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Sectoral water use responses to droughts and heatwaves: analyses from local to global scales for 1990–2019

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Abstract

Water use for various sectors (e.g. irrigation, livestock, domestic, energy and manufacturing) is increasing due to a growing global population and economic development. Additionally, increases in frequency and severity of droughts, heatwaves and compound drought-heatwave events, also lead to responses in sectoral water use and a reduction in water availability, intensifying water scarcity. However, limited knowledge exists on the responses in sectoral water use during these hydroclimatic extremes. In this study we quantify the impacts of droughts, heatwaves and compound events on water use of irrigation, livestock, domestic, energy and manufacturing sectors at global, country and local scales. To achieve this, datasets of reported and downscaled sectoral water use (i.e. withdrawal and consumption) were evaluated during these hydroclimatic extremes and compared to normal (non-extreme) periods for 1990–2019. Our analysis shows that these hydroclimatic extremes affect water use patterns differently per sector and region. Reported data show that domestic and irrigation water use increases during heatwaves in Eastern Europe and central continental United States, while water use decreases for thermoelectric sector, particularly in Europe while it increases in north and Eastern Asia. Additionally, global water use response patterns reveal that irrigation and domestic sectors are mostly prioritized over livestock, thermoelectric and manufacturing. Reported local-scale data reveal that for most sectors and regions/locations, stronger water use responses are found for heatwaves and compound events compared to impacts during hydrological droughts. Our outcomes provide improved understanding of sectoral water use behaviour under hydroclimatic extremes. Nonetheless, given the future threats to water availability and the limited accessible information of water use, there is an urgency to collect more monitored-driven data of sectoral water use for improved assessments of water scarcity under these extremes. Consequently, this research reveals the necessity of more realistic water use models to better represent the sectoral responses to hydroclimatic extremes.

1. Introduction

More than half of the global population currently lives under conditions of severe water scarcity for at least one month every year (Mekonnen and Hoekstra 2016). Moreover, global population and economic growth will likely increase water demand for various sectors. In case water supply is insufficient to fulfil the demands, this may increase water scarcity (Vörösmarty *et al* 2000, Hanasaki *et al* 2013, Wada *et al* 2014a, van Vliet *et al* 2017) and threaten food security and basic needs (e.g. domestic and irrigation use), which depend on almost 90% of worldwide water withdrawals (FAO & UN-Water 2021). Furthermore, the occurrence of hydroclimatic extremes, such as droughts, heatwaves and compound events, affect the availability, demand and withdrawal of water. These extreme events are expected to increase in frequency, magnitude and duration (Alizadeh *et al* 2020, Meehl and Tebaldi 2004, FAO & UN-Water 2021), impacting both water quantity (availability and sectoral water use) and water quality

(Jones and van Vliet 2018). This, in turn, is expected to lead to an increase in water scarcity levels in the coming decades for various regions across the world (Vörösmarty *et al* 2000, Schewe *et al* 2014, van Vliet *et al* 2017, 2021).

The concept of water demand is inherently related to the development of human activities and plays a key role in the global water scarcity issue. The role of sectoral water use in water scarcity has been assessed at a global scale (Ward *et al* 2010, Wada *et al* 2014a, 2016, Jägermeyr *et al* 2015) and has been used as the basis to calculate water scarcity indices (FAO & UN-Water 2021, van Vliet *et al* 2017, 2021).

Several studies have assessed sectoral water use and its impact on water scarcity, although only under average hydroclimatic conditions and overall disregarding hydroclimatic extremes (Ward *et al* 2010, Wada *et al* 2014a, 2016, Jägermeyr *et al* 2015, Baldassarre *et al* 2018). Other studies have mainly evaluated the effectiveness of national policies or the economic impact of droughts on water resources and water scarcity (Kahil *et al* 2015, Dobson *et al* 2020). However, these studies are mainly conducted at the country level and have a stronger focus on water supply impacts under droughts compared to sectoral water use. Due to the importance of effective water use monitoring, there have been various governmental initiatives to collect information on water withdrawals at different scales and sectors over regular time intervals (e.g. United States Geological Survey, Food and Agriculture Organization). Nonetheless, there still exists a lack of understanding of how sectoral water use is affected by droughts, heatwaves and compound events in different locations worldwide, as well as of how socio-economic factors (e.g. income or policies) influence water use behaviour under these extremes. Understanding the sectoral water use response to hydroclimatic extremes is essential to correctly project how water use will develop under future climate change, where the frequency and severity of extremes are expected to increase in many parts of the world (Alizadeh *et al* 2020, Meehl and Tebaldi 2004, FAO & UN-Water 2021).

The identification of the response to sectoral water use at the global scale is, however, hampered by the fact that almost all reported data on sectoral water use are at the yearly time scale or coarser. For these data we may expect that years with droughts and heatwaves have different water use characteristics compared to non-drought and non-heatwave years, but it does not reveal what happens at the sub-yearly scale during extreme event occurrence. For this, we need to rely on reported data that are further downscaled with statistical or model-assisted methods.

This study aims to identify and analyse responses of sectoral water use (i.e. domestic, irrigation, livestock, thermoelectric and manufacturing) to droughts, heatwaves and compound events during the last 30 years (1990–2019) across the world. To achieve this, sectoral water use (withdrawal and consumption) records from various databases at global, country (US) and local (large cities) levels were collected (section 2.1). Simultaneously, droughts, heatwaves and compound events were identified using threshold-based methods (section 2.2). Responses in sectoral water use behaviour and prioritization patterns under these extreme events were subsequently analysed (sections 2.3) at the global (section 3.1), country (section 3.2) and local levels (section 3.3). Here we first analysed reported water use data downscaled using statistically and model-assisted methods (i.e. Huang *et al* 2018) to observe how this data responds to extreme events at the global scale. Next, we used the limited reported water use records at global, country and local scales available to compare and verify water use responses under hydroclimatic extremes derived from the reported model-assisted downscaled water use data (i.e. Huang *et al* 2018). In addition, we discuss the main uncertainties, compare our main findings with other water use studies, and elaborate on the contribution of this work and directions for future research (section 4).

2. Methodology

A three-step approach was followed to assess the sectoral water use responses during extreme events, focussing on hydrological and agricultural droughts, heatwaves and compound drought-heatwave events (figure 1). Further description of the data and methodology used in this paper can be found in the supplementary information (SI).

2.1. Sectoral water use data collection

Water use can be classified by its dimensions of use in potential and actual use. *Potential water use*, or water demand, refers to the water required by an activity, either the exact amount (net demand) or including efficiency factors that increase this amount (gross demand). *Actual water use* considers water availability, and is sub-classified in withdrawal, consumption and return flows (Wada *et al* 2011, 2014b, Flörke *et al* 2013, Sutanudjaja *et al* 2018). While *water withdrawal* refers to the amount of water extracted from a water source to satisfy the gross demand, *water consumption* is the amount of water consumed to satisfy the net demand. *Return flow* is the water withdrawn, but which is not consumed and thus reinstated to the water source, either surface or groundwater (i.e. withdrawal minus consumption).

For this study, data on sectoral water withdrawals and consumptions was collected at different spatial resolutions (e.g. gridded globally, at city or power plant level), at 5-yearly, monthly and daily time-steps

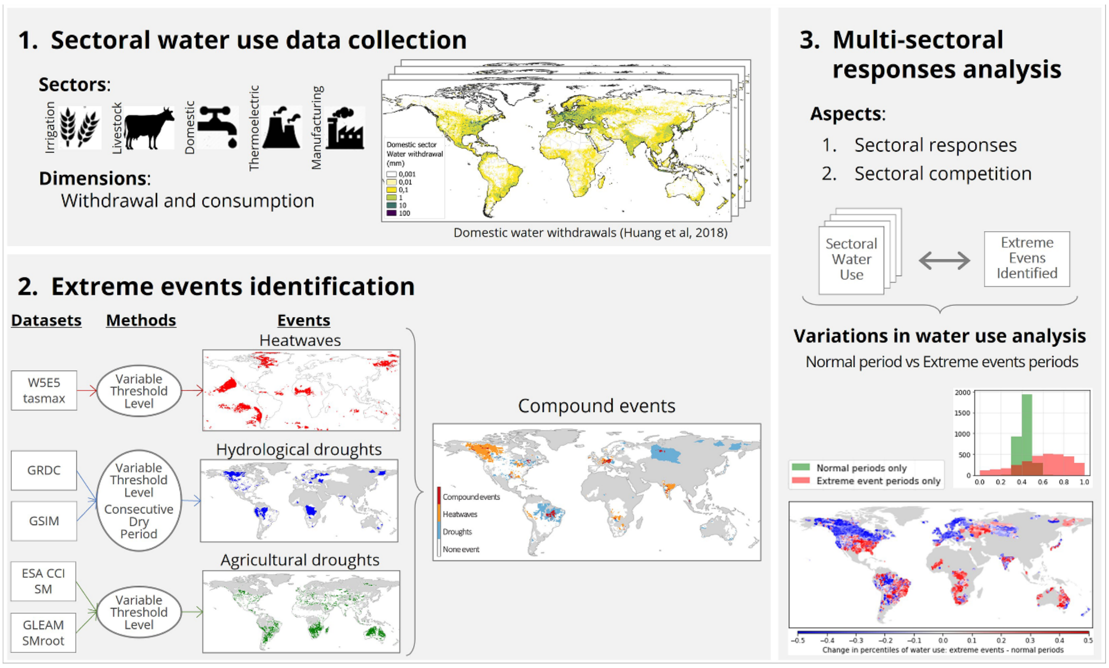

Figure 1. Methodological steps to assess the sectoral water use responses to drought-heatwave events. Further details are presented in the following sub sections.

(table 1). Available information of water withdrawals does however not distinguish between water sources (i.e. surface water or groundwater). Table SI 1 in the supplementary information presents the datasets analysed, including a description of the data (e.g. spatial-temporal scales), the sectors involved and the water use dimension (i.e. withdrawal, consumption). Based on the available information collected, three spatial scales were selected for the analysis: global, country and local scales.

At the global level, the datasets developed by Huang *et al* (2018) were analysed regarding water withdrawal and consumption for irrigation, livestock, domestic and industrial (only manufacturing and thermoelectric) sectors for the period 1990–2010. These datasets are the result of the temporal and spatial downscaling of reported water withdrawals recorded at country level using statistical and model-assisted methods based on environmental and socio-economic parameters (e.g. air temperature, population density) (see SI for details). Additionally, we used global reported data from AQUASTAT for water withdrawals for irrigation, municipal, industrial, thermoelectric and livestock sectors for the period 1990–2019, which are provided at a country level (FAO AQUASTAT 2023). Municipal sector includes domestic and manufacturing sectors connected to water-supply network; while industrial sector includes manufacturing and thermoelectric sectors that use self-supplied water.

For the United States (country scale), we used data of water withdrawals from the USGS National Water Information System for domestic, industrial (manufacturing), thermoelectric, livestock and irrigation sectors for the period 1985–2015 (USGS National Water Information System 2023). In addition, data of thermoelectric cooling water withdrawals and net electricity generated per power plant was retrieved from the US Energy Information Administration (US EIA) at a monthly scale (U.S. Energy Information Administration 2021b). This data includes reported withdrawal and consumption from thermoelectric power plants considering different technologies (i.e. nuclear, coal, gas fired) and cooling system types (i.e. once-through, recirculation cooling with wet cooling towers).

At a local scale, we used data of water withdrawals collected by water suppliers and local governmental institutions. Here we have been able to obtain data from Los Angeles, San Diego and Sacramento in California (US), New York City (US), Saskatoon, Regina, Prince Albert, Moose Jaw and Yorkton in Saskatchewan (Canada) and Melbourne (Australia) (table 1). These locations were selected based on three criteria: large cities, drought and heatwaves, and the availability of water use data.

2.2. Extreme events identification

Droughts, heatwaves and compound events were identified at a global gridded scale employing the commonly used threshold-based methods (van Loon *et al* 2012, Lavaysse *et al* 2018, Sutanto and van Lanen 2020, Floriancic *et al* 2021) variable threshold level (Dracup *et al* 1980) and consecutive dry period (van Huijgevoort *et al* 2012). Extreme events were identified as monthly-scale independent occurrences.

Table 1. Datasets considered for sectoral water use analysis and extreme events identification (for details, see SI—section 1).

				Resolution	
N^0	Dataset	Acronym	Period	Temporal	Spatial
Water use datasets					
1	Global reconstructed water use data for 1971–2010 v2.0	Huang *et al* (2018)	1971–2010	Monthly	Global 30 arcmin
2	Food and Agriculture Organization (FAO) AQUASTAT: Water use—Water withdrawal by sector	AQUASTAT	1990–2019	5 yearly	Global country-level
3	National Water Information System: USGS water use data for the nation	USGS	1990–2015	5 yearly	United States county-level
4	US Energy Information Administration	US EIA	2014–2020	Monthly	United States points (power plants)
5	Urban Water Supplier Monitoring Reports—California	—	2014–2020	Monthly	City
6	Water Consumption and Cost—New York City	—	2013–2020	Monthly	City
7	Community water use records—Saskatchewan	—	2006–2020	Monthly	City
8	Daily water use (households and businesses)—Melbourne	—	1990–2021	Daily	City
Hydroclimatic datasets					
9	WFDE5 over land merged with ERA5 over the ocean v2.0: Daily Maximum Near-Surface Air Temperature	W5E5 tasmax	1979–2019	Daily	Global 30 arcmin
10	Global Runoff Dataset Centre database	GRDC	1920–2020	Daily	Global points (discharge monitoring station)
11	Global Streamflow Indices and Metadata Archive	GSIM	1920–2016	Monthly	Global points (discharge monitoring station)
12	European Space Agency—Climate Change Initiative: Soil Moisture v6.1	ESA CCI SM	1979–2019	Daily	Global 15 arcmin
13	Global Land Evaporation Amsterdam Model v3.5a: Root-zone soil moisture	GLEAM SMroot	1980–2020	Daily	Global 15 arcmin
Other datasets					
14	Geocoded Disasters	GDIS	1960–2018	Yearly	Global points

Access data links:
[1] https://doi.org/10.5281/zenodo.1209296
[2] www.fao.org/aquastat/statistics/query/index.html
[3] https://waterdata.usgs.gov/nwis/water_use/
[4] www.eia.gov/electricity/data/water/
[5] https://data.ca.gov/dataset/e4b31aa4-0a61-4e03-84bd-2ae46183db59/resource/0c231d4c-1ea7-43c5-a041-a3a6b02bac5e/download/uw_supplier_data020122.csv
[6] https://data.cityofnewyork.us/Housing-Development/Water-Consumption-And-Cost-2013-2020-/66be-66yr
[7] www.wsask.ca/about/publications/water-use/
[8] www.melbournewater.com.au/water-data-and-education/water-storage-levels#/ws/freq/daily/type/wateruse
[9] https://data.isimip.org/datasets/38d4a8f4-12e8-44ff-afe3-0c7ce0e0dad6/
[10] https://portal.grdc.bafg.de/applications/public.html?publicuser=PublicUser#dataDownload/Home
[11] https://doi.pangaea.de/10.1594/PANGAEA.887477
[12] www.esa-soilmoisture-cci.org/index.php?q=dataregistration
[13] www.gleam.eu/
[14] https://sedac.ciesin.columbia.edu/data/set/pend-gdis-1960-2018/data-download.

For droughts, a distinction was made between agricultural and hydrological droughts, as these affect the irrigation sector differently. Agricultural droughts were identified based on soil moisture data and hydrological droughts based on streamflow. Impacts of agricultural droughts on compound events were analysed for irrigation water use specifically, while for the other sectors impacts of hydrological droughts on compound events were considered.

For heatwaves, we analysed the maximum daily temperature data from W5E5 v2.0 dataset (Lange *et al* 2021) using the variable threshold level method (Dracup *et al* 1980). To account for the temporal variability within a year, a 5 days moving window centred on the day of interest was used for the threshold analysis. A heatwave was identified when the maximum daily temperature value exceeds the 90th percentile during three consecutive days (Sutanto *et al* 2020). In addition, only values over the 50th percentile of each time-series were considered to avoid the identification of heatwaves during cold seasons. Heatwaves were identified at a daily-timestep first, and in a next step aggregated to monthly-scale when the occurrence of at least three daily events were identified during a month.

For hydrological droughts, we combined the daily discharge records from the Global Runoff Data Centre (GRDC 2011) and the monthly discharge values from the Global Streamflow Indices and Metadata Archive (GSIM) (Do *et al* 2018, Gudmundsson *et al* 2018). The resulting monthly dataset was evaluated using both the variable threshold level (Dracup *et al* 1980) and the consecutive dry period (van Huijgevoort *et al* 2012) methods, the latter being particularly advantageous for assessing droughts in dry areas with prolonged periods without flow. Only hydrological stations with less than 25% of data gaps were used for the analysis. Hydrological drought events were considered when the monthly discharge value was lower than the 20th percentile. This resulted in a monthly dataset of hydrological drought events (see SI for details).

For agricultural droughts, we combined the daily soil moisture records from the European Space Agency—Climate Change Initiative: Soil Moisture v6.1 (ESA CCI SM) dataset (Dorigo *et al* 2017) with the Global Land Evaporation Amsterdam Model v3.5a: Root-zone soil moisture (GLEAM SMroot) dataset (Martens *et al* 2017) (see SI for details). This dataset was evaluated using the variable threshold level method, such that agricultural droughts were identified when the monthly soil moisture is lower than the 20th percentile. This resulted in a monthly dataset of agricultural drought events.

To identify the compound events, the resulting single-event datasets were assigned an ID based on the type of event (i.e. hydrological drought, agricultural drought or heatwave), spatially overlapped and summed. Figure SI 1 depicts the methodology, the range of resulting IDs and its corresponding category. The outcome is a global dataset with hydrological and agricultural droughts, heatwaves and compound drought-heatwave events on monthly level over the period 1990–2019 (see figure 1 and SI for details). Nonetheless, as only the irrigation sector considers the effect of agricultural droughts, the compound events identified for the other sectors considered only heatwaves and hydrological droughts.

Finally, to evaluate the consistency of identified heatwaves and droughts (hydrological and agricultural), we compared our results with recorded occurrences from the Geocoded Disasters dataset (GDIS) (Rosvold and Buhaug 2021). The analysis was undertaken at an annual scale, evaluating their agreement by calculating the matching rate of detected hydroclimatic extreme events compared to the reported ones in the GDIS dataset, expressed as a percentage (see SI for details).

2.3. Multi-sectoral responses analysis

To assess the impacts of droughts, heatwaves and compound events on sectoral water use, we evaluated the change in water use under the extreme events compared to the normal (non-extreme) period.

First, we analysed Huang *et al* (2018) dataset to get a global view of water use responses to extreme events. A linear detrending of sectoral water use time-series was done to remove the effect of external factors (e.g. increase in water demand due population growth and extension of area under irrigation) that could hinder the detection of patterns related to the occurrence of the extreme events over the 1990–2019 period, where available. Finally, the variations in response in water use were calculated as the difference between the median percentile of the use of water during the extreme event minus the median percentile during the normal (non-extreme event) period per sector.

Two aspects were assessed: (1) sectoral responses, and (2) sectoral water use competition. We evaluated the *sectoral responses* by comparing the change in the magnitude of the water used per sector, also exploring seasonal variations. *Sectoral competition* was evaluated by comparing the change in the percentage of water used per sector relative to the total water used.

Next, we evaluated whether sectoral water use responses under extremes derived from the reported model-assisted downscaled water use dataset (Huang *et al* 2018) correspond with those derived from reported data at a global, country and local scales.

At a global and country-scales, we evaluated the water use responses from AQUASTAT and USGS datasets to extreme events, respectively. Due to the coarse temporal and spatial resolution of those data, the extreme events identified (section 2.2) were spatial-temporally aggregated to yearly time-step and country or county scale, respectively (see SI for details). Given the limited data available, water use records were grouped by regions that shared socio-economic and environmental characteristics using the global MESSAGE (Huppmann *et al* 2019) regions and Unified Interior Regional boundaries (US Department of the Interior 2019), respectively (figure SI 3). The changes in water use response were evaluated by comparing the percentile distributions of the water use during extreme event periods and normal (non-extreme event) period, independently, per sector.

For the local-scale (i.e. city) analysis, hydrological drought data was retrieved from the closest water source or upstream location of the city. Therefore, identified hydrological droughts and heatwaves were retrieved from different grid cells for the same city. Also, for country (i.e. US EIA) and local (e.g. city level) scales water use data we compared the changes in water use responses to extreme events with those as obtained from the Huang *et al* (2018) dataset, i.e. to check the consistency of reported model-assisted downscaled data vs. fully reported data.

3. Results

Extreme hydroclimatic events were identified globally for the period 1990–2019 at a monthly scale. This identification was compared to the GDIS dataset records of registered heatwaves and climatological droughts to validate its representativity. Our identified extreme events matched the reported ones 72% of the times for heatwaves, 79% and 85% for hydrological droughts and agricultural droughts, respectively. In the following results, droughts refer to agricultural droughts for irrigation sector, whereas it refers to hydrological droughts for the other sectors. Thus, the compound events represent the simultaneous occurrence of heatwaves and their correspondent droughts (i.e. agricultural or hydrological).

3.1. Global-scale analysis

3.1.1. Reported model-assisted downscaled water use (Huang et al 2018)

Our global analyses of sectoral water use responses based on the Huang *et al* (2018) dataset show that drought-heatwave events strongly influence the response in the sectoral water withdrawal and consumption (figure 2). Median percentile values of both water withdrawal and consumption during extreme events (red bars) vary more compared to normal (non-extreme) periods (green bars) for all sectors, implying that different areas worldwide respond differently to these extreme events, i.e. increasing or decreasing their water use. In addition, larger responses in sectoral water withdrawal were identified mainly during heatwaves and compound events compared to droughts only (i.e. agricultural drought in case of irrigation water use and hydrological drought for other sectoral uses). For instance, irrigation and domestic sectors show a predominant increase in water withdrawal and consumption (negative skewness) globally.

Water withdrawals and consumption present a similar response pattern per type of event and sector (figure 2), with Pearson correlation coefficients ranging between 0.66 and 1 (figure SI 4), and significant with a confidence level of 0.05. Due to the similarity in withdrawal and consumption responses, we mainly focus on analysis of sectoral water withdrawals, while our results of sectoral water consumption are shown in the SI (figures SI 6–8).

The largest changes in water withdrawals worldwide during extreme events compared to normal periods are mainly for compound events (figure 3). For irrigation and domestic sectors, there is a general increase in water withdrawals except for parts of the US, South America and India. In contrast, the thermoelectric sector shows an overall decrease in water withdrawal, mainly in Europe, the northernmost part of North America and central Asia. Responses from the manufacturing and livestock sectors vary across the world. For most sectors our results show that responses are overall more moderate during droughts compared to heatwaves and compound events.

Variations in seasonal responses were identified in water withdrawals per hemisphere and per sector (figures 4 and SI 5). Our results show that the increase in irrigation water withdrawal under heatwaves and compound events is larger in the northern hemisphere than in the southern hemisphere. This may be because larger food bowl regions are in the northern hemisphere (e.g. California and Great Plains in US, Mediterranean and Eastern European countries, India) that have a food demand to meet. In addition, water withdrawals decrease between June and August in the southern hemisphere (winter period) but increases the next months as the crop calendars begin, whereas the northern hemisphere shows an increase in water withdrawals from June onward, when higher temperatures are recorded.

For the domestic sector, water withdrawals during heatwaves and compound events have overall a similar response in both hemispheres. Larger changes in domestic water withdrawals occur over the month following summer (i.e. September and March for Northern and Southern hemisphere, respectively). Conversely, for the thermoelectric sector, less amount of water is withdrawn for cooling purposes in the northern hemisphere during heatwaves and compound events compared to the southern hemisphere.

Sectoral water use competition was studied by comparing the change in the percentage of water used per sector relative to the total water used during the extreme events (figure 5). During heatwaves and compound events there is a highest priority of water use for domestic and, depending on region, also to irrigation sectors. This is followed by manufacturing, livestock and thermoelectric water use.

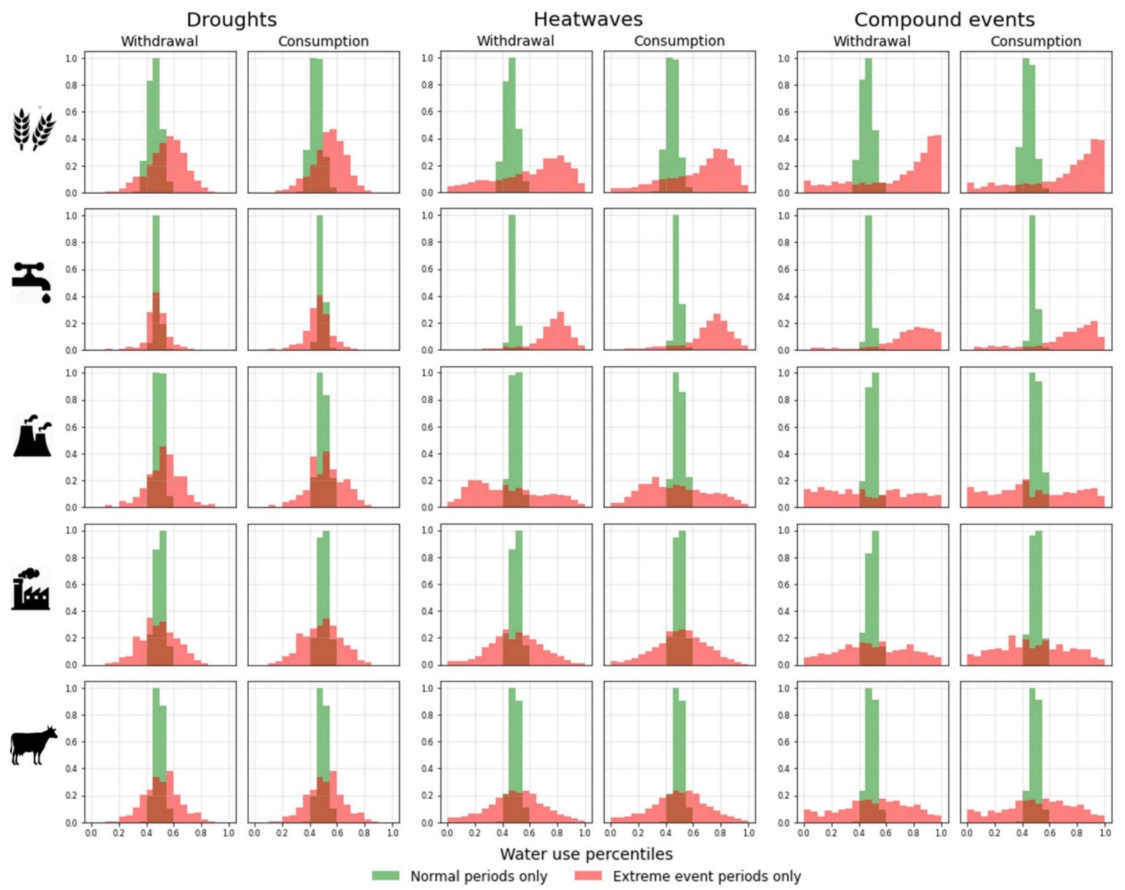

Figure 2. Histograms comparing sectoral water use (withdrawal and consumption) responses to extreme hydroclimatic events (droughts, heatwaves and compound events) for the irrigation, domestic, thermoelectric (cooling), manufacturing and livestock sectors. Scaled number of extreme events occurrences are presented on the vertical axis, and water use percentiles on the horizontal axis. Bins represent the median percentile values during the occurrence of extreme events (red bars) and the normal (non-extreme) periods (green) for 1990–2010.

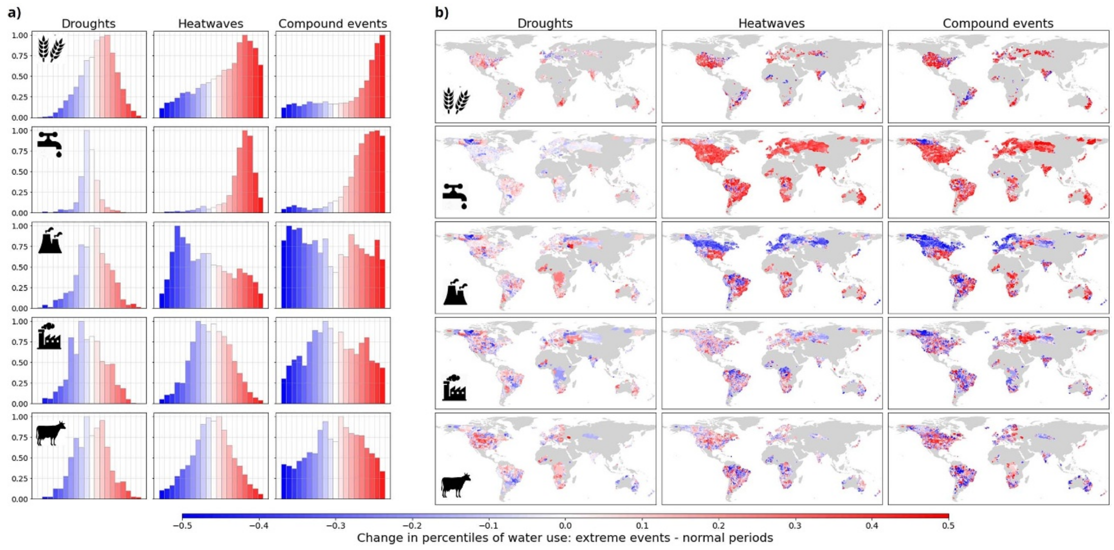

Figure 3. Global distribution of sectoral water withdrawal responses to extreme hydroclimatic events for irrigation, domestic, thermoelectric (cooling), manufacturing and livestock sectors: change in percentiles of water withdrawals during extreme event compared to normal (non-extreme) periods as (a) histograms and (b) global spatial distribution maps. Positive change (red) means an increase in the water withdrawal during these extreme events, and vice versa, whereas white locations imply no change.

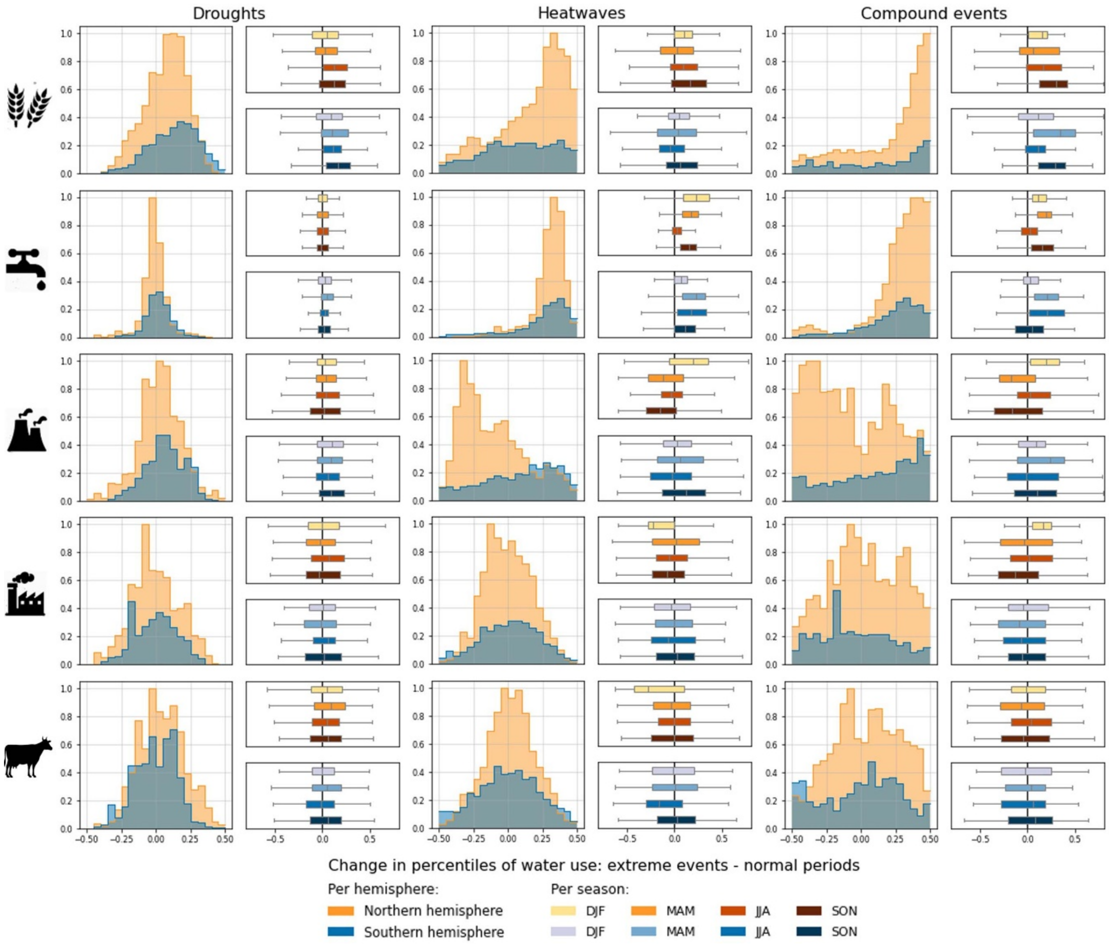

Figure 4. Seasonal comparison of change in water withdrawal percentiles during extreme compared to normal (non-extreme) periods for northern and southern hemisphere for the main water use sectors irrigation, domestic, thermoelectric (cooling), manufacturing and livestock for 1990–2010. Histograms (left panels) present the scaled number of extreme events occurrences per hemisphere on the vertical axis, change in percentiles (extreme events minus normal periods) on the horizontal axis. Boxplots (right panels) present the change in percentiles per seasons in the northern hemisphere (upper right panel) and southern hemisphere (lower right panel). Boxplots represent the change of median percentiles in water withdrawal from normal periods to extreme events: sector and/or a driver is more impacted by the extreme event when it is farther from the zero line. Where: DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November.

For the domestic sector, although there is a general increase in priority during heatwaves, this pattern changes during compound events mostly in northern regions where the irrigation sector receives the priority. During droughts, there is a clear prioritisation for irrigation for most regions, except for central Europe. Here priority is given to domestic and thermoelectric sectors, whereas other sectors show different responses in prioritization over different regions across the world.

3.1.2. *AQUASTAT—reported water withdrawals*

Global responses in sectoral water withdrawal to extreme events obtained from the reported model-assisted downscaled data (Huang *et al* 2018) were aggregated and compared to responses derived from reported water withdrawals from AQUASTAT. Our results show that water withdrawals responses derived from Huang *et al* (2018) are consistent with reported data in Western Europe (WEU), Eastern Europe (EEU) and Former Soviet Union (FSU) (figures 6 and SI 9). However, more divergent responses in water use during these extreme years were obtained for Latin America and Caribbean (LAC) and AFR (Sub-Saharan Africa). Also, the industrial sector (thermoelectric and manufacturing) presents the highest number of regions with consistent responses compared to reported data while the domestic sector presents less agreement in identified responses. For drought years the identified responses of different datasets are more consistent than for years with heatwaves for most regions. The remaining six regions did not have enough reported data to compare water use responses.

Reported irrigation water withdrawal during extreme events show an overall increase in Europe (i.e. WEU and EEU) and a general decrease in other regions. For the domestic sector, there is a decrease

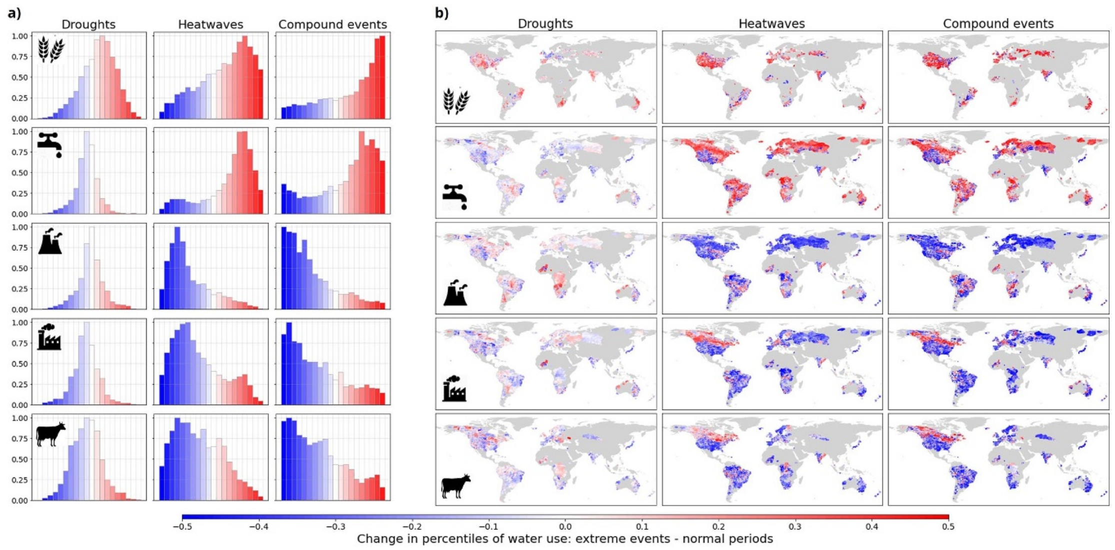

Figure 5. Sectoral water withdrawal competition for irrigation, domestic, thermoelectric (cooling), manufacturing and livestock sectors during droughts, heatwaves and compound events. Change in percentiles of water withdrawals compared to total water withdrawn for extreme event periods to normal periods are presented as (a) histograms and (b) global spatial distribution maps. Positive values imply a prioritization of the sector during the occurrence of extreme events, and vice versa.

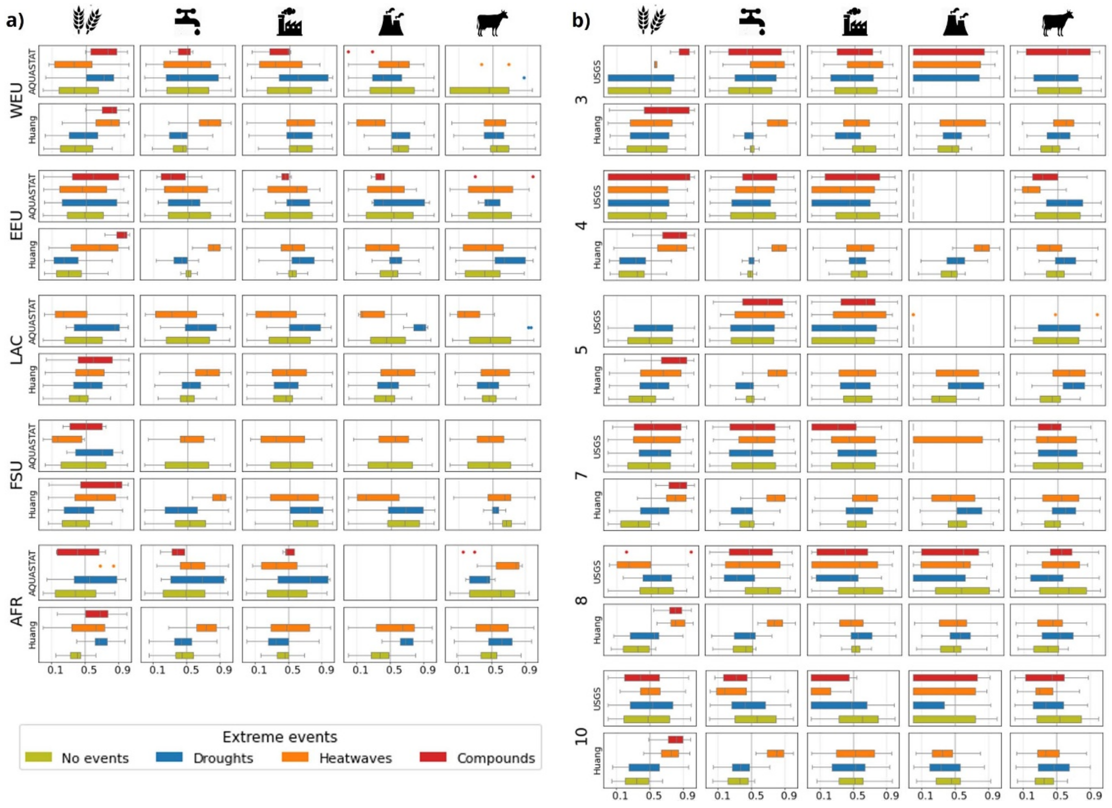

Figure 6. Comparison of sectoral water withdrawal responses during droughts, heatwaves and compound events between reported model-assisted data (Huang *et al* 2018) and reported data for the irrigation, domestic, industrial/manufacturing, thermoelectric (cooling) and livestock sectors for a) AQUASTAT aggregated to macroregional level (MESSAGE regions) and b) USGS (UIR regions). Results are grouped by regions, presented on the *y*-axis (see figure SI 3 for description of acronyms), comparing reported (i.e. AQUASTAT, USGS) (upper panels) and Huang *et al* (2018) (lower panels) data. Boxplots represent percentiles in water withdrawal during normal (non-extreme) periods and extreme events periods: a sector and/or a region is more impacted by the extreme event when the extreme event boxplot (blue, orange or red) is more shifted compared to the non-event boxplot (green). Datasets are consistent if water withdrawal response patterns are similar for both datasets. See figure SI 9 for full set of regions.

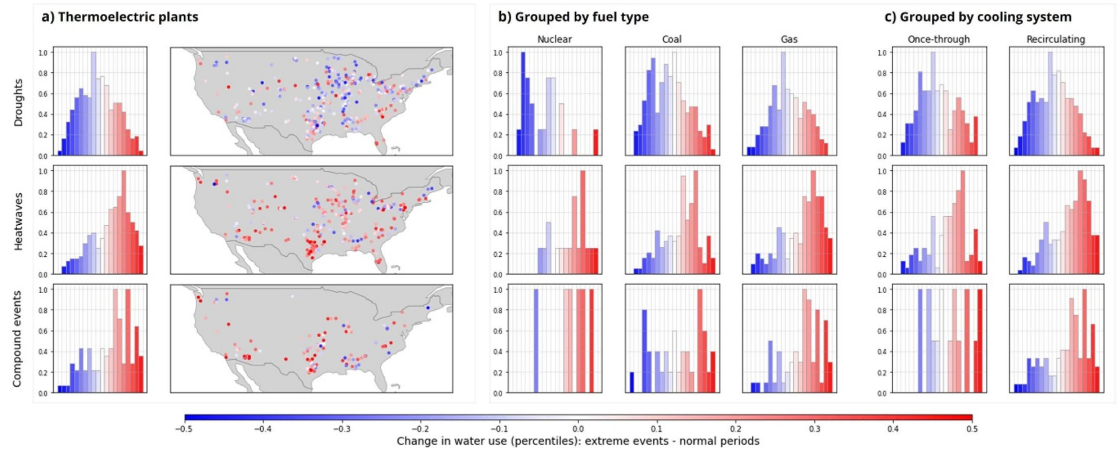

Figure 7. Change in cooling water withdrawal by thermoelectric power plants during extreme events at monthly scale. Case study: USA: (a) all thermoelectric plants, (b) thermoelectric plants grouped by fuel type (nuclear, coal, gas), (c) thermoelectric plants grouped by cooling system type (once-through, recirculation). Each row shares the same type of extreme event.

Table 2. Change in sectoral water withdrawal responses from normal periods to extreme events at a local scale for domestic and manufacturing sectors.

Sector	Dataset		Droughts	Heatwaves	Compound events
Municipal (domestic + manufacturing)	Melbourne		−0.22	0.24	−0.10
	Saskatchewan	Saskatoon	0.15	0.33	0.43
		Regina	−0.06	0.49	0.28
		Prince Albert	0.01	0.46	0.21
		Moose Jaw	−0.13	0.46	—
		Yorkton	0.25	0.26	—
	New York	Queens	0.27	−0.17	—
		Brooklyn	−0.15	−0.20	—
		Bronx	0.14	0.09	—
		Manhattan	−0.08	0.27	—
		Staten Island	0.38	−0.11	—
Domestic	California	Los Angeles	0.15	0.44	0.45
		Sacramento	0.19	0.47	0.21
		San Diego	0.18	0.25	0.37
Manufacturing		Los Angeles	0.18	0.49	0.34
		Sacramento	0.13	0.40	0.18
		San Diego	0.16	0.27	0.45

Note: Locations where no compound event were identified during the period with available data are denoted with a '—'.
Colours represent the change in sectoral water withdrawal responses (percentiles) from normal periods to extreme events, ranging from −0.5 (blue) to +0.5 (red).

of water withdrawals in the Pacific OECD (PAO) and EEU regions, and an increase for WEU during these extremes.

3.2. Country-scale analysis: United States

3.2.1. USGS—reported water withdrawals

USGS water withdrawal responses to extreme events show two major regions with common water use responses: western (i.e. 3, 4, 5 and 6 UIR regions) and central (i.e. 7, 8, 9 and 10 UIR regions) continental US. While western regions present an overall decrease in water withdrawals during extreme events for all sectors, central regions increase their withdrawals, except for livestock sector.

Some regions in the US present consistent water withdrawal responses to extreme events when comparing results from Huang *et al* (2018) datasets and USGS reports (figures 6 and SI 9). Regions in central continental US present an overall good agreement between responses derived from the Huang *et al* (2018) dataset with reported data during extremes, whereas regions in western regions show less consistency in identified responses. The manufacturing sector presents more consistent responses. Similar to reported data from AQUASTAT, water withdrawal responses during drought years are more consistent compared to responses during heatwave years for most regions.

Table 3. Overview of consistency in sectoral water withdrawal responses during droughts, heatwaves and compound events between reported data and reported model-assisted data (Huang *et al* 2018) for the irrigation, domestic, industrial/manufacturing, thermoelectric (cooling) and livestock sectors at global, country and local scales.

Sectors	Consistency	Droughts	Heatwaves	Compound events
Global scale				
Irrigation	Consistent Non-consistent	LAC, WEU, FSU, AFR EEU, CPA, PAO	EEU LAC, WEU, FSU	WEU, EEU FSU, PAO, AFR
Municipal	Consistent Non-consistent	LAC WEU, EEU, AFR	WEU, FSU LAC, EEU, CPA, PAO, AFR	— —
Industrial	Consistent Non-consistent	LAC, WEU, EEU AFR	EEU, FSU LAC, WEU, AFR	— —
Thermoelectric	Consistent Non-consistent	LAC, WEU, EEU —	EEU LAC, WEU, FSU	— —
Livestock	Consistent Non-consistent	— EEU, AFR	EEU, FSU, AFR LAC	— —
Country scale				
Irrigation	Consistent Non-consistent	1, 2, 3, 4, 5, 10 7, 8, 9	4, 7, 9 1, 2, 3, 8, 10	3, 4, 7, 8 1, 2, 9, 10
Domestic	Consistent Non-consistent	1, 2, 3, 5, 6, 7, 9, 11 4, 8, 10	3, 4, 5, 11 1, 2, 6, 7, 8, 9, 10	— —
Manufacturing	Consistent Non-consistent	2, 3, 4, 5, 6, 9, 11 1, 7, 8, 10	2, 5, 6, 8, 9, 11 1, 3, 4, 7, 10	— —
Thermoelectric	Consistent Non-consistent	— 1, 8, 10	1 8, 10	— —
Livestock	Consistent Non-consistent	1, 4, 5, 6, 9 2, 3, 7, 8, 10	1, 2, 4, 5 6, 7, 8, 9, 10	— —
Local scale				
Municipal	Consistent non-consistent	Regina, Prince Albert, Moose Jaw Saskatoon	Saskatoon, Regina, Prince Albert, Moose Jaw —	Saskatoon, Regina, Prince Albert —

Note: Locations where non hydroclimatic extremes were identified during the period with available data or sectoral water withdrawal data was insufficient are denoted with a '—'. Global-scale locations correspond to IMAGE regions while country-scale locations to IUR regions (section 2.3). At a local-scale, comparison using Huang *et al* (2018) dataset was possible only with Saskatoon, Regina, Prince Albert and Moose Jaw cities.

3.2.2. US EIA—thermoelectric water use

Changes in responses in cooling water withdrawal were evaluated for thermoelectric power plants in continental US for drought, heatwaves and compound event compared to normal (non-extreme) periods (figure 7). Here the response patterns were analysed for power plants which were grouped by source of fuel and cooling system types.

The general response is an increase in cooling water withdrawals during heatwaves and compound events and a decrease during droughts (figure 7(a)). Locations where more cooling water is withdrawn, regardless of the type of event, are mainly on the eastern part the country, which is where the largest population densities are situated. Thermoelectric power plants using gas as source of fuel clearly increase the net electric generation (figure SI 11(b)) and thus water withdrawal during heatwaves and compound events in comparison to nuclear and coal fuel types which have lower efficiencies and therefore higher cooling water demands (figure 7(b)). Likewise, thermoelectric power plants with recirculating cooling systems present a larger increase in water withdrawal (figure 7(c)) compared to power plants with once-through cooling systems which show more (environmental) constraints in water use under heatwaves and compound events. This response is expected as recirculating cooling systems withdraw considerably less volumes of freshwater compared to once-through cooling systems and face less issues in terms of environmental constraints in cooling water use under high water temperatures during heatwaves and compound events (van Vliet *et al* 2016a).

Comparison of water withdrawal responses to extreme events obtained using Huang *et al* (2018) data and US EIA data shows a reasonable consistency (figure SI 12). Both datasets display an overall larger cooling water withdrawal during heatwaves and compound events. The US EIA reported dataset indicates an overall decrease of water withdrawals under droughts, which is not captured by the Huang *et al* (2018) data.

3.3. Local-scale analysis: domestic and manufacturing for large cities

The change in percentiles of water withdrawal to extreme events compared to normal (non-extreme) periods on city level (local-scale) for domestic and manufacturing sectors shows larger changes occurring during heatwaves and compound events compared to droughts (table 2). As municipal water use data was provided by water supplier organizations, no distinction was made between domestic and manufacturing water use, except for California.

In Melbourne, municipal (i.e. sum of domestic and manufacturing) water withdrawal decreases during droughts and compound events caused by the limited water resources available in this area (Melbourne Water 2017). Conversely, in Saskatchewan, there is an overall increase in water withdrawal regardless of the type of extreme event. This is mainly because water availability in Saskatchewan surpasses water demands (Pomeroy *et al* 2005), allowing larger water to use during extreme events.

In New York city there is a mixed response to extreme events whereas in California, where water is grouped by sector in domestic and manufacturing, there is a general increase in water withdrawal regardless of the extreme. Although, New York city and California have water capping policies for water shortage periods (State of California 2023), the difference in response could be explained by higher reliance on groundwater sources in California (Lund *et al* 2018).

Water withdrawal responses during extreme events were compared between reported model-assisted downscaled data (Huang *et al* 2018) and reported data in locations where both sources have information available (i.e. Saskatoon, Regina, Prince Albert and Moose Jaw). Huang *et al* (2018) data shows consistent responses for domestic sector compared to reported data for all types of extreme events, showing a slight decrease in water withdrawal during hydrological droughts and a clear increase during heatwaves and compound events.

Table 3 summarises the consistency in estimated water use responses during hydroclimatic extremes between reported data and model-assisted downscaled data (Huang *et al* 2018).

4. Discussion and conclusion

Although there is extensive research on global water scarcity including sectoral water use from local to global scales (Ward *et al* 2010, Wada *et al* 2014a, 2016, Jägermeyr *et al* 2015, Baldassarre *et al* 2018), little is known about the responses in sectoral water use under hydroclimatic extremes. This study provides a first step to evaluate multi-sectoral water use responses during droughts, heatwaves and compound events over the 1990–2019 period at multiple spatial scales (global, country (US) and local (city) levels).

Due to a lack of globally available water use information which are fully observation-driven, we used reported data downscaled using model-assisted methods (e.g. Huang *et al* 2018). Additionally, we used the limited reported water use data available to verify the consistency of the identified responses. This analysis, undertaken at global (AQUASTAT), country (USGS) and local levels, revealed that the consistency in responses derived from the Huang *et al* (2018) dataset with fully reported data differs between sectors and regions (table 3). Better correspondence in water use responses were identified for well-studied areas with highest availability of reported water use data (e.g. Europe, US—Mississippi river basin). In addition, water use responses obtained from local-scale data show a reasonable agreement with those derived from the reported model-assisted downscaled datasets (Huang *et al* 2018) in many locations and all sectors for which a comparison could be made (e.g. domestic, manufacturing, thermoelectric). This highlights the need of more accessible local to global-scale reported data of water use to better understand the implications of extreme events and climate change on different water use sectors.

Our overall results indicate that extreme events affect water use patterns differently per sector and region across the world. These differences are likely associated with various factors, such as population density, climate conditions, access to water supply systems, public water management plans or institutional regulatory policies, hampering the delineation of large regions with homogeneous water use responses. Nonetheless, technical and press reports, together with the limited scientific assessments existing, support our findings. For instance, an increase in domestic water use during droughts and heatwaves was reported for Australia after the ‘Millennium’ drought (ABC News 2009, Wells 2014, Scopelianos 2016, Press Australian Associated 2017, Seqwater 2019), as well as in Canada and Europe (e.g. Spain, Cyprus or Netherlands), particularly for heatwaves (European Environment Agency 2009, Santos 2019, Cleugh 2021). However, locations that experienced long drought events, like California (US), decreased their domestic water use due to lack of available water (Lund *et al* 2018). For the irrigation sector, temporary stronger increases in water use were found during heatwaves (Santos 2019), while longer-lasting events such as droughts lead to prolonged depletion of water sources and reduced water use (European Environment Agency 2009, Zhang *et al* 2022). For the thermoelectric sector, demands for cooling water increase while there is a general decrease in potential for cooling water use by power plants and thus a lower power generation during heatwaves and compound drought-heatwave events in various locations worldwide, such as Iran, US and Europe (e.g. Belgium, France, Switzerland). Particularly in Europe and the US, these constraints in cooling water use, are commonly driven by environmental legislation in cooling water use and a lack of available water resources (Bizaer 2018, FoodLog 2022, Saelens 2022) or exceeded water temperature limits (Rübbelke and Vögele 2011, Miara *et al* 2013, van Vliet *et al* 2016b). Nonetheless, the development of more efficient electric generation technologies leads in a continuous decrease of cooling water demands (U.S. Energy Information Administration 2021a).

Another potential driver is related to country-level public water management plans during extreme events, such as prioritization rules or institutional regulatory policies. For water prioritization, our global assessment using the reported model-assisted downscaled data of Huang *et al* (2018) is in accordance with scientific literature and technical reports (OECD 2015, EurEau 2020, Sousa Estácio *et al* 2022). National water prioritization schemes in various locations emphasize domestic sector as the priority sector, generally followed by agriculture (irrigation and livestock) (OECD 2015, EurEau 2020). Similarly, research focused on water prioritization during extreme events, although scarce, show a prioritization of the domestic sector, reducing the water availability for irrigation (Sousa Estácio *et al* 2022). Institutional regulatory policies of countries are expected to restrict the water use during extreme events due to environmental protection policies. This results in a reduction in water use during extreme events, in accordance with technical and press reports (DutchNews.nl. 2018, Harvey 2018, Santos 2019). However, country-scale particular measures during extreme events vary across the same region. For instance, Germany imposed water restrictions and fines for domestic water use (Santos 2019), while the Netherlands advised water saving practices for domestic water use during a major drought event (DutchNews.nl. 2018). Conversely, for irrigation sector, water withdrawal was banned in certain Dutch provinces (Limburg, Brabant, Gelderland, Overijssel, Drenthe), whereas in U.K. farmers were allowed to extract more water from the rivers during a heatwave event (Harvey 2018).

Extreme events not only affect the amount of water extracted but could also impact the source of water used. For instance, reports show that agricultural areas in the US rely more on groundwater when drought events occur (Lund *et al* 2018, Lowen 2022), for instance increasing its water use with 72% in California. Furthermore, the occurrence of longer-lasting heatwaves induces the use of desalinated water for irrigation (Lowen 2022).

Research focused on drought events in Africa show the critical dependence on groundwater of countries, such as Botswana, Namibia and Zimbabwe (Calow *et al* 2010). Moreover, locations like the East African Rift valley present an increase in groundwater use (i.e. 34%) during dry seasons due to the reduced available surface water (Thomas *et al* 2019). This also poses challenges under an increase in frequency, severity and coverage of droughts (Masih *et al* 2014) with an increasing reliance on hand-pumped and motorized boreholes in rural areas (MacAllister *et al* 2020) and the danger of shallow wells running dry as already reported in Ethiopia and Malawi (Calow *et al* 2010).

This study also demonstrates that heatwaves and compound events overall result in stronger impacts on water withdrawals (and consumption) in comparison to droughts for reported model-assisted downscaled data (Huang *et al* 2018) and most (local) reported data. This implies overall larger water use responses (either increase or decrease) under heatwaves and compound drought-heatwave events. Although water use responses derived from AQUASTAT reported data partially support this behaviour, the temporal aggregation of the data in both space and time attenuates the magnitude of the water use responses. Hence, more local-scale information from data-scarce regions is needed to verify sectoral water use behaviour.

Projections show that overall water demand will increase from 20% to 55% by 2050, implying an increase of approximately 40%–250%, 400% and 85%–140% for domestic, manufacturing and thermoelectric sectors respectively (OECD 2015, Wada *et al* 2016, Boretti and Rosa 2019). However, a drop in water use is also projected due to (seasonal) decrease in available water due to climate change (Boretti and Rosa 2019). Considering this expected increase in sectoral water demands together with the projected increase in frequency and intensity of hydroclimatic extremes events (Alizadeh *et al* 2020, Meehl and Tebaldi 2004, FAO & UN-Water 2021), a better understanding of sectoral water use responses under future droughts, heatwaves and compound events across the world is urgently needed. Our study highlights the need of more accessible water use data at finer temporal resolution, specially recorded during extreme hydroclimatic events in different regions of the world. Consequently, our results set the foundation for the development of a new global sectoral water use model that will allow more accurate quantifications of water use response and water scarcity during present and future projected droughts and heatwaves globally.

Data availability statements

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.8122382.

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