), the Arvan Rud (to 6.0 km^3 yr^{-1}) and the Yellow River (to 1.0 km^3 yr^{-1}). However, even in the SSP2-EFR scenario transgressions still occur (SI figure 3(b)). Globally, the percentage of river length that reaches its targets is still only 89.1%, an increase of just 1.8% compared to the SSP2 baseline scenario. These transgressions are caused by climate change, withdrawals upstream, allocation of dams and reservoirs, or high interannual variability of flows that is not considered in the 30 year MMFs.

However, the impact of the EFR policy is clearly visible on the basin scale (figure 2(a)). For some basins, the differences in percentage of river length that meets the EFR targets reaches up to 30%. Changes in food production and water consumption for EIH in SSP2-EFR show similar spatial patterns
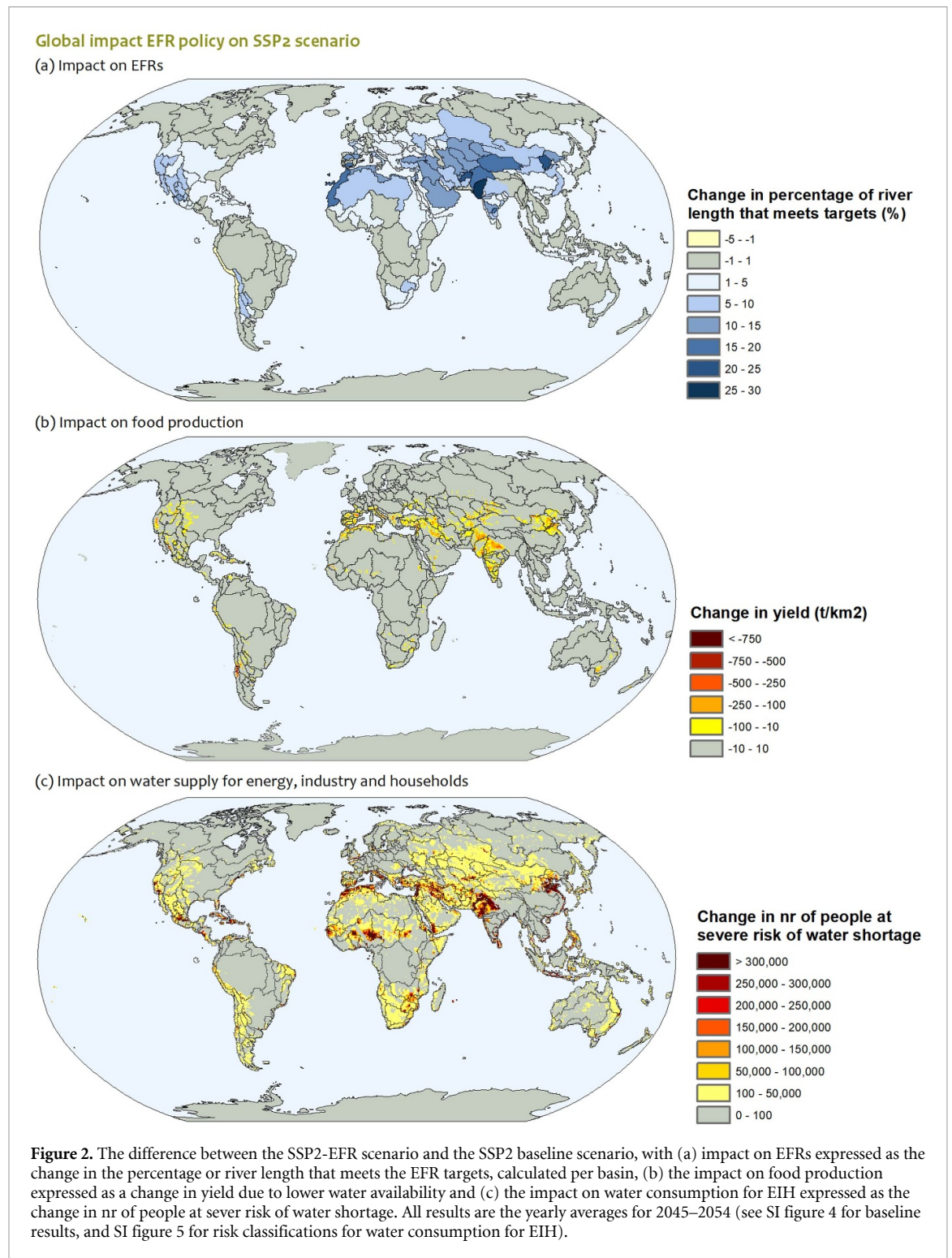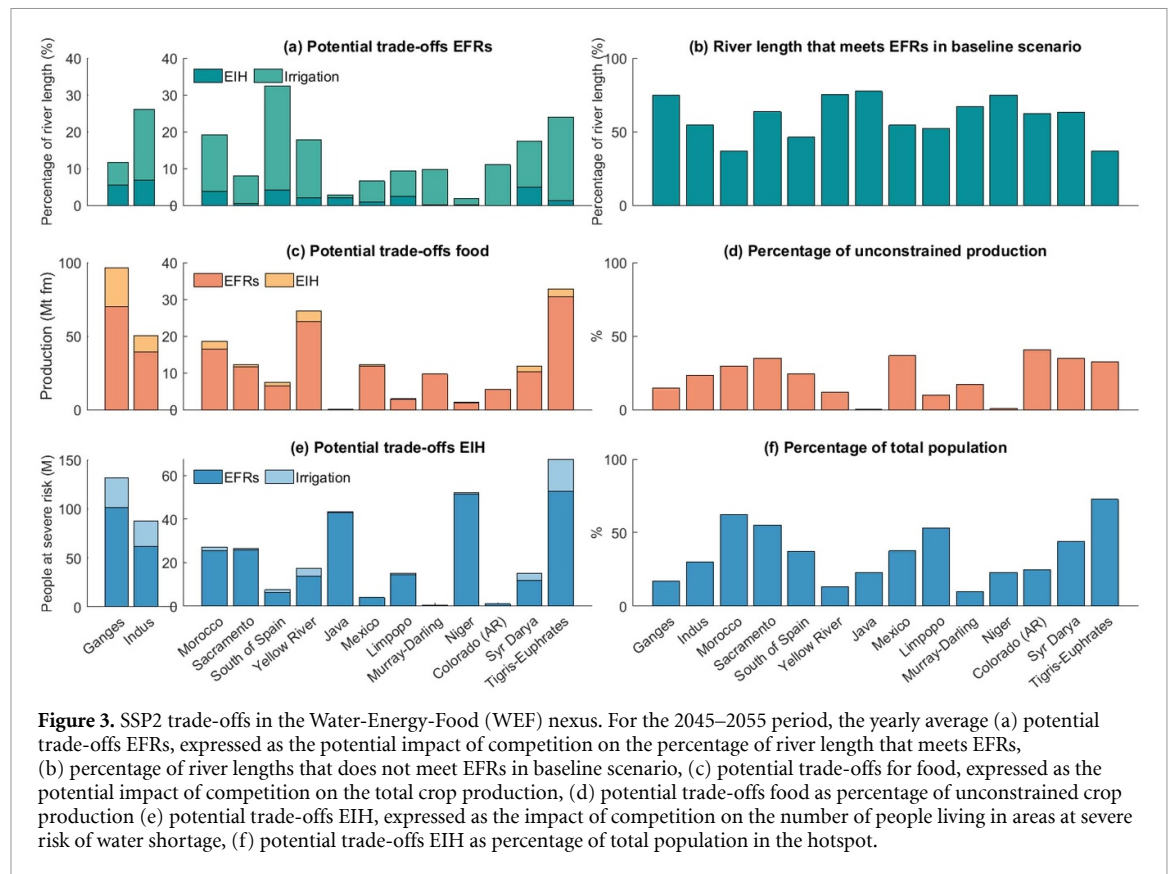
Figure 2. The difference between the SSP2-EFR scenario and the SSP2 baseline scenario, with (a) impact on EFRs expressed as the change in the percentage or river length that meets the EFR targets, calculated per basin, (b) the impact on food production expressed as a change in yield due to lower water availability and (c) the impact on water consumption for EIH expressed as the change in nr of people at sever risk of water shortage. All results are the yearly averages for 2045–2054 (see SI figure 4 for baseline results, and SI figure 5 for risk classifications for water consumption for EIH).

Table 5. Results for SSP2 baseline and the SSP2-EFR scenario. All values are yearly averages for the 2045–2055 period.

	SSP2 baseline	SSP2-EFR	% change
Water withdrawals (km^3)	3914	2943	−24.8%
EIH	*1954*	*1577*	*−19.3%*
Irrigation	*1959*	*1366*	*−30.3%*
Water consumption (km^3)	1518	1111	−26.8%
EIH	*447*	*356*	*−20.3%*
Irrigation	*1071*	*755*	*−29.5%*
Food production (Mt fm)	13, 2E + 3	12, 6E + 3	−4.9%
Nr of people at severe risk of water shortage (million)	267	1889	+605%
Percentage of river length that meets EFRs (%)	87.4	89.2	+2%

Figure 3. SSP2 trade-offs in the Water-Energy-Food (WEF) nexus. For the 2045–2055 period, the yearly average (a) potential trade-offs EFRs, expressed as the potential impact of competition on the percentage of river length that meets EFRs, (b) percentage of river lengths that does not meet EFRs in baseline scenario, (c) potential trade-offs for food, expressed as the potential impact of competition on the total crop production, (d) potential trade-offs food as percentage of unconstrained crop production (e) potential trade-offs EIH, expressed as the impact of competition on the number of people living in areas at severe risk of water shortage, (f) potential trade-offs EIH as percentage of total population in the hotspot.

of affected areas (figures 2(b) and (c)). Globally, the SSP2-EFR scenario leads to a decrease of food production of 647 Mt (−4.9%), and an increase of 1621 million people living in areas that face severe risk of water shortage for EIH (17.5% of the global population).

3.2. Potential trade-offs in hotspots

Zooming in on the hotspots (as defined in section 2.2.2) reveals large variation in impacts on the WEF nexus across locations (figure 3 and SI table 2). For the EFRs, potential trade-offs are particularly high in the South of Spain, where the percentage of river length that meets EFRs is only 46% when competition in the nexus is considered (figure 3(b)). Without competition this is 79% (SI table 2), resulting in potential trade-offs of 33% of river length for this hotspot (figure 3(a)). Other hotspots that show significant trade-offs are the Indus basin (26%, from 80% to 54%) and the Tigris-Euphrates basin (24%, from 61% to 37%) closely followed by the Moroccan coastal zone (19%, from 56% to 37%) and the Syr Darya basin (18%, from 81% to 63%). For almost all hotspots, irrigation has a higher contribution to the trade-offs for EFRs than water consumption for EIH. Java is the only region where there is almost no impact from irrigation, but where the high population density and resulting water demands for EIH are dominant (SI figures 6 and 7 for EIH demands per sector for each hotspot). In contrast, the Murray-Darling

and Colorado (AR) basins have relatively low population density and show barely any trade-offs with the water demands for EIH. Some hotspots show significant trade-offs with both sectors, e.g. the Indus and Ganges basins.

For several hotspots, crop production could be significantly affected by competition for water resources (figure 3(c)). The Ganges basin in particular shows high potential trade-offs for food (96 Mt), which is 15% of the unconstrained production (without competition). This result is followed by the Indus River basin (50 Mt), the Tigris-Euphrates Rivers basin (33 Mt) and the Yellow River basin (27 Mt). For several hotspots, the potential trade-offs are especially high compared to the unconstrained production. For example, in the Colorado (AR) basin 41% (5.5 Mt) of the unconstrained production could be affected by trade-offs. Other hotspots that show large trade-offs in relation to the unconstrained production are the coastal zone of NW Mexico (37%, 12 Mt), the Syr Darya River basin (35%, 12 Mt), the Sacramento river basin (35%, 12 Mt), and the Tigris-Euphrates river basin (33%, 33 Mt). For all hotspots, EFRs have a much larger contribution to the potential trade-offs than water consumption for EIH.

Consideration of irrigation and EFRs could significantly impact the water consumption for EIH (figure 3(e)). Potential trade-offs are highest for the Ganges basin, with 134 million people living in areas with severe risk of water shortage when consumption for EIH is competing with irrigation and EFRs,

Table 6. Global results potential trade-offs.

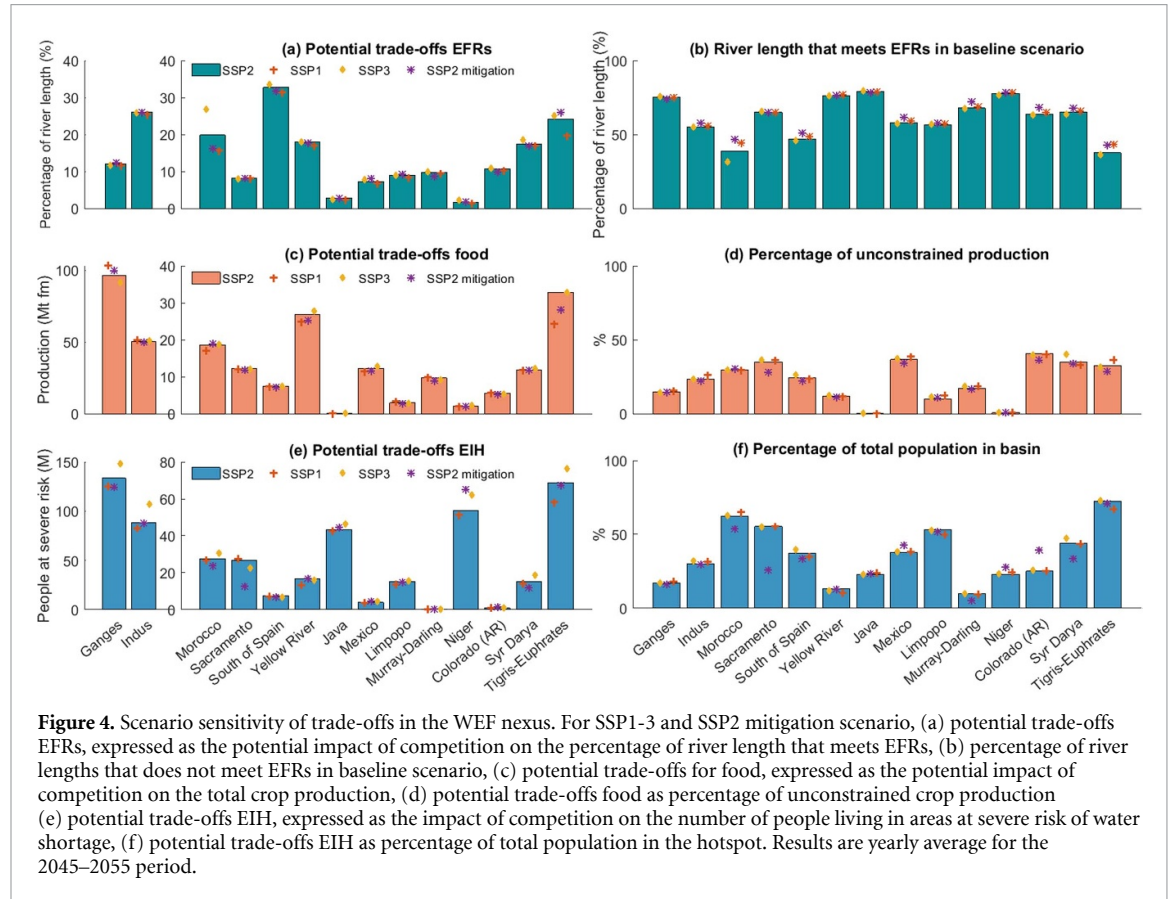|	Potential trade-offs	Unconstrained supply	Competed supply
EFR	2.7%	90.1%	87.4%
Food	762 Mt fm	13, 3E + 3 Mt fm	12, 6E + 3 Mt fm
EIH	1693 million at severe risk	196 million at severe risk	1889 million at severe risk

Figure 4. Scenario sensitivity of trade-offs in the WEF nexus. For SSP1-3 and SSP2 mitigation scenario, (a) potential trade-offs EFRs, expressed as the potential impact of competition on the percentage of river length that meets EFRs, (b) percentage of river lengths that does not meet EFRs in baseline scenario, (c) potential trade-offs for food, expressed as the potential impact of competition on the total crop production, (d) potential trade-offs food as percentage of unconstrained crop production (e) potential trade-offs EIH, expressed as the impact of competition on the number of people living in areas at severe risk of water shortage, (f) potential trade-offs EIH as percentage of total population in the hotspot. Results are yearly average for the 2045–2055 period.

which is an increase of 132 million compared to the case of unconstrained supply. Other hotspots with high trade-offs are the Indus basin (2–90 million), the Tigris-Euphrates basin (∼0–68 million), the Niger basin (1–53 million) and the Java region (∼0–44 million). In the Tigris-Euphrates, Limpopo and Sacramento basins, as well as the Moroccan coastal zone, over half of the population would be at severe risk of water shortage due to competition (73%, 53%, 56% and 62%, respectively, figure 3(f) and SI table 2). Also here, the impact from EFRs is dominant over the impact from irrigation. Table 6 presents the gobal results for the potential trade-offs per sector.

3.3. Scenario sensitivity analyses
To evaluate how sensitive the results are to the different policy assumptions in each SSP scenario, the trade-offs have been calculated for SSP1, SSP3 and a SSP2 mitigation scenario (figure 4). Variation between the scenarios is the highest for tradeoffs with EIH (figure 4(e)), which can be explained by the difference in projected population size (SI figure 8). For most hotspots, population increase is highest

in SSP3. The exceptions are the Sacramento and Murray-Darling basins and the South of Spain, due to assumptions on stricter immigration policies in SSP3. In these areas, population growth is highest in SSP1. However, this does not lead to higher water demands due to assumptions on efficiency increase (SI figure 9). This indicates that the improvements in efficiency are able to ameliorate some of the pressure on the nexus.

Scenario sensitivity appears small for the potential trade-offs of EFRs and food. Most of the variability is explained by the variation in irrigated area and water availability between the scenarios (SI figures 10 and 11). For most hotspots, the mitigation scenario leads to higher water availability, and thus lower transgressions of EFRs in the baseline scenario (figure 4(b)). In the Morocco region, the higher irrigation demands and lower water availability in SSP3 lead to higher trade-offs with EFRs (figure 4(a)). The effects of climate mitigation are visible in some of the trade-offs with food (figure 4(c)), e.g. the Tigris-Euphrates and Yellow River basin both show lower trade-offs in the mitigation scenario. In SSP3, both

these basins show higher trade-offs with food due to a higher production demand. In the SSP1 scenario irrigated area in these hotspots is lower, leading to lower potential trade-offs for food. In the Ganges basin, water availability is lower in the mitigation and SSP1 scenario, leading to slightly higher trade-offs with food. While the impact of climate and demand is clearly visible, some deviations occur. For example, in the Ganges basin the SSP1 scenario leads to higher trade-offs with food than the mitigation scenario, even though the overall food demand is less, and water availability is higher. This is explained by the occurring mismatch in demand and supply, due to changes in seasonality.

4. Discussion

In this study we show that reserving part of the discharge in rivers to protect freshwater ecosystems could result in major conflicts between water users in the WEF nexus. Globally, an SSP2 scenario without EFR policy showed that water withdrawals for irrigation and EIH cause high transgressions of EFRs for the Middle-East region, South, East and Central Asia and South-East Australia. Areas in North America, North and South Africa, South-East Australia and South America are also affected. This spatial pattern is consistent with other global studies of future water scarcity (Wada *et al* 2011, Jägermeyr *et al* 2017, Greve *et al* 2018). The results furthermore show that to sustain environmental flows in the SSP2 scenario, irrigation water withdrawals would have to decrease by 30%. This is in line with the findings of Pastor *et al* (2019). In addition, global withdrawals for energy, industries and households would have to decrease with 19%. Projected irrigation withdrawals in this study are on the lower end of the range of most global studies (Wisser *et al* 2008). This is caused by the assumption that only surface water and sustainable groundwater sources are available for irrigation. In reality, unsustainable groundwater resources are expected to account for ~20% of global irrigation withdrawals (Wada *et al* 2012). Consistent with the sustainable policy of EFRs it was chosen to include only sustainable groundwater resources in this study.

Our hotspot results furthermore show that locally, potential trade-offs within the nexus are significant. While on a global scale on average only 2.7% of the environmental flow requirements might be affected by nexus competition, for the hotspots up to 33% of the river length is at risk due to withdrawals for irrigation and EIH. For food production, global results show that 752 Mt (5.7%) of the unconstrained production is vulnerable to competition. While this might seem small on the global scale, 304 Mt of this production is located in the hotspots. Locally, up to

41% of unconstrained production could be affected. The biggest impact is caused by sustaining environmental flows, which confirms earlier studies that found EFRs to be the biggest restriction to agricultural water availability (Strzepek and Boehlert 2010, Jägermeyr *et al* 2017, Pastor *et al* 2019). Potential trade-offs for water consumption for EIH are also found to be significant on the local scale. From the 1673 million people that could be affected by nexus competition, 492 million live in the 14 selected hotspot areas. The hotspot results furthermore indicate that up to 70% of the local population could be affected by withdrawals for irrigation and protection of EFRs.

It should be noted that this is not directly comparable with other definitions of people at risk of water scarcity, since this study (a) focuses only at water consumption for EIH, and (b) looks at actual consumption instead of water availability, thereby also allowing for a less conservative definition of severe risk (Hanasaki *et al* 2008, Mekonnen and Hoekstra 2016). For most hotspots, trade-offs and their scenario dependency become larger over time (SI figures 12 and 13). This is especially the case for areas that are already under pressure. For example, the Ganges and Tigris-Euphrates area show particularly high increases in potential trade-offs on food and EIH over time. Potential trade-offs for EFRs also increase over time, however not as significantly as the trade-offs for food and EIH. This suggests that while there is an increase of competition in the nexus, the locations of EFR transgressions that are caused by withdrawals remain similar.

These findings highlight the increasing challenges posed by water demands in the WEF nexus on a local scale. Smaller-scale studies confirm the increasingly competing claims on limiting water resources, e.g. through increasing pressure from climate and irrigation water demand in the Guadalquiver basin in Spain (Rodríguez Díaz *et al* 2007), increasing population and depletion of groundwater resources in the Indus basin (Laghari *et al* 2012), and pressure on water resources caused by expansion of irrigated areas in the Tigris-Euphrates basin (Yilmaz *et al* 2019). The results furthermore indicate that irrigation has a larger impact on EFR transgressions than water consumption for EIH. This is according to the expectation, since other studies have found relatively higher withdrawals for irrigation in semi-arid and arid regions (Khan & Hanjra 2009, Döll *et al* 2012). Several studies have shown potential to mitigate pressure in the nexus through measures involving irrigation efficiency improvements, renewable electricity generation, trade and land use change (Fricko *et al* 2016, Davis *et al* 2017, Jägermeyr *et al* 2017, Rosa *et al* 2018a, Pastor *et al* 2019, Zipper *et al* 2020). While the range of SSP scenarios does capture some of these

measures in their storylines (e.g. variation in land use, electricity sources, change of diets), additional measures have not been taken into account, focusing merely on the potential trade-offs in the existing baseline scenarios. This is an important direction for future research.

For the purpose of this study, some simplifications of the trade-offs were necessary. For example, it would be interesting to quantify the impact of water shortage on actual electricity supply (see for example Byers *et al* (2020)). In the current IMAGE framework, this feedback is not yet included. The impact of EFR transgressions would ideally be quantified using a response variable like aquatic biodiversity (Gleeson *et al* 2020). However, there is still insufficient research in this field to account for this relation on a global scale, which is why it was chosen to use the percentage of river length where EFRs are met, as also suggested in Gleeson *et al* (2020). It also remains a discussion what flow is used as 'pristine' flow. In this study it has been chosen to use natural flows without land use and without dams and reservoirs, even though some developments might not be reversible. Studies by Bijl *et al* (2018) and Wimmer *et al* (2015) furthermore demonstrated that the priority rules of allocation can have impact on the outcome. The potential trade-offs for water consumption for EIH are therefore expected to be higher if irrigation is given priority. However, impact from upstream withdrawals for irrigation is still included since the prioritization only occurs at the scale of the grid cell. Finally, the representation at the grid level could be improved. For example, it is assumed that withdrawals for EIH only use surface water, while in reality groundwater storage may be used as well. This is dealt with however by having a 30 d buffer in which the demands for EIH can still be met in case of water shortage (Rost *et al* 2008). Furthermore, the water demands for EIH are allocated according to population on a yearly basis. It might be improved by accounting for seasonal variability and for locations of withdrawals (e.g. the locations of specific types of power plants, see also Bijl *et al* (2016)). However, it is not believed that this would significantly alter the results of this study. This is enforced by our findings in the scenario sensitivity analysis, that show limited variation for different scenarios of water use.

5. Conclusion

The results of this study show that trade-offs in the global WEF nexus can be significant at local scales. Globally, the implementation of EFR policy would reduce water withdrawals with 25% in the SSP2 scenario. While benefits of the policy appear small on a global scale, the hotspot results show considerable trade-offs between water needs for food, utilities and

the environment. The amount with which these elements influence each other varies per location. For most hotspots, meeting the EFR targets would considerably increase the pressure on local food production and on communities who need the water for EIHs. At the same time, the percentage of river length that reaches EFR targets increases with up to 33% if water withdrawals for irrigation and EIHs would be abandoned. The limited scenario sensitivity furthermore indicated that mitigation of climate change is not sufficient to decrease the trade-offs in the nexus, implying that a more efficient use of water resources is necessary.

The trade-offs that are exposed in this study present clear challenges for policy makers that need to be dealt with to achieve a sustainable living environment across all regions. In order to meet future water demands, while at the same time respecting EFRs, it is paramount that solution strategies include methods to either improve water management or redistribute demand, or both. This notion highlights the need for an integrated approach to create scenarios that deal with issues of water stress within the global WEF nexus.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

ORCID iDs

Lotte de Vos ⬤ https://orcid.org/0000-0001-5841-9873
Hester Biemans ⬤ https://orcid.org/0000-0001-8750-2553
Jonathan C Doelman ⬤ https://orcid.org/0000-0002-6842-573X
Elke Stehfest ⬤ https://orcid.org/0000-0003-3016-2679
Detlef P van Vuuren ⬤ https://orcid.org/0000-0003-0398-2831

References

Albrecht T R, Crootof A and Scott C A 2018 The water-energy-food nexus: a systematic review of methods for nexus assessment *Environ. Res. Lett.* **13** 043002

Alexandratos N and Bruinsma J 2012 World agriculture towards 2030/2050: the 2012 revision. ESA Working Paper No. 12-03 (Food and Agriculture Organization of the United Nations, Rome) (available at: https://ageconsearch.umn.edu/record/288998/)

Biemans H, Haddeland I, Kabat P, Ludwig F, Hutjes R W A, Heinke J, Von Bloh W and Gerten D 2011 Impact of reservoirs on river discharge and irrigation water supply during the 20th century *Water Resour. Res.* **47**

Bierkens M F P 2015 Global hydrology 2015: state, trends, and directions *Water Resour. Res.* **51** 4923–47

Bijl D L, Biemans H, Bogaart P W, Dekker S C, Doelman J C, Stehfest E and Van Vuuren D P 2018 A global analysis of future water deficit based on different allocation mechanisms *Water Resour. Res.* **54** 5803–24

Bijl D L, Bogaart P W, Kram T, De Vries B J M and Van Vuuren D P 2016 Long-term water demand for electricity, industry and households *Environ. Sci. Policy* **55** 75–86

Bondeau A *et al* 2007 Modelling the role of agriculture for the 20th century global terrestrial carbon balance *Glob. Change Biol.* **13** 679–706

Byers E A, Coxon G, Freer J and Hall J W 2020 Drought and climate change impacts on cooling water shortages and electricity prices in Great Britain *Nat. Commun.* **11** 2239

D'Odorico P *et al* 2018 The global food-energy-water nexus *Rev. Geophys.* **56** 456–531

Darwall W *et al* 2018 The alliance for freshwater life: a global call to unite efforts for freshwater biodiversity science and conservation *Aquatic Conservation Mar. Freshwater Ecosyst.* **28** 1015–22

Davis K F, Rulli M C, Seveso A and D'Odorico P 2017 Increased food production and reduced water use through optimized crop distribution *Nat. Geosci.* **10** 919–24

Doelman J C *et al* 2018 Exploring SSP land-use dynamics using the IMAGE model: regional and gridded scenarios of land-use change and land-based climate change mitigation *Glob. Environ. Change* **48** 119–35

Döll P, Fiedler K and Zhang J 2009 Global-scale analysis of river flow alterations due to water withdrawals and reservoirs *Hydrol. Earth Syst. Sci.* **13** 2413–32

Döll P, Hoffmann-Dobrev H, Portmann F T, Siebert S, Eicker A, Rodell M, Strassberg G and Scanlon B R 2012 Impact of water withdrawals from groundwater and surface water on continental water storage variations *J. Geodyn.* **59–60** 143–56

FAO 2016 *AQUASTAT Main database* (available at: www.fao.org/nr/water/aquastat/)

Fricko O, Parkinson S C, Johnson N, Strubegger M, Van Vliet M T H and Riahi K 2016 Energy sector water use implications of a 2 °C climate policy *Environ. Res. Lett.* **11** 034011

Gerten D, Heinke J, Hoff H, Biemans H, Fader M and Waha K 2011 Global water availability and requirements for future food production *J. Hydrometeorol.* **12** 885–99

Gerten D, Hoff H, Rockström J, Jägermeyr J, Kummu M and Pastor A V 2013 Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements *Curr. Opin. Environ. Sustain.* **5** 551–8

Gleeson T *et al* 2020 The water planetary boundary: interrogation and revision *One Earth* **2** 223–34

Gleick P H and Palaniappan M 2010 Peak water limits to freshwater withdrawal and use *Proc. Natl Acad. Sci. USA* **107** 11155–62

Grafton R Q, Williams J and Jiang Q 2017 Possible pathways and tensions in the food and water nexus *Earth's Future* **5** 449–62

Greve P *et al* 2018 Global assessment of water challenges under uncertainty in water scarcity projections *Nat. Sustain.* **1** 486–94

Hanasaki N *et al* 2013 A global water scarcity assessment under shared socio-economic pathways—part 2: water availability and scarcity *Hydrol. Earth Syst. Sci.* **17** 2393–413

Hanasaki N, Kanae S, Oki T, Masuda K, Motoya K, Shirakawa N, Shen Y and Tanaka K 2008 An integrated model for the assessment of global water resources—part 2: applications and assessments *Hydrol. Earth Syst. Sci.* **12** 1027–37

Hempel S, Frieler K, Warszawski L, Schewe J and Piontek F 2013 A trend-preserving bias correction—the ISI-MIP approach *Earth Syst. Dyn.* **4** 219–36

IRF—International River Foundation 2007 The Brisbane declaration *10th Int. RiverSymp. and Int. Environmental Flows Conf.* p 5 (available at: http://riverfoundation.org.au/wp-content/uploads/2017/02/THE-BRISBANE-DECLARATION.pdf)

Jägermeyr J, Gerten D, Heinke J, Schaphoff S, Kummu M and Lucht W 2015 Water savings potentials of irrigation systems: global simulation of processes and linkages *Hydrol. Earth Syst. Sci.* **19** 3073–91

Jägermeyr J, Pastor A, Biemans H and Gerten D 2017 Reconciling irrigated food production with environmental flows for sustainable development goals implementation *Nat. Commun.* **8** 15900

Johnson N *et al* 2019 Integrated solutions for thewater-energy-land nexus: are global models rising to the challenge? *Water* **11** 2223

Khan S and Hanjra M A 2009 Footprints of water and energy inputs in food production – Global perspectives *Food Policy* **34** 130–40

Laghari A N, Vanham D and Rauch W 2012 The Indus basin in the framework of current and future water resources management *Hydrol. Earth Syst. Sci.* **16** 1063–83

Lehner B *et al* 2011 High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management *Front. Ecol. Environ.* **9** 494–502

Macknick J, Newmark R, Heath G and Hallett K C 2011 A review of operational water consumption and withdrawal factors for electricity generating technologies (available at: www.osti.gov/bridge)

Meinshausen M, Raper S C B and Wigley T M L 2011 Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—Part 1: model description and calibration *Atmos. Chem. Phys.* **11** 1417–56

Mekonnen M M and Hoekstra A Y 2016 Four billion people facing severe water scarcity *Sci. Adv.* **2** e1500323

Müller C, Stehfest E, Van Minnen J G, Strengers B, Von Bloh W, Beusen A H W, Schaphoff S, Kram T and Lucht W 2016 Drivers and patterns of land biosphere carbon balance reversal *Environ. Res. Lett.* **11** 044002

New M, Hulme M and Jones P 2000 Representing twentieth-century space-time climate variability. Part II: development of 1901–96 monthly grids of terrestrial surface climate *J. Clim.* **13** 2217–38

O'Neill B C *et al* 2017 The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century *Glob. Environ. Change* **42** 169–80

Pastor A V, Ludwig F, Biemans H, Hoff H and Kabat P 2014 Accounting for environmental flow requirements in global water assessments *Hydrol. Earth Syst. Sci.* **18** 5041–59

Pastor A V, Palazzo A, Havlik P, Biemans H, Wada Y, Obersteiner M, Kabat P and Ludwig F 2019 The global nexus of food–trade–water sustaining environmental flows by 2050 *Nat. Sustain.* **2** 499–507

Poff N L and Zimmerman J H 2010 Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows *Freshwater Biol.* **55** 194–205

Riahi K *et al* 2017 The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68

Richter B D, Davis M M, Apse C and Konrad C 2012 A presumptive standard for environmental flow protection *River Res. Appl.* **28** 1312–21

Rockström J *et al* 2009 Planetary boundaries: exploring the safe operating space for humanity *Ecology and Society* **14** 32 (available at: https://about.jstor.org/terms)

Rodríguez Díaz J A, Weatherhead E K, Knox J W and Camacho E 2007 Climate change impacts on irrigation water requirements in the Guadalquivir river basin in Spain *Reg. Environ. Change* **7** 149–59

Rosa L, Rulli M C, Davis K F, Chiarelli D D, Passera C and D'Odorico P 2018a Closing the yield gap while ensuring water sustainability *Environ. Res. Lett.* **13** 104002

Rosa L, Rulli M C, Davis K F and D'Odorico P 2018b The water-energy nexus of hydraulic fracturing: a global hydrologic analysis for shale oil and gas extraction *Earth's Future* **6** 745–56

Rost S, Gerten D, Bondeau A, Lucht W, Rohwer J and Schaphoff S 2008 Agricultural green and blue water consumption and its influence on the global water system *Water Resour. Res.* **44**

Scanlon B R, Ruddell B L, Reed P M, Hook R I, Zheng C, Tidwell V C and Siebert S 2017 The food-energy-water nexus: transforming science for society *Water Resour. Res.* **53** 3550–6

Stehfest E *et al* 2014 *Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model Description and Policy Applications* (The Hague: PBL Netherlands Environmental Assessment Agency) (available at: https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation)

Strzepek K and Boehlert B 2010 Competition for water for the food system *Phil. Trans. R. Soc. B* **365** 2927–40

Van Vuuren D P, Bijl D L, Bogaart P, Stehfest E, Biemans H, Dekker S C, Doelman J C, Gernaat D E H J and Harmsen M 2019 Integrated scenarios to support analysis of the food–energy–water nexus *Nat. Sustain.* **2** 1132–41

Van Vuuren D P, Riahi K, Calvin K, Dellink R, Emmerling J, Fujimori S, Kc S, Kriegler E and O'Neill B 2017 The Shared Socio-economic Pathways: trajectories for human development and global environmental change *Glob. Environ. Change* **42** 148–52

Vörösmarty C J *et al* 2010 Global threats to human water security and river biodiversity *Nature* **467** 555–61

Wada Y, Graaf I E M and Van Beek L P H 2016 High-resolution modeling of human and climate impacts on global water resources *J. Adv. Model. Earth Syst.* **8** 735–63

Wada Y, Van Beek L P H and Bierkens M F P 2012 Nonsustainable groundwater sustaining irrigation: a global assessment *Water Resour. Res.* **48**

Wada Y, Van Beek L P H, Viviroli D, Dürr H H, Weingartner R and Bierkens M F P 2011 Global monthly water stress: 2. Water demand and severity of water stress *Water Resour. Res.* **47**

Wimmer F, Audsley E, Malsy M, Savin C, Dunford R, Harrison P A, Schaldach R and Flörke M 2015 Modelling the effects of cross-sectoral water allocation schemes in Europe *Clim. Change* **128** 229–44

Wisser D, Frolking S, Douglas E M, Fekete B M, Vörösmarty C J and Schumann A H 2008 Global irrigation water demand: variability and uncertainties arising from agricultural and climate data sets *Geophys. Res. Lett.* **35**

Woltjer G and Kuiper M 2014 The MAGNET model: module description *Wageningen UR* 144 (available at: www.wageningenUR.nl/en/lei)

WWF 2020 Living planet report *A Banson Production* (available at: www.ecoguinea.org/papers-development.html)

Yilmaz Y A, Sen O L and Turuncoglu U U 2019 Modeling the hydroclimatic effects of local land use and land cover changes on the water budget in the upper Euphrates—Tigris basin *J. Hydrol.* **576** 596–609

Zipper S C *et al* 2020 Integrating the water planetary boundary with water management from local to global scales *Earth's Future* **8**