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Global river water quality under climate change and hydroclimatic extremes

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Supplementary information

Global river water quality under climate change and extremes

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1. Literature search

1.1 General literature search

We used the ISI Web of Science (WoS) database to search for relevant literature quantifying changes in each water quality constituent (water temperature, dissolved oxygen, algae, suspended sediment, salinity, nutrients, organic pollution (biochemical oxygen demand), microorganisms, metals, plastics and pharmaceuticals) under each investigated short-term hydroclimatic extreme (droughts, heatwaves, rainstorms/floods) and long-term climate change. We included all studies between the years 2000-2022. For each unique water quality constituent, a separate search string was developed, in accordance with the template below (Table 1). This template was used for all water quality constituents, by changing the search terms of search block number 1.

After each search string was conducted, the data extractor inspected the WoS search results, first by topic selections and included studies that were within the relevant fields for this study. Following this, the remaining articles were all extracted to excel, where they were first screened at the title and abstract level. For papers that were judged as relevant to this study based on the title and abstract, a full text review then followed and relevant data on river water quality responses were extracted.

Table 1. Illustration of search string blocks used in the Web of Science database to find relevant literature for each water quality constituent, here exemplified for pharmaceuticals.

No	Search string block
	Water quality constituent group: pharmaceuticals
1	((TS=(pharmaceutical* OR drug* OR steroid* OR antibiotic* OR analgesic* OR estrogen* OR hormon*))
	Water media: rivers/streams
2	TS=(river* OR "stream" OR "streams" OR "surface waters" OR ("surface water" NOT lake*) OR ("surface water" NOT wetland*)))
	Driver: climate change or extremes
3	TS=("climate change" OR "climate changes" OR "climatic change" OR "climatic changes" OR "hydroclimatic change" OR "hydroclimatic changes" OR "Extreme event" OR "extreme events" OR "extreme event" OR drought* OR flooding OR flood* OR heatwave* OR "climate change impacts")
	Combination of search string blocks[$]
4	1 AND 2 AND 3
	Limit to years: 2000-2022 (1st Nov)[#]

** = An asterisk represents any group of characters, including no character*

“ “ = Citation Marks searches for an exact phrase

[$]*<u>To combine the search strings:</u> we used the button “Add to query”, and the “And” term in between search string 1,2 and 3.*

[#]*<u>Filter on publication years</u> (left side column) to include only studies from 2000, until Nov 1st 2022.*

1.2 Full search string per water quality constituent

Water temperature:
((TS=("water temperature" OR "stream temperature" OR "river temperature")) AND TS=(river* OR "stream" OR "streams" OR "surface waters" OR ("surface water" NOT lake*) OR ("surface water" NOT wetland*))) AND TS=("climate change" OR "climate changes" OR "climatic change" OR "climatic changes" OR "hydroclimatic change" OR "hydroclimatic changes" OR "Extreme event" OR "extreme events" OR "extreme event" OR drought* OR flooding OR flood* OR heatwave* OR "climate change impacts")

Dissolved oxygen:
((TS=("Dissolved oxygen" OR "oxygen")) AND TS=(river* OR "stream" OR "streams" OR "surface waters" OR ("surface water" NOT lake*) OR ("surface water" NOT wetland*))) AND TS=("climate change" OR "climate changes" OR "climatic change" OR "climatic changes" OR "hydroclimatic change" OR "hydroclimatic changes" OR "Extreme event" OR "extreme events" OR "extreme event" OR drought* OR flooding OR flood* OR heatwave* OR "climate change impacts")

Algae:
((TS=("Algae" OR algal* OR "HAB" OR "harmful algal blooms" OR "Chlorophyll a")) AND TS=(river* OR "stream" OR "streams" OR "surface waters" OR ("surface water" NOT lake*) OR ("surface water" NOT wetland*))) AND TS=("climate change" OR "climate changes" OR "climatic change" OR "climatic changes" OR "hydroclimatic change" OR "hydroclimatic changes" OR "Extreme event" OR "extreme events" OR "extreme event" OR drought* OR flooding OR flood* OR heatwave* OR "climate change impacts")

Suspended sediment:
((TS=("suspended sediment concentration" OR "Suspended sediments" OR "total suspended solids" OR "TSS" OR "SSC")) AND TS=(river* OR "stream" OR "streams" OR "surface waters" OR ("surface water" NOT lake*) OR ("surface water" NOT wetland*))) AND TS=("climate change" OR "climate changes" OR "climatic change" OR "climatic changes" OR "hydroclimatic change" OR "hydroclimatic changes" OR "Extreme event" OR "extreme events" OR "extreme event" OR drought* OR flooding OR flood* OR heatwave* OR "climate change impacts")

Nutrients:
((TS=(nutrient* OR nitrogen OR phosphorus AND concentrat* OR load*)) AND TS=(river* OR "stream" OR "streams" OR "surface waters" OR ("surface water" NOT lake*) OR ("surface water" NOT wetland*) OR ("surface water" NOT estuar*))) AND TS=("climate change" OR "climate changes" OR "climatic change" OR "climatic changes" OR "hydroclimatic change" OR "hydroclimatic changes" OR "Extreme event" OR "extreme events" OR "extreme event" OR drought* OR flooding OR flood* OR heatwave* OR "climate change impacts")

Refining the search to the WoS categories (as these were the largest categories):
- only included the WoS category Environmental Sciences,

- and the Citation Topics Meso: Soil Science, Marine Biology, Climate Change, Water Resources, and Environmental Sciences.

Organic pollution - biochemical oxygen demand (BOD):
((TS=(“organic pollution” OR “biological oxygen demand” OR “biochemical oxygen demand" OR BOD)) AND TS=(river* OR "stream" OR "streams" OR "surface waters" OR ("surface water" NOT lake*) OR ("surface water" NOT wetland*) OR ("surface water" NOT estuar*))) AND TS=("climate change" OR "climate changes" OR "climatic change" OR "climatic changes" OR "hydroclimatic change" OR "hydroclimatic changes" OR "Extreme event" OR "extreme events" OR "extreme event" OR drought* OR flooding OR flood* OR heatwave* OR "climate change impacts")

Microorganisms:
((TS=(pathogen* OR bacteria OR virus* OR protozoa OR helminth OR feacal coliform* OR fecal coliform* OR enterococ*OR "E. coli" OR "Escherichia coli" OR adenovirus OR hepatitis OR norovirus OR caliovirus OR papillomavirus OR poliovirus OR enterovirus OR polyomavirus OR rotavirus OR astrovirus OR aeromonas OR arcobacter OR campylobacter OR shigella OR helicobacter OR leptosp* OR salmonella OR cholera* OR balantidium OR blastocyst* OR cyclospora OR cryptosporidium OR entamoeba OR toxoplasma OR giardia OR microsporidia OR diphyllobothriida* OR echinococcus OR taenia OR ascaris OR hookworm OR toxocara OR trichuris OR clonorchis OR opistorchis OR metorchis OR heterophyida* OR echinostomatida* OR paragonimus OR schistosoma OR microorganism* OR microbial AND concentrat* OR load*)) AND TS=(river* OR "stream" OR "streams" OR "surface waters" OR ("surface water" NOT lake*) OR ("surface water" NOT wetland*) OR ("surface water" NOT estuar*))) AND TS=("climate change" OR "climate changes" OR "climatic change" OR "climatic changes" OR "hydroclimatic change" OR "hydroclimatic changes" OR "Extreme event" OR "extreme events" OR "extreme event" OR drought* OR flooding OR flood* OR heatwave* OR "climate change impacts")

The list of microorganism names included in the search was based on the list provided in Rose and Jiménez-Cisneros (2019).[1]
TS=(concentrat* OR load*) was added to reduce the number of articles.
Refining the search to the WoS category (as this was the largest category):

- only included the WoS category Environmental Sciences

Metals:
((TS=(metalloid* OR "heavy metal" OR "heavy metals" OR "metalloids" OR "Mercury" OR "Lead" OR "Chromium" OR "Cadmium" OR "Arsenic" OR "Potentially Toxic Elements" OR "Potentially Toxic Element" OR "metals" OR "metal")) AND TS=(river* OR "stream" OR "streams" OR "surface waters" OR ("surface water" NOT lake*) OR ("surface water" NOT wetland*) OR ("surface water" NOT estuar*))) AND TS=("climate change" OR "climate changes" OR "climatic change" OR

[1] *Rose, J. , & Jimenez, B. ,. (2019). Sanitation and Disease in the 21st Century: Health and Microbiological Aspects of Excreta and Wastewater Management. Global Water Pathogen Project, Michigan State University. https://waterpathogens.org*

"climatic changes" OR "hydroclimatic change" OR "hydroclimatic changes" OR "Extreme event" OR "extreme events" OR "extreme event" OR drought* OR flooding OR flood* OR heatwave* OR "climate change impacts")

Plastics:
((TS=(*plastic* NOT "plasticity")) AND TS=(river* OR "stream" OR "streams" OR "surface waters" OR ("surface water" NOT lake*) OR ("surface water" NOT wetland*) OR ("surface water" NOT estuar*))) AND TS=("climate change" OR "climate changes" OR "climatic change" OR "climatic changes" OR "hydroclimatic change" OR "hydroclimatic changes" OR "Extreme event" OR "extreme events" OR "extreme event" OR drought* OR flooding OR flood* OR heatwave* OR "climate change impacts")

The search term in Web of Science (WoS):
(((TS=(river* OR "stream" OR "streams" OR "surface waters" OR ("surface water" NOT lake*) OR ("surface water" NOT wetland*))) AND TS=("climate change" OR "climate changes" OR "climatic change" OR "climatic changes" OR "hydroclimatic change" OR "hydroclimatic changes" OR "Extreme event" OR "extreme events" OR "extreme event" OR drought* OR flooding OR flood* OR heatwave* OR "climate change impacts")))
Refining the search to the WoS categories (as these were the largest categories):

- Environmental Sciences,
- Water Resources,
- Marine Freshwater Biology,
- Geosciences Multidisciplinary,
- and Ecology.

Pharmaceuticals:
((TS=(pharmaceutical* OR drug* OR steroid* OR antibiotic* OR analgesic* OR estrogen* OR hormon*)) AND TS=(river* OR "stream" OR "streams" OR "surface waters" OR ("surface water" NOT lake*) OR ("surface water" NOT wetland*))) AND TS=("climate change" OR "climate changes" OR "climatic change" OR "climatic changes" OR "hydroclimatic change" OR "hydroclimatic changes" OR "Extreme event" OR "extreme events" OR "extreme event" OR drought* OR flooding OR flood* OR heatwave* OR "climate change impacts")

2. Water temperature

2.1 Present state, hotspots and human drivers

River water temperature plays a crucial role in many physical, chemical, and biological processes and is therefore of major importance for aquatic ecosystems and sectoral water uses[1]. Changes in water temperature affect the rate of open water evaporation, formation of ice and solubility of gases. In addition water impacts growth rate and distribution of freshwater organisms [2]. Water temperature also strongly influences other water quality constituents by impacting the rate of chemical processes (e.g. denitrification)[3], dissolved oxygen saturation rates and concentrations[4–7], inactivation rate of microorganisms[8,9] and the decay transformation rates of chemical substances (e.g. pharmaceuticals)[10,11].

Spatial water temperature patterns and thermal regimes strongly correspond with climate zones and hydrological conditions[12]. In addition, anthropogenic influences, like thermal effluents from power plants [13–15], flow regulation and construction of reservoirs [16], and land use changes (e.g. urbanisation[17]) also affect water temperature. These anthropogenic influences vary considerably between catchments and river basins [1].

2.2 Long-term water temperature responses under climate change

Historical water temperature trends in relation to hydroclimatic drivers

Over the last decades to century, increasing trends in water temperatures are reported for rivers in North America[18,19], Europe[15,20] and Eurasian Arctic rivers[21,22], for which most long-term water temperature records are available. The general trend in water temperature increases in European freshwaters was 0.05-0.8°C decade^{-1} during the past 30-50 years. For rivers and streams in the United States, an increase in mean water temperature of 0.09-0.77°C decade^{-1} was observed during the 20th century[19]. Large-scale increasing trends have also been identified based on global-scale water temperature modelling, showing a global average water temperature increase of 0.16°C per decade over the 1960–2014 period[23].

Overall, observed changes in water temperature strongly relate to changes in air temperature, which largely reflect changes in the energy (heat) budget [24]. In addition, trends in river water temperature are also explained by changes in streamflow, which affect capacities for heat storage (thermal capacity) of the river course and, therefore, the sensitivities to changes in the energy budget [24]. For example, for the Danube an increase in water temperature was observed as a consequence of lower summer flow, resulting from earlier onset of the snowmelt period and decreased summer precipitation [25].

Water temperature trends in major rivers over the past century are thus a complex function of both climate and hydrological changes[15], but in addition human drivers such as the increase in heat effluents from power plants and industries, reservoir construction and land use changes (increased urbanisation) also contributed to long-term water temperature changes [13,16,17].

Future water temperature trends in relation to hydroclimatic drivers
Future river water temperature projections for the whole 21st century has been produced at (sub)river basin [26–28] to global scales[12,29]. These studies show overall increasing trends for the full range of climate scenarios considered and an intensification of thermal regimes with highest increases in high (summer) river temperatures. At the global level, largest water temperature increases are projected for the United States, Europe, eastern China and parts of southern Africa and Australia[12]. In these regions, the sensitivities are exacerbated by projected decreases in low flows (resulting in a reduced thermal capacity)[12].

2.3 Short-term surface water temperature processes under hydroclimatic extremes

Drought impacts on river water temperature
Hydrological droughts (extreme low flow) can contribute to increases in water temperature by reducing the capacities for heat storage (thermal capacity) of the river course and, therefore, increasing the sensitivities to atmospheric warming[30]. Several studies reported on water temperature increases under drought, e.g. for Sacramento river in the US ([31], Rhine and Meuse rivers in Europe [32–34], the Biobío River (Central Chile)[35]. Analyses of global water temperature monitoring data also showed the impact of decreases in discharge under drought on water temperature increases under summer periods[30].

Heatwave impacts on river water temperature
Climatic heatwaves can also translate to extreme heat events in river systems, strongly increasing water temperatures. For instance, Tassone et al.[36] found for US streams a doubling in the mean number of heatwave days per year from 1996 to 2021, with particular associations to summer and fall seasons, mid- to high-order streams, low discharge conditions, and position in the landscape relative to a reservoir.

Piccolroaz et al.[37] focused on quantifying the thermal response to the three most significant heatwave events that occurred in Central Europe since 1950 (July–August 2003, July 2006, and July 2015). They found that the thermal response of the analysed rivers depended strongly on the river hydrological regime, where low-land rivers were extremely sensitive to heatwaves. In contrast, high-altitude snow-fed rivers and regulated rivers receiving cold water from higher altitude hydropower reservoirs or diversions showed a damped thermal response under heatwave events [37].

Flood/rainstorm impacts on river water temperature
No study on impacts of floods or rainstorm on river water temperature were found in the literature review.

2.4 Potential impacts on sectoral uses and ecosystems

Increasing temperatures of river systems is a major global issue, with direct impacts for both aquatic ecosystem health and human water uses. Potential alterations in thermal river regimes due to climate change and increases in droughts and heatwaves may affect water quality [38], freshwater ecosystems and biodiversity [39–4142], and human water use functions like thermoelectric power production[43–45], drinking water production [46–48] and recreation (e.g. swimming water, fisheries). For most of these water uses, specific water temperature threshold values that reflect a deterioration or reduction in water usage potential are defined. For instance, for cooling water use, environmental standards are defined based on regulations to protect the freshwater ecosystems from thermal pollution (European Water Framework Directive and Fish Directive, and U.S. Clean Water Act).

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3. Dissolved oxygen

3.1 Present state, hotspots and human drivers

Dissolved oxygen (DO) is a vital parameter to measure the health of river's ecosystems. Low DO (hypoxia) and no DO (anoxia) conditions are detrimental to ecosystems with fish kills. Aerobic aquatic life, especially fauna, is put under stress when DO level drops below certain levels (e.g., 2 or 5 mg/L)[1–3]. In river systems, dissolved oxygen is sourced from aeration from the atmosphere due to wind and wave, and from photosynthesis by aquatic plants, which is strongly associated with climate variables such as wind speed, solar radiation, and temperature. Blaszczak et al.[4] found that water temperature is the most important predictor of stream DO concentration in the United States. Low DO levels can result from excessive inputs of organic waste loadings (e.g., from sewage effluents, erosion of organic-rich topsoils), which requires dissolved oxygen to decompose through aerobic biochemical actions[5]. Another main driver is the die-off and decomposition of algae that grow excessively due to anthropogenic inputs of nutrients from agriculture, intensive livestock production, urban runoff among others[5].

Contrasting from conventional belief that hypoxia mostly takes place in coastal water and lakes [1] and is rare in rivers, a recent study found that 12.6% of all locations across 53 countries suffer from infrequent riverine hypoxia (DO<2 mg/L)[4], despite that extended periods of hypoxia are rare in rivers. These are yet underestimated values due to sampling timing (daytime while lowest DO is typically before sunrise) and scarcity of measurement data from many regions, such as Africa. This widespread, short-term occurrence of hypoxia in rivers across the globe is concerning given its determinantal impacts on aquatic ecosystems.

3.2 Long-term water quality responses under climate change

We searched for articles that were published between 1 January 2000 and 1 November 2022 using Web of Science. In total 33 articles were selected for this review because of their relevance for climate-related impacts on DO in riverine systems. Of the 33 articles, 17 articles (about 51 %) report on the impacts of climate change (1 article focusing on historical trends and the rest focusing on the projected future trends), 10 articles (about 30 %) focusing on flood and or heavy rainfall related events and 10 articles focusing on drought events. Below, we elaborate separately on the impacts of climate change and climate extremes on DO in rivers.

Historical water quality trends in relation to hydroclimatic drivers

Only one of the reviewed articles focused on the impact of historical climate change on riverine DO concentration. A decreasing trend in instream DO was reported due to climate change, especially warming in summer months [6]. A 29% drop in DO was reported due to climate change at one site in US and this was mainly attributed to an increase in water temperature. However, large-scale long-term observations in the US showed no significant trend for hypoxia prevalence from 1950s to 2018 for the proportion of observations exhibiting hypoxia [4].

Future water quality trends in relation to hydroclimatic drivers

Future projections consistently reported a decrease of DO due to climate change across different world regions, including in Asia [7–10], North America [11–13], Europe [14–16] and Oceania [17] for a wide range of hypothetic and model-based climate scenarios and different time spans (e.g., 2050 and 2100). More significant reduction of DO is projected with stronger climate change scenarios and later periods[12,16]. The relative change ranges from less than 0.5% [17] to up to 35% [10]. In addition, for every 1°C increase in river water temperature, about 2.3% decrease in DO saturation concentrations was estimated over Indian catchments under climate signals[18]. In most cases, the changes are more pronounced in drier and warmer years or periods [7,11,12,14,16,19,20]. Since these periods are already characterised with low DO levels, additional more pronounced DO reductions can be detrimental to aquatic life. An exception was reported by Hosseini et al[13] that decrease in DO was less significant in summer but more during ice cover winter months.

Most of the studies attributed the DO decline to increasing water temperature. Increasing water temperature lowers oxygen saturation concentration [8,9,11,14,20] and oxygen solubility[19], increases decay rate of organic matter [14] and reduces rates of re-aeration from the atmosphere[7]. Meanwhile, several studies indicated that the reduction of streamflow can be an important factor leading to reduction in instream DO [14,15,17,20] and vice versa [13]. This is also attributed to lower reaeration rate due to lower water velocity and flow rate [13]. However, low flows in shallow reaches can increase re-aeration rates, which can partly compensate for the net effects on DO reduction [14].

However, it seems that for snowmelt-dominated basins and seasons, climate impacts on instream DO is more complex and less consistent compared with other climate regions. One of the reviewed studies projected an overall increase in DO due to climate change in Canada[21], predominantly in winter months. This was related to the projected decrease in air temperature and increase in river flows in these months. Although DO is projected to increase in most months, DO concentrations will decline in months where DO is relatively small, which is still a threat to aquatic life. In addition, small DO increases were found for the high-elevation subbasins in the southern Sierra Nevada[20] and in January in a Qu'Appelle River in Canada[13]. These again can be linked to the diffidence in climate change signals including increases in streamflow volume and decrease in air and stream temperature[13,20]. Overall, the change in flow is more impactful than other climate change indicators, particularly temperature under these climate conditions[13].

3.3 Short-term surface water quality processes under hydroclimatic extremes

Drought impacts on river water quality

Based on the results and mechanisms of climate change impacts on DO, one would expect that droughts lead to a decrease in DO concentrations due to higher water temperatures and lower river discharge (less dilution capacity). This was generally observed in the US [22–25], some rivers in Chile [26] and Europe [27,28] with ranges of 5%-23%. However, most of the decreasing trends were not statistically significant, because for large rivers with dynamic flowing water, DO remained relatively stable during droughts due to good re-aeration. Gomez-Gener et al.[28] also observed that reduction in oxygen concentrations was more pronounced in low-order streams draining headwater catchments during the 2018 drought in Europe. On the other hand, DO increased during historical droughts in three studies for multiple sites in the UK, US and Netherlands and different drought events by a slightly smaller magnitude (2.7%-15%). The growth of algae during droughts can make the DO dynamics more complex. Photosynthesis by overgrowing algae can cause supersaturation and makes DO concentration way beyond the saturated DO level in river in daytime [27]. The mixed response of DO during droughts was also reported in an earlier review by Mosley [29].

Heatwave impacts on river water quality

The capacity of water to dissolve and hold oxygen (saturated dissolved oxygen) reduces with increasing temperature. Higher temperature during heatwaves theoretically reduces DO concentration. No study was found that specifically investigated the impact of heatwave on instream DO. However, quite a few drought impact studies above referred to temperature increase as drivers for decreasing DO level, which indicates compounding effects of drought and heatwave to reducing riverine DO concentrations [22,24,30]. On average, DO concentrations decrease by approximately 1 mg/L with every 5 °C temperature rise. In addition, Rajesh and Rehana[18] estimated a 2.3% decrease in DO saturation concentrations for every 1 °C increase in river water temperature over Indian catchments under climate change. These are direct indicators that heatwave can lead to DO drop in rivers due to rising river water temperature.

Flood/rainstorm impacts on river water quality

A strong consistency was found for the decrease of DO level during and after flood events including hurricanes [31–39]. DO recovery around peak flow was observed in a small catchment during moderate storms, which was attributed to re-aeration due to high flow rate and velocity[37]. During flood events, the decrease was attributed to large supply of oxygen-depleted discharge[33,37]. Post-flood DO decline was attributed to the increased intensity of heterotrophic microbial activities (e.g., re-mineralization of organic matters, benthic respiration) both in the water column and sediment, resulting from enhanced riverine inputs of organic matters due to flushing [31,32,34,37,39] and sewage overflow [37]. In addition, floods strengthen and re-establish water exchange between the main river channel and surrounding floodplains that typically have lower DO level [35,40]. In extreme cases such as Hurricane Gustav, wind-driven resuspension of benthic sediment is another driver because it increases sediment oxygen demand. Additionally, high turbidity level during heavy rainfall events leads to lower light penetration and lower phytoplankton production relative to respiration, which temporarily shifts system productivity towards heterotrophy with less oxygen production [36,38]. A major problem may occur after heavy floods if a long-term drought or sequence of multiple droughts occurred beforehand. During droughts, large amounts of organic matters and nutrients, especially from forest and agricultural areas, are accumulated on land. Subsequent floods wash them off into rivers and readily deplete riverine dissolved oxygen [32].

3.4 Potential impacts on sectoral uses and ecosystems

Many aquatic species require a minimum dissolved oxygen level to survive. DO is therefore essential to maintain aquatic ecosystem and ecosystem services. This also includes the fishery and aquaculture sectors. Both drought and post-flood periods experience DO drops, which impacts productivity of the sectors, and in worst cases, leads to extensive fish mortality [36]. Hurricane Gustav in 2008 alone resulted in an estimated of 128 million fish kills throughout the Atchafalaya River Basin in south-central Louisiana, USA [36]. An estimated 5 million fish died in the Darling River between 2018-2019, mainly due to low dissolved oxygen during a hydrological drought[60]. Low DO levels, especially during climate extremes and coupled with excessive nutrient loading, promote the growth of harmful algal blooms[41]. Cyanobacterial algae blooms produce cyanotoxins in water[42], which poses a threat to water use for drinking, recreation, bathing and irrigation. The secondary impacts are therefore both in human health and economic losses.

3.5 References

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4. Algae

4.1 Present state, hotspots and human drivers

Algae is a natural part of freshwater ecosystems. However, human-driven nutrient enrichment (i.e., eutrophication) and favorable climate conditions promotes excessive algae growth, sometimes harmful algal blooms (HABs), causing undesirable disturbances to the ecosystems and undermining ecosystem services that human depends upon. *Chlorophyll-a* concentration is often used as an operational indicator of algae biomass to determine the trophic status of water bodies. Harmful algal blooms (HABs) have been a concern in the past decades and have been widely studied for lakes, estuaries, coastal areas, including potential responses to climate change[1–6]. Its assessment in river is however limited. Eutrophication of coastal ecosystems were found increasing globally in the past century due to human activities[7]. By 2010, among the 762 coastal areas with observed eutrophication and/or hypoxia, only 55 sites had an improving trend [8]. Similarly, it is widely perceived that HABs have been increasing in the last decades. However, Hallegraeff et al.[9] found no uniform global trend in the number of harmful algal events and their distribution over time from 1985 t0 2018. The authors concluded that intensified monitoring efforts are responsible for the perceived increase in harmful algae events. Six out of the 12 world regions showed statistically significant increases in HAB events, including East Coast USA/Canada, Greenland, Florida, Caribbean, Central America, Venezuela, West Coast USA/Canada, Alaska, Southeast Asia, Mediterranean and West/North Europe including Scandinavia. For future projections, a Special Report by United Nations' Intergovernmental Panel on Climate Change (IPCC) [10] concluded that “the occurrence of HABs, their toxicity and risk on natural and human systems are projected to continue to increase with warming and rising CO_2 in the 21st century”.

4.2 Long-term water quality responses under climate change

We searched for articles that were published between 1 January 2000 and 1 November 2022 using Web of Science. In total 27 articles were selected for this review because of their relevance for climate-related impacts on algae in riverine-dominated systems. Of the 27 articles, 11 articles report on drought events (41%), 9 articles (about 33 %) on the impacts of climate change (2 article focusing on historical trends and the rest focusing on the projected future trends), 9 articles (about 33 %) focusing on flood and or heavy rainfall related events and one on heatwave. Below, we elaborate separately on the impacts of climate change and climate extremes on algae in rivers. Noteworthily, the reviewed studies do not exclusively focus on riverine algae, due to the limited number of studies on riverine algae growth. Estuary, coastal and lagoons systems with strong riverine inputs and impacts are also considered and the review summaries below focus on the riverine rather than marine/brackish sites in these studies.

Historical water quality trends in relation to hydroclimatic drivers
Only one of the reviewed studies focuses on impact of historical climate change on river water quality, including algae. No long-term significant trend of *chlorophyll-a* concentration was found

in most of the 10 assessed river catchments in Czech Republic. However, the concentrations of *chlorophyll-a* were found very sensitive to increases in water temperature and decreases in river flow [11]. In most basins, *chlorophyll-a* concentration has a positive dependence on water temperature, while for the basins with high human influence, such dependence was not observed [11]. HAB frequency has increased along Chinese coasts at a rate of 40 ± 4% per decade, with earlier timing by 5.50 ± 1.78 days per decade[12] with elevated dissolved inorganic nutrient concentration and amplified further with regional warming.

Future water quality trends in relation to hydroclimatic drivers

Future projections mostly reported an increase of algae concentration in rivers, lagoons, and coastal areas due to climate change across different world regions, including Europe[13–16], North America [17], Asia [18] and Oceania [19] for a wide range of hypothetic and model-based climate scenarios and different time spans (e.g., 2050 and 2100). More significant increase in algae concentration and duration of elevated concentration is projected with stronger climate change scenarios [13,16–18] and in warmer months [13,15–17]. Only in scenarios with the most sustainable developments, reductions of algae concentration were reported[14] . A shift and lengthening of peak concentrations were observed towards later seasons [13,17]. Due to temperature rise, a shift of phytoplankton composition was projected towards favoring species that are more resilient to warmer temperatures, leading to increase of cyanobacteria and diatoms and disappearing of native diatom species[13]. Note that the reviewed studies here are mostly for the downstream part near the river outlet on the estuary and coastline. Quiel et al[15] found that there is an upstream shift for increased phytoplankton growth.

Main drivers underlying increasing algae concentration differ among basins and their climate characteristics. Some of the reported drivers include rising water temperatures due to air temperature increase [13,15,17–19], decreasing flows and high residence times due to decreasing precipitation [15,18,19] and increasing light availability due to either higher solar radiation or lower turbidity [14,15,18]. Longer residence time not only gives more time available for phytoplankton growth, but also results in lower turbidity that increase light availability for phytoplankton growth. On the other hand, projected increase in precipitation can lead to algae concentration increases. Wetter scenarios or future increasing precipitation increase river discharge, which brings in more nutrient loads and contribute to increasing in-bloom severity [16,17] . In at least two[15,17] out of the seven studies, climate change dominated effect on *chlorophyll-a* concentration with land use and other socio-economic changes playing a minimal role.

4.3 Short-term surface water quality processes under hydroclimatic extremes

Drought impacts on river water quality

The response is mixed for algae growth and *chlorophyll-a* concentration in rivers due to drought. More studies found increase in *chlorophyll-a* concentration in rivers [20–25]. This is especially the case for rivers with lower flow, because large rivers with less stagnant conditions are less favourable for algae growth, even during droughts [20]. In addition, during sustained drought conditions, algal blooms can be enhanced towards later phases of the droughts[24]. Similarly for harmful algal blooms, mean *microcystin* (a toxin produced by cyanobacteria) concentration was found seven times higher than that of a wet year [26]. The increase in HABs is driven by drought related conditions of elevated water temperature and long residence time due to low streamflow. Meanwhile, several studies also reported decrease of *chlorophyll-a* concentrations [20,21,25,27] or no trends [28,29] in responses to drought.

The mixed response is strongly associated with the complex mechanisms underlying algae growth in water bodies, involving multiple interacting physical, chemical and biological mechanisms, including nutrient loading and retention due to discharge change[27,29], algae growth and zooplankton grazing[25], flushing or residence time[21,25,29], light penetration due to turbidity change[25,27], temperature effect on biological activities[21,22,27,29], and physical dilution and concentration effects [22]. The relative importance for the mechanisms and factors depends on individual systems. For example, Geyer et al [25] attributed the positive correlation to increased light availability, longer residence time, and decreased grazing pressures allowing for more *chlorophyll* a biomass to accumulate during drought. Pereira et al.[27] found that *chlorophyll-a* concentration is statistically significantly correlated to turbidity, as well as water temperature, phosphate concentration, total dissolved phosphorus concentration, and dissolved silica concentration. However, a considerable amount of variability remains unexplained [22].

Heatwave impacts on river water quality
Limited studies focus on heatwave impacting on riverine algae concentration. One study[30] is therefore included investigating marine heatwaves to shed some light on potential impact for inland rivers. During the heatwaves in 2015 and 2019, reduction in river discharge (by 46-48%), its influence on the estuarine hydrodynamics and increase in water temperature (by 1-2 ℃) drove phytoplankton assemblage transition to brackish and marine phytoplankton species, especially HAB taxa (e.g., *Pseudo-nitzschia* spp. and *Gymnodinium catenatum*).

Flood/rainstorm impacts on river water quality
Similar to algae response to drought, algae response to floods are mixed and the responses tend to differ during and after the flood events. Liao et al[31] reported a *chlorophyll*-a increase of 130% before and during storm events due to water temperature increase by only 2%. Pepelnik et al[32] reported significantly higher *chlorophyll* a concentration one-year after the flood event instead of during or immediately after the event. The flood event remobilised large amounts of sediment and thus elevated loads of organic substances in the river. The algae bloom might have been triggered by this and the favourable conditions one year later (high water temperature, low water depth/flow, high solar radiation). Reyna et al.[33] reported sustained high levels of *chlorophyll* a both during and after the storm and prompted a shift in phytoplankton community composition towards cyanobacteria-dominated specifically *Cyanobium* spp. *Chlorophyll-a* concentration rapidly increased during three sequential hurricanes, from pre-storm levels of 5 to 10 ug/L [34]. Nitrogen inputs were attributed as the most probable controlling factor for this increase. The elevated *chlorophyll-a* concentration lasted for roughly 8 months and retuned back to pre-hurricane levels within a year. However, phytoplankton community compositional changes continued long beyond the time span of the climatic events. Data in de Cabo et al.[22] showed that

chlorophyll-a concentration in high-flow period was 38% higher than the normal discharge period.

A few studies reported decrease of *chlorophyll-a* during flood events, mostly due to flushing. Bukaveckas et al[35] found that increase in discharge in riverine segments reduce *chlorophyll-a* in high riverine discharge during flooding. Geyer et al[25] reported that tropical cyclones and subsequent increases in river discharge increased flushing and reduced light penetration, leading to reduced *chlorophyll* a in the Bay. In Hagy et al[36], *chlorophyll-a* initially decreased due to flushing during a hurricane. After a few days a phytoplankton bloom was stimulated with twofold greater *chlorophyll-a* concentration than before the hurricane. A reduction of *chlorophyll-a* concentration was found by Filippino et al[37] during Hurricane Irene. This was due to the wash-out of a dinoflagellate bloom that existed prior to the hurricane, leading to reduced *chlorophyll-a* immediately after the hurricane. However, a mixed diatom community merged afterwards, indicating a short-term shift of phytoplankton community after the hurricane.

4.4 Potential impacts on sectoral uses and ecosystems

Climate change, especially extreme events, can have profound impact on the phytoplankton community composition and therefore ecosystem functioning and services. Excessive algae growth produces unpleasure odour and appearance, undermining their drinking, recreational and touristic uses. The more extreme cases of HABs, due to the compounding effect of excessive nutrient loading and climate change, have long known to pose significant impact on public health, ecosystem health and biodiversity (e.g., fish kills and shifting phytoplankton community), fishery and aquaculture, recreation, and tourism[4,9,38]. HABs in lake, coastal and marine ecosystems are known to produce toxins[9,39]. These toxins are responsible for wild and aquaculture fish-kills, interfere with drinking, recreational uses of water and cause economic losses to fishery and aquaculture and tourism sectors. Although drinking water treatment facilities can remove a large fraction of toxins produced in HABs, the residual amount ends up in drinking water and impacting millions of people[39]. Cattle deaths from cyanobacterial toxins have been reported since 1878 and diarrhetic, amnesic and azaspiracid shellfish poisoning from dinoflagellates and diatom toxins are recently recognized[9]. In 2017, fish provided about 3.3 billion people with almost 20% of their average per capita intake of animal protein[40]. Long-term management to reduce and eliminate HABs is therefore essential to ensure future food security in this aspect.

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5. Suspended sediment

5.1 Present state, hotspots and human drivers

Suspended sediment conveyance in fluvial systems has critical implications for the functioning and resilience of aquatic ecological habitants [1], global biogeochemical cycles [2], nutrient transfers [3], global denudation cycle [4], river morpho-dynamics [5] and functioning of coastal and marine ecosystems [6]. Despite being an essential part of the river system, high levels of suspended sediment concentration in rivers constitute major water quality challenges, such as the transportation of sediment-bound pollutants [7], siltation [8] and disruption of river ecosystems [9]. Transport of suspended sediments in global riverine systems is a complex function of anthropogenic disturbances [10] (e.g. land use changes [11] and damming [12]) and shifts in weather patterns (e.g climate change [13] and extremes [14]). Recently, the global river suspended sediment flux to the ocean has drastically been reshaped with the dominant sources of suspended sediment shifting from Asia (driven by sediment retention in dammed reservoirs) to South America (driven by land use changes) [10, 15]. Considering global rivers with a drainage area > 20,000 km^2, the regional river suspended sediment concentration in the global south is on average 41 ± 7% greater than in the 1980s, mainly driven by land use changes that have increased soil loss due to water erosion [10]. However, the driving factors related to human activities and/or climate change for suspended sediments in small rivers at local scales could be different due to the buffering characteristics of large rivers [16].

5.2 Long-term water quality responses under climate change

We searched for articles that were published between 1 January 2000 and 1 November 2022 using Web of Science. In total 30 articles were selected for this review because of their relevance for climate-related impacts on suspended sediments in riverine systems. Of the 30 articles, 15 articles (about 50 %) report on the impacts of climate change (1 article focusing on historical trends and 14 articles focusing on the projected future trends), 14 articles (about 47 %) focusing on flood and or heavy rainfall related events and only one article focusing on drought events. The paltry of studies focusing on impacts of climate change on historical trends of suspended river sediments can mainly be attributed to the inadequate long term historical observational records of suspended sediments for most global rivers [17, 18], especially in tropical and subtropical regions [10]. Below, we elaborate separately on the impacts of climate change on suspended river sediments mainly focusing on future trends with examples.

Historical water quality trends in relation to hydroclimatic drivers

Globally, 40 % of the world's large rivers (drainage area ≥ 1000 km^2) are experiencing significant changes in suspended sediment fluxes especially declining trends in suspended sediment concentrations in Asia's large rivers and an increasing trend in the Amazon river [15]. Studies [10, 15] urge that climate change, mostly precipitation variation has not significantly contributed to the historical changes in suspended sediment fluxes of large rivers, with mostly human impacts causing these changes. For example, in the recent five to ten years, the global land-ocean sediment flux has decreased by 20.8 % with 13.2 % contributed by Asian rivers due to accelerated human disturbance of river sediments through dam constructions [15]. However, less large rivers show a significant correlation between historical temperature and suspended sediment fluxes [15]. Cohen et al. [19] also reports that intra-basin precipitation dynamics could explain most of the continental differences in suspended sediment and river discharge relationships.

Future water quality trends in relation to hydroclimatic drivers

Reviewed articles report both increasing and decreasing trends of suspended river sediments with projected climate change. Projected changes in air temperature and rainfall could have implications for riverine systems due to changes in hydromorphology and hydrological regimes [20], and hence, the mobility of suspended sediments due to water erosion and/or local resuspension of river sediment [21]. At a local scale, in Vietnam, suspended sediment concentrations are projected to increase in the rivers of the Mekong basin [22, 23] and in the upper Dong Nai river basin [24] under future scenarios of different RCPs (4.5 and 8.5). These projected increases were attributed to a wetter future in both river basins leading to an increase in river discharge. However, the projected increases in suspended sediment concentrations exceeded projected increases in river discharge suggesting that suspended sediments could have a stronger response to climate change than river discharge. In North America, different riverine systems are projected to have increases (e.g. Athabasca river [5], Des Plaines River [25], Esopus Creek [6], Broad Run [26], Sacramento River [27]) and decreases (e.g. Thornton, Mercer and Issaquah Creeks [28], Wolf Bay [29]) in future suspended sediment concentrations with the direction of change in projected suspended sediments following the direction of change in precipitation and river discharge. By end of the 21st century, climate change effects on fluvial discharges of Vouga and Antuã rivers in Portugal [30] and Koiliaris river in Greece [31] will induce a suspended sediment concentration decrease of 33 % and 54.5 % respectively, in response to the fluvial discharges cut back. In South Korea, five major river basins (Han, Nakdong, Geum, Seomjin, and Yeongsan) are projected to experience a reduction in suspended sediment under climate change projections until the near future (up to 2050) under RCP 4.5 and 8.5 scenarios [32].

At a global scale, suspended river sediment for large rivers is projected to increase in some parts of Africa, South and East Asia, high latitudes in the Northern Hemisphere, Northern Europe, most of North America, and some parts of South America due to changes in climate-induced present century natural discharge [18]. Contrary, Europe, Mediterranean regions, central Asia, some parts of North and South America and central regions of Africa will experience larger decreasing rates in suspended river sediments [18]. However, a global net increase is projected for suspended river sediments under RCP 2.6, 4.5, 6.0 and 8.5 scenarios, with increasing warming levels increasing the magnitudes and inter-annual variability of the suspended river sediments [18]. In contrast, Dunn et al. [33] reports that the majority of river deltas have been projected to experience a decline in the suspended sediment fluxes, mainly due to the anthropogenic activities (e.g. damming and changing land management practices) overwhelming the increases driven by climate change in the future. It is worth noting that, high uncertainties in the direction and magnitudes of changes in suspended sediments due to the different projections of climate change among different climate models [34] and the structure of different water quality models used have been reported[24,35]. Thus, the uncertainty should be considered in both suspended sediment management and climate change adaptation strategies.

5.3 Short-term surface water quality processes under hydroclimatic extremes

Drought impacts on river water quality

Based on the reviewed literature, there were limited studies on impacts of suspended river sediments under drought conditions (see section 2). Yet, important implications of drought on suspended sediment dynamics have been reported in Central Chile [36, 37]. The suspended sediment fluxes reduced between 28 % and 67 % during the Mega-drought period (2010 – 2017) as compared to the pre-drought period (1987 – 2009) in Itata river [37]. The decrease in suspended sediment discharge was attributed to a reduced fluvial capacity to transport sediment due to lower river discharge [38] during the drought period [37]. Additionally, the drought period induced a shift in the seasonality of maximum sediment discharge likely related to the deficit in rainfall that caused a longer time window for sediment routing to reach a minimum amount of accumulated rainfall and runoff to mobilise sediment [37]. If droughts persist in Chile [39] or other parts of the world [40], it is likely that low surface runoff and river discharge conditions will persist, resulting in reduced suspended sediment concentrations which could affect the functioning and resilience of aquatic ecological habitants.

Heatwave impacts on river water quality

No study has been identified in the reviewed literature focusing on heatwaves and suspended river sediments.

Flood/rainstorm impacts on river water quality

From the reviewed studies, flood events/heavy rainfall have led to both increases (e.g. Houay Xon river in Laos [42], Pahang river in Malaysia [43], Loushui river in China [8], Rewa river in Fiji [44], Laidley Creek in Australia [45], Tijuana river in Mexico [46], Rhone river in France [47], Goodwin Creek [48] and Niobrara river in USA [14]) and decreases in riverine suspended sediment concentrations e.g. in several watersheds of the USA [49, 50]. The upsurges in riverine suspended sediment concentrations reported were more than 50 % [8, 14, 42 - 48] as compared to the pre-flood periods while the reported declines in riverine suspended sediment concentrations were more than 36 % [49, 50]. Flood events may amplify the effects of land use changes or even cause high erosion rates leading to high export rates of suspended sediment in steep mountainous watersheds, without any disturbances over recent years [51, 52]. The timing and magnitude of high-load events of suspended sediments is strongly correlated with those of high-flow events [28] because suspended sediments respond to flushing more than dilution within a watershed [25, 53]. Hence, under flood/heavy rainfall conditions, small increases in discharge will mostly facilitate greater erosion, flushing and rapid increases in suspended sediment concentration. However, as sediment sources (e.g. runoff erosion, bank erosion or resuspension of deposited river sediments) are depleted, suspended sediment concentration will rapidly decline, often long before a drop in discharge [48]. Land use composition and slope are also important factors of suspended sediment concentrations in rivers. For example, having middle and high residential land in a watershed could potentially be better for mitigating high levels of suspended sediment loadings during heavy precipitation events [25].

5.4 Potential impacts on sectoral uses and ecosystems

Under natural conditions, all riverine systems carry some suspended sediment [54]. However, enhanced concentrations cause water deterioration by altering the chemical, physical and biological properties of rivers [55]. Literature has pointed out that certain pollutants (e.g metals [56], phosphorous nutrients [57], particulate organic carbon (POC) [58]) sometimes attach to suspended sediments. Hence, increases in suspended sediments may also contribute to the transportation of other non-point source pollutants, which degrades the river water quality resulting into higher costs of water treatment.

Additionally, suspended sediments with a high organic content may induce both direct and indirect sublethal stress on fish due to depletion of dissolved oxygen in water as a result of organic decomposition[55, 59].

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6. Salinity

6.1 Present state, hotspots and human drivers

Elevated salinity of freshwater resources is one of the most common global water quality issues, with impacts for both human water-use and ecosystem health[1,2] The issues of freshwater salinization have been well known for coastal and arid regions over multiple decades. More recently however, increasing examples of elevated salinity levels of rivers and streams in humid regions also occur. For instance, a recent study has shown that over 3 % of all river basin areas of the US are salinized [3] and that more than 200 (sub)river basins across the world, with different climate, experience increasing salinization trends over the 1980-2010 period[4]. The salinity of freshwaters can naturally vary, since salts originate from rock weathering of different mineral compositions. Although the main drivers of increasing freshwater salinization are often human activities, including irrigation, the use of deicing road salts and mining[4–7] , the problems are further aggravated by both long-term climatic changes, as well as short term hydroclimatic extremes[8,9].

6.2 Long-term water quality responses under climate change

Historical water quality trends in relation to hydroclimatic drivers

There are multiple processes impacting salinity under climate change, one of the main being evapo-concentration of salts, i.e. the enrichment of salt in shrinking water volumes [10]. Because many arid and semi-arid regions are projected to become even drier during continued climatic changes[11], salinity risks increasing significantly in these regions due to increasing water temperature and evapotranspiration[12]. Higher aridity may also cause lowering of streamflow levels, which limits the dilution capacity of salinity levels in rivers and streams. Such reductions of river runoff have been predicted to happen for major river basins around the world, including the Nile, Yangtze, Amazon and Congo[12]. Another well-known region with salinity problems is Australia, where high salinity levels of both soil and freshwater systems is a widespread issue. A main cause of salinization is here attributed to climate-driven rainfall reductions, causing land desiccation and soil salinization, which then can further spread to surface and groundwater systems.

Other long-term climatic change sea water level rise and intrusion in coastal areas will also w salinity levels next to hydrological changes[13]. Rising sea levels caused by global warming have been shown to increase saltwater intrusion plume lengths in rivers [14]. With sea level rise, the invasion of salt water may progress further upstream. Specific examples include the Mekong delta, where salt water intrusion lengths of up to 40km inland, causing salinity concentration to rise to levels greater than 4 g/l in upstream river branches (a critical threshold for rice yield impacts)[15]. Similarly, in the Indus River in Pakistan, saline water intrusion lengths of up to 65 km into the delta and main river branches have been reported[16].

Future water quality trends in relation to hydroclimatic drivers

Further salinisation of freshwaters in delta regions are expected to be further exacerbated by drought, lower rainfall and increasing sectoral water use and demand (e.g. for irrigation), which are all expected to become more present under future climate changes [2,17]. For example, climate-change induced sea level rise has been projected to, on average, increase salinity levels in the Mekong delta with up to 4500 µS cm^{-1}, adding 6 % to its salt affected coastal areas by 2040[18].

For inland regions, recent estimates suggest that the number of streams in the US with salinity thresholds exceeding irrigation water use thresholds (2000 µS cm^{-1}), will double by the year 2100, due to joint impacts of climate and land use changes[19]. Another study by Le et al. [20] predicted salinity levels across German rivers under climate change, using a machine learning approach. Their results suggest that salinity increases of up to 50 % may occur in multiple streams across Germany, in the period 2070 to 2100.

Overall, there are however limited studies that have projected future salinity levels of rivers and streams due to climate change for cross-regional inland regions. This knowledge gap also includes how climate-driven freshwater salinization interacts with other, human drivers of salinization, which almost solely have been researched in Europe, North America and Australia[21].

6.3 Short-term surface water quality processes under hydroclimatic extremes

Drought impacts on river water quality

The most well-known hydroclimatic extreme event which impacts salinity levels is drought[10]. Due to the processes of evapo-concentration and lowered dilution capacity, as described above, the impacts of drought events can substantially elevate salinity issues in rivers and streams. Drought impacts across multiple streams of the southern US have been seen to cause a 20% increase in median salinity levels[22]. A study from the Lower Murray River, in Australia, also highlights significant salinity increases at five river sites during a recorded extreme low flow period, resulting from droughts[23]. Another recent study from Iran, showed salinity levels of rivers to increase between 20-58%, under moderate to severe drought conditions, compared to non-drought conditions[24].

Salinity in delta and coastal regions are also particularly vulnerable to drought, with saline wedges from estuaries reaching inland river systems during periods of droughts [17,23]. The Mekong delta is one of the most studied regions in terms of drought and salinity issues. Here, multiple drought events have been shown to increase salt water intrusion lengths into the main river channels, with the recent 2020 drought reaching as far as 130 km upstream, which is further than any recent historical event [25]. Such impacts will likely become an increasing risk under future increasing drought conditions, not only for the Mekong delta.

Heatwave impacts on river water quality

No study on heatwave impacts on salinity was found in the literature using the search terms above.

Flood/rainstorm impacts on river water quality
In contrast to droughts, projected increases in extreme precipitation and flood intensity [26] may either cause a dilution of salinity levels in streams, or, bring more salt from land areas with runoff, into the hydrological system. These impacts are to a large degree governed by land-use practices [27]. Although flooding is most known for having a dilution effect on stream salinity levels, recent quantifications for 259 rivers across the US showed floods to cause salinity changes between 100 % decrease, but also up to 34 % increase (relative to long-term average levels). Additionally, studies have mentioned that increasing extreme precipitation events also increase the risks of dam embarkment flooding, which can cause flooding of nearby waters with saline water, if the stored water has high salinity levels [8].

6.4 Potential impacts on sectoral uses and ecosystems

Increases in river salinity levels have important impacts on aquatic ecosystems and multiple human sectoral water use including irrigation, domestic use and some manufacturing activities increasing salinity driven water scarcity[22,28,29]. In addition, drinking water with high salinity has been found to be associated with cardiovascular diseases (CVD), diarrhoea, and abdominal pain[30]. There is also a large body of literature reporting on impacts of high salinity on crop production. For instance in parts of Bangladesh, rise production reduced by
by up to 30% in the past 10-15 years with associated negative economic impacts, and these impacts are expected to worsen under future climate changes[31].

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7. Nutrients

7.1 Present state, hotspots and human drivers

Nutrients such as nitrogen (N) and phosphorus (P) are important for food security [1]. However, too many nutrients in the waters cause eutrophication-associated impacts. This includes blooms of harmful algae (e.g., cyanobacteria), hypoxia and fish kills [2,3]. Nutrient-associated eutrophication has been reported since the 1970s in many world regions including Europe, North America and Asia [4]. In the future, more pollution is especially expected in many African basins compared to today because of rapid increases in population [5]. The main human drivers of nutrient pollution are land-based activities such as agriculture (overuse of synthetic fertilisers and animal manure), sewage discharges, untreated human waste [5-7] and aquaculture [6]. Agriculture is often a diffuse source of nutrients in many global rivers [6]. Sewage systems are point sources of N and P in many rivers [8]. Globally, agriculture is considered an important cause of N pollution in rivers and sewage is an important cause of P pollution in rivers [9,10]. However, this differs largely among regions [6]. For example, the contribution of aquaculture to nutrient pollution is generally higher for basins draining into the Pacific Ocean [6]. For China, direct discharges of manure to rivers are important point sources of nutrients in rivers [11].

7.2 Long-term water quality responses under climate change

We searched for articles that were published between 1 January 2000 and 1 November 2022 using Web of Science. We identified 1592 articles from the search, of which 129 articles were selected for this review because of their relevance for climate-related impacts on nutrients in the water. Among those 129 articles, around 53% (69 articles) focus on historical trends (mostly observation-based), 40% focus on future trends (model-based) and the rest articles report both historical and future trends. Below, we elaborate separately on historical and future trends with examples.

Historical water quality trends in relation to hydroclimatic drivers

Reviewed articles report both increases and decreases in water quality levels for nutrients over the past decades. These trends depend on nutrient form, climate change-related impact, location and period. For example, Benítez-Gilabert, et al. [12] reported mainly an increase in water quality (NO_3, and soluble reactive P) for 15 Spanish catchments between 1973 and 2005 based on observations. They found that increases in concentrations of soluble reactive phosphorus in Eastern Spanish rivers are correlated with increased variability in air temperature. Positive correlations between increased air temperature and concentrations of NO_3 in rivers were also found for other catchments. Another example is the model-based study of Beusen, et al. [6] on historical trends in total N and P fluxes in global rivers between 1980-2015. Globally, increases of approximately 40% in total N and P export by rivers (Tg/year) are calculated between 1980 and 2015, but with variability among regions. For China and India, total N loadings per grid of 0.5˚ are modelled to increase largely between 1980 (1-5 Gg/year) and 2015 (over 10 Gg/year for many grids located in China). In contrast, the delivery of total N and P is modelled to decrease (approximately by 25-30%) for rivers draining into the Mediterranean and Black seas during 1980-2015. These trends are the net effect of changes in surface runoff (the major pathway of nutrient deliveries to rivers), temperature (influencing processes of nutrients in river systems) and human activities (determining the sources of nutrient pollution).

Future water quality trends in relation to hydroclimatic drivers

Reviewed articles report both increasing and decreasing projections for future nutrient pollution levels in waters as a result of climate change. The magnitude of these future trends varies considerably among rivers and depends on several aspects such as nutrient form, model, scenario, and period. Studies modelled long-term water quality projections (by 2100) for individual rivers [13,14,15], regions [16,17] and globe [6]. They cover total N and P loads [6,13-15,18-20] and concentrations [21,22-24] as well as dissolved inorganic (e.g., NO_3, NH_4) [19,23,25-28] and organic[28] forms. In general, more studies report future trends for total N and P compared to inorganic and organic forms. Studies focused on many catchments in the United Kingdom (total N and P concentrations by 2070 [21] and NO_3 and NH_4 by 2080 [25,26]), India (total P concentrations by 2090 [22]), Northern Italy (total P load by 2100 [13]), Finland (NO_3-N and total P concentrations by 2064 [23] and total N and P loads by 2100 [14]), Poland (N load by 2099 [15]), the USA (total N and P load by 2065 [29] and 2099 [16,17], NO_3 concentrations by 2100 [27]), Western Canada (total N and P by 2069 [30]), Indus river basin (dissolved inorganic and organic N and P loads by 2050 [28]), China (dissolved inorganic and organic N and P loads by 2050 [18], NO_3-N and NH_4-N loads by 2080 [19]), Central Ethiopia (NO_3 and total P loads by 2080 [20]), European Union countries (NO_3 and P concentrations by 2060 [24]) and globally (total N and P loads by 2050 [6]). Many studies focused on the combination of Shared Socio-economic Pathways (SSPs) with Representative Concentration Pathways (RCPs) that reflect the impact of climate change.

In general, increasing trends are reported for nutrient pollution under socioeconomic scenarios that are combined with high global warming (RCP8.5). For example, N concentrations in the Upper Themes (the United Kingdom) are projected to increase by 0.3 mg/l between the baseline (2009-2012) and 2050-2070 under SSP3-RCP8.5 [21]. However, a decreasing trend (0.7 mg/l) is projected under SSP2-RCP4.5, which assumes fewer variabilities in climate change compared to RCP8.5. Another example is for the Aura river catchment in southwest Finland [14] for which increasing trends in total N loads are projected under SSP3-RCP8.5 compared to decreasing trends under SSP2-RCP2.6 during 2070-2100. Likewise, China rivers are projected to export 52% more total dissolved N and 56% more total dissolved P by 2050 under SSP3-RCP8.5 [31]. Whitehead, et al. [26] reported a large range in increases (1-122%) of mean daily in-stream NO_3-N concentrations in the River Kennet (UK) in the future depending on location (upper, lower), scenario (A2, B2) and year (the 2050s, 2080s).

Depending on the region and its characteristics, the impacts of climate change on water quality may differ. For some regions, climate change is an important reason to explain future trends in nutrient pollution while for other regions the reasons are often the combination of both climate and socioeconomic drivers. For Example, for 12 Chinese rivers, river export of total dissolved N and total dissolved P (loads) is projected to increase by 24% and 16%, respectively in the year 2050 [31]. These percentages show the difference between the two scenarios with low (RCP2.6) and high (RCP8.5) climate change impacts. This indicates that Chinese rivers may become more polluted as a result of changes in river discharges associated with global warming (more runoff and thus more nutrient loadings). Sinha, et al. [17] projected a 20% increase in nitrogen in the US rivers as a result of increased precipitation in the future according to RCP8.5. In contrast, for Ethiopia, Bussi, et al. [20] reported a decreasing trend of 4-32% in NO_3 and P loads in the Upper Awash River between the baseline (1986 - 2016) and the future period (2031-2055). This future period is projected to have less runoff, but higher temperatures. It is expected to result in slightly decreased nutrient concentrations. However, the largest threat to the water quality of the Awash River is population growth, which is expected to increase nutrient loads by 15 to 20% (NO_3) and 30 to 40% (phosphorus) in the river by the second half of the 21st century. Wade, et al. [24] showed changes in stream water nitrate and phosphorus concentrations at each site of nine European catchments between the baseline (1981–2010) and future (2031–2060) periods due to climate change and land cover change. They concluded that the climate change effects alone were smaller for nutrient pollution compared to the effects of land use changes.

7.3 Short-term surface water quality processes under hydroclimatic extremes

Reviewed articles cover the impacts of climate change including floods, rainfall and/or extreme events, droughts, and wildfire events. Among 129 reviewed articles, 47% (60 articles) report the impact of climate change, 41% (53 articles) reflect specifically on the impact of floods, rainfall, and/or extreme events, 9% (12 articles) focus on droughts and wildfire events, and the remainder 3% (4 articles) reflect on both droughts and rainfall-associated impacts. Articles on climate change impacts focus on both historical (observation-based) and future (model-based) trends. Around half of them is about total N and P. Articles on the impacts of floods, rainfall, and/or extreme events are largely historically based on inorganic nutrients. Likewise, the focus of articles on the impacts of droughts and/or wildfire events is mainly on historical trends and largely on inorganic and/or organic nutrients. Below, we elaborate separately on the impacts of climate change, floods and droughts by giving examples.

Drought impacts on river water quality
Based on the reviewed articles, we can distinguish three main responses of nutrient pollution to droughts. First, droughts can lead to higher concentrations of nutrients in rivers [32]. The main mechanisms are associated with lower river flows leading to and thus higher nutrient concentrations. For example, the model-based study of Baccour, et al. [32] reported that drought events increase NO_3 concentrations by up to 63% because of decreased water availability by 42% at the mouth of the Ebro River.

Second, droughts can also lead to lower concentrations and/or loads of nutrients in waters [33,34]. The main mechanisms are associated with lower runoff from land (fewer nutrient loads), and longer water residence time (fewer nutrients in the water column). For example, the year 1988 was with the droughts in the lower Mississippi river resulting in a decrease of average annual NO_3

concentrations to 0.92 mg/l, which was the lowest observed value during the period of 1983-2000 [33]. In addition, the lowest concentrations of NO_3 were also measured in the year 2012 (0.22 mg/l in September) for this river [34]. This was attributed to the lower water depth and longer water residence times that may have increased instream N retention in both small headwater streams and larger tributaries.

Third, after the drought periods, river loads of nutrients can increase [35,36]. The main mechanism is associated with the soil memory effects of the basins. For example, Lee, et al. [35] analysed river loads of dissolved inorganic N for 118 basins worldwide. These basins were classified based on the soil memory effects: strong, weak, and no effects. Generally, 48 basins were with strong memory effects (e.g., Yellow, Rhine). For those basins, river-dissolved inorganic N loads were calculated to be higher by 43% (21-88%) after drought years than after the following average years. This is because dry years contribute to more N staying in the soil. Basins with high memory effects can accumulate more N because of less denitrification, N uptake, and leaching. At the end of the dry years, the soil has more N surpluses that are potentially available to reach rivers.

Heatwave impacts on river water quality

No papers in this review reported on impact of heatwaves on the concentration of nutrients.

Flood/rainstorm impacts on river water quality

In general, floods and extreme events can have short- and/or long-term[17,37,38] impacts on nutrient pollution [39]. Based on the reviewed articles, we can distinguish three main responses to nutrient pollution. First, nutrient loads to rivers can increase as a result of increased runoff from land [13,40-43]. Floods can bring more nutrients to rivers from fertilised soils[17] and sewage overflows [13]. More water on land can also increase nutrient mobilisation in soils leading to more leaching [44]. Due to extreme rainfall events, the water residence time is also lower leading to a lower potential for nutrients to be retained in soils and sediments and thus more nutrients in the water column. For example, total P loads in the Lambro River (Italy) are calculated to increase by 40% by 2100 as a result of a 20% increase in rainfall intensity [13]. N loads in the Yuqiao watershed (China) are calculated to increase by 3-4 times under the wet climate conditions compared to the dry climate conditions during the period of 1984-2013 [40]. A 400% increase in dissolved inorganic N loads is calculated for the North Jiulong River (southeastern China) due to extreme storm events in 2010 [42].

Second, nutrient concentrations in rivers can decrease as a result of floods[45]. The mechanisms are associated with different factors such as dilution effects and decreased mobilisation. For example, Chen, et al. [45] revealed that NO_3-N concentrations in the Niobrara River (USA) decreased by around 92% between the periods of 1990-2018 (pre-flood) and 2019-2020 (post-flood). The authors explained this trend for several reasons. One of them is that floods may have changed organic processes leading to decreased N mineralization or/and increased NO_3-N uptake (leading to less NO_3-N in river water). Another reason was the connection with the floodplain which may have higher denitrification due to floods (more denitrification means less N in rivers).

Third, floods and heavy rainfall events can be responsible for considerable amounts of the total nutrients in rivers [46,47]. For example, Bernal, et al. [47] reported that 75% of the annual N export in northeastern Spain was delivered during the stormflow of 2000-2001. Pan, et al. [46] reported relatively high linear correlations between annual precipitation and average river exports of NH_4 (0.60) NO_3 (0.62), and organic N (0.75) in several watersheds of the USA. This indicates the importance of precipitation for the interannual variability of these river exports.

7.4 Potential impacts on sectoral uses and ecosystems

Nutrient pollution can have impacts on human and ecosystem health. For human health, impacts are, for example, the blue baby syndrome [48,49]. People can be exposed to these impacts when drinking water that has too high nitrate concentrations. For ecosystems, this is eutrophication, hypoxia, and fish kills (see Section 1). Depending on the sector (e.g., drinking, aquatic system), nutrient thresholds vary among pollutants and also the country. Often, the thresholds are given as water quality standards.

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8. Organic pollution - biochemical oxygen demand (BOD):

8.1 Present state, hotspots and human drivers

Organic pollution is a good indicator of the state of a water body in general, but especially provides information on the status of treatment within a basin. A widely used indicator for organic pollution is Biochemical Oxygen Demand (BOD). According to this literature research hotspots of high BOD concentrations can be found in different countries on all continents of the world (except Australia, Greenland, and Antarctica). Some rivers, like the Soummam River in Algeria, transport high loads of BOD expressed by concentration levels well above 50 mg/l [1]. Comparable high values were measured in the Dareh Morad Beik River, Iran, during 2005-2006 [2]. The picture is mixed in Brazil, where BOD concentrations were measured above the national limit (5 mg/l). High or elevated values occur both during periods of low flow discharges and during the rainy season [3,4].
Untreated or not properly treated wastewater discharges from municipal and industrial sources are the dominant sources of BOD concentrations in rivers exceeding national thresholds [5,2,4, 6]. This becomes obvious when rivers flow through urban areas. In addition, BOD concentrations were also found to be high in agricultural areas indicating that agricultural practices cause water quality degradation in Brazil [7]. Dilution plays a key role in intra- and inter-annual variability of BOD concentrations in rivers, but river discharge is not always sufficient to reduce high loadings. This becomes obvious during low flow conditions [5,2]. Contrary to this result are CBOD dynamics measured in Athabasca River (Canada) where concentrations are high during spring freshet and storm events [8].

8.2 Long-term water quality responses under climate change

Historical water quality trends in relation to hydroclimatic drivers
Observations of BOD concentrations over 32 years (1977-2008) in the Middle Loire decreased progressively since 1987. The reduction is contrary to expectations from the observed locally reduced discharge and increased temperature. Moreover, improvements in wastewater treatment because of the EU Urban Wastewater Treatment Directive together with an increase of the number of households connected to sewers and treatment plants seem to have reduced BOD concentrations [9]. A decreasing trend in BOD concentration of about 50% was measured in the Cau River (Vietnam), but mainly related to anthropogenic changes rather than hydroclimatic drivers [10].

Future water quality trends in relation to hydroclimatic drivers
The importance of hydroclimatic drivers becomes obvious because rivers will lose the capacity to dilute BOD loads if river discharge decreases in the future. A modelling study analysed the impact of climate change on BOD concentrations of the Ali Efenti basin (Greece) for the 2050s based on input from two GCMs [11]. Overall, higher air temperatures and lower precipitation for both GCMs

result in a significant decrease of the average monthly river discharge of up to -46%. The lower dilution capacity of the river in turn leads to increased BOD concentrations (1%-18%) [11]. The outcomes of a modelling study of the Old Woman Creek (OWC) watershed in the U.S. (using SWAT) showed an increase in CBOD loads, particularly in fall. Model results based on CMIP5 climate data tend to show an increase in CBOD loading in the short- to long-term future. Here, changes in CBOD directly follow the intra-annual variability of simulated river discharge [12].

BOD is expected to increase in the Adyar River in India due to climate change and population growth [13]. The authors analysed the impact of climate change, according to the input of two GCMs (RCP4.5 and RCP8.5), and population growth until 2030. Their study revealed a further increase of BOD concentrations on average of 27% in the future of which about 13% can be attributed to climatic changes. Comparable results are found in another study for the Ciliwung River in Indonesia [14].

A scenario analysis was conducted by Nguyen et al. (2021) [15] to evaluate the future water quality in the Hau River in Vietnam in 2030. The model outcomes indicate an increase in BOD concentration without any measures in 2030 due to changes in climate, population, and industrial growth. However, BOD levels will increase by 16% in the wet season compared to 28% in the dry season, indicating the impact of low flow conditions.

Santy et al. (2020) [16] created hypothetical climate change scenarios to examine the impacts on water quality. Regarding BOD, an increase in temperature alone led to a reduction in BOD concentration whereas scenarios of increased temperature and reduced streamflow likely result in growing concentrations.

However, the influence of climate change does not necessarily lead to higher concentrations. The development of CBOD concentrations in the future were studied in the Athabasca River Basin (Alberta province, Canada) by Shrestha and Wang (2018) [8]. According to model results concentrations are expected to decrease in the mid- and long-term future under RCP4.5 and RCP8.5 scenarios due to higher biodegradation (driven by higher temperatures) and the higher dilution capacity of the river. It turned out that the dilution effect is more prominent in the higher emission scenario RCP8.5 and for the end-century period [8]. A decrease of BOD concentrations of 3.8%-10% is expected in the Anyangcheon River, Korea, under the A1B and A2 scenarios [17]. In addition to the influence of climate change, it could be shown that future urban developments will have a significantly higher influence on future concentrations. In contrast to the influence of climate change, urban changes under the A1B and A2 scenarios lead to a substantial increase in BOD concentrations. [17]

8.3 Short-term surface water quality processes under hydroclimatic extremes

Drought impacts on river water quality

BOD concentration measurements were analysed in 11 river basins in the Brazilian state of Ceará between 2009 and 2015, focusing on dry and wet seasons [3]. The study concluded that BOD increased in dry periods, i.e., at seasonal and interannual scales. Outliers in the time series occurred during a severe drought in 2014-2015 and may be attributed to the extreme hydroclimatic conditions. However, Piffer et al. (2022) [7] came to the same conclusion when observing substantial increases in BOD concentration in the 2014-2015 drought in southern and eastern portions of the state of São Paulo.

Heatwave impacts on river water quality

No papers in this review reported on impact of heatwaves on organic pollution or BOD concentrations.

Flood/rainstorm impacts on river water quality

In urban areas, BOD concentrations are high in the rainy season because higher discharge does not always lead to a dilution of pollutants below a threshold of 5 mg/l representing good conditions [3,4]. In the Athabasca River Basin in the Alberta province of Canada, CBOD values (up to 15 mg/l) are high during spring freshet and storm events while concentrations are below limits during low flow conditions [8]. The typhoon Morakot led to a huge flood in Taiwan in August 2009. Also affected was the Kaoping River Basin where high BOD concentrations were measured as a result of huge loads from hog farms and domestic wastewaters [18].

8.4 Potential impacts on sectoral uses and ecosystems

Zooplankton community attributes and composition were considerably affected by the runoff in agricultural areas carrying higher BOD loads [19].

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9. Microorganisms

9.1 Present state, hotspots and human drivers

Diarrhoeal diseases still are one of the main causes of death in children under five years of age. Unsafe water and sanitation are leading risk factors[1]. Main causes of diarrhoea included, for a study across seven countries in Asia and Africa, *Shigella*, rotavirus, adenovirus, heat-stable enterotoxin-producing *E. coli* (ST-ETEC), *Cryptosporidium* and *Campylobacter*[2], but many more pathogens exist and can be transmitted through water. Pathogens comprise viruses, bacteria, protozoans and helminths. Each pathogen has its own size and persistence in the environment. To understand concentrations in water and related health riskd, it is therefore important to consider different pathogens in assessments. Observational data on pathogens in rivers is sparse, even in areas of the world that are usually data rich. Faecal coliforms, *E. coli* and enterococci are often used as microbial indicators for pathogens. Data on these microbial indicator bacteria are more frequently available than pathogen data, because they are more easy and less expensive to measure than pathogens and because, for instance, to evaluate bathing water standards *E. coli* data are required. However, microbial indicator data do not paint the full picture and using *E. coli* data alone may lead to an underestimation of health problems[3].

Main sources of microorganisms include human faeces and / or animal manure. Many microorganisms are zoonotic, which means that they are spread from animals to humans and vice versa. Through different pathways, the microorganisms in the faeces and manure reach the rivers. Modelled data on microorganisms helps to understand microorganism hotspots and sources. For *Cryptosporidium* a global modelling analysis has been performed, and hotspots include densely populated areas across the world. Human sources are relatively more dominant than animal sources[4].

The way climate change influences microorganisms in rivers is explained in Hofstra[5], among others. Briefly, temperature increases are expected to increase the decay rate of microorganisms. Most waterborne microorganisms have not been found to grow outside the human or animal body and in particular not in flowing river water, but some bacteria may do in river sediment and in those cases increased temperatures may increase bacteria growth. The travel time of the microorganisms in the river will determine the relevance of the increased decay or growth. Changes in precipitation and discharge can influence microorganism concentrations in different ways. In some regions, increased precipitation and discharge can increase the runoff of faeces and manure off the land and thus increase the concentration in rivers. In other areas, increased precipitation can dilute the microorganisms in the rivers and therefore decrease the concentrations. Similarly, reduced precipitation and river flow can concentrate the microorganisms in rivers and consequently increase concentrations. Extreme events, in particular floods and droughts, can influence microorganism concentrations. Extreme events can lead to sewer overflows and increased resuspension of river sediments, which can both lead to increased concentrations[5]. Events have been regularly reported where, in particular, high precipitation events after a dry period first lead to increased concentrations of microorganisms (first flush) that later decrease[6].

Climate change can potentially influence microorganism concentrations in rivers through different mechanisms that are a lot harder to study. These mechanisms could directly and indirectly influence microorganism concentrations in rivers. For instance, microorganisms are living organisms that have the ability to adapt. This could have all sorts of consequences, including adaptation of the organism to survive longer in less favourable conditions. Such adaptations and their impact on concentrations in rivers are difficult to envisage. Additionally, new microorganisms could emerge when the climate changes. These mechanisms and relations were not the focus of this study.

We searched for articles that were published between 1 January 2000 and 1 November 2022 using Web of Science. We identified 485 articles from the search, of which 117 articles were selected after initial check of the abstract. After reading the full document, 63 studies were included in this review because of their relevance for climate-related impacts on microorganisms in the water. One article was added[7], because of known relevance. Among the 64 articles, around 70% (45 articles) focus on historical trends (mostly observation-based), 30% (19 articles) focus on future trends (model-based). One of the papers was a meta-analysis for the impacts of weather extremes and climate variables on *Cryptosporidium* and *Giardia* presence and concentration in surface water[8]. Among the 64 reviewed articles, 59% (38 articles) report the general impact of climate change, 41% (26 articles) reflect specifically on the impact of floods, rainfall, and/or extreme events, in many cases also related to preceding dry periods, 0% (0 articles) focus on droughts, wildfire events or heatwaves. Many articles provide information on several microorganisms. 43 of the 64 articles evaluate *E. coli*, 13 enterococci and 13 faecal coliforms, *Cryptosporidium* is evaluated in 9 articles, norovirus in 7, adenovirus and *Campylobacter* in 6, *Salmonella*, enterovirus and *Giardia* in 5, rotavirus and total coliforms in 4, somatic coliphages in 3, polyomavirus, leptospira, marker HF183 bacteroides and *Shigella* in 2, and the following microorganisms have been evaluated in 1 paper: enterobacteriacaea, thermotolerant coliforms, saprophytic bacteria, *Vibrio spp.*, *Vibrio cholerae*, faecal streptococci, hepatitis A and E virus, clostridia, human MST marker, GA17 bacteriophages, bifidobacterium molecular marker and aeromonas. While different microorganism groups (viruses, bacteria, protozoans, helminths) may respond to climate change differently, i.e. their persistence can be influenced differently, there is insufficient data to discuss results separately for these different groups.

Most studies come from developed nations (17 from Europe, 16 from North America and 6 from Oceania), although also a number of studies are available from Asia (16). Africa (2 studies) and South America (6) lag behind in studies on this topic.

9.2 Long-term water quality responses under climate change

Historical water quality trends in relation to hydroclimatic drivers
Long-term (30+ year) historical trends are not available for microorganisms, let alone long-term trends in relation to hydroclimatic variables. However, also through correlation analyses and analyses of seasonality the link between microorganism concentrations and hydroclimatic variables can be evaluated. Some, but not all, of these papers were found and included here.

In most studies a negative relation is found between water temperature and microorganism concentrations[9–12]. However, the result is not conclusive for all microorganisms. For instance, Rusinol *et al*.[11] find this negative relation for norovirus, but not the other virueses in their study and Schijven & de Roda Husman[10] find the negative relation for enteroviruses and *Giardia*, but find a positive relation for *Cryptosporidium*. A positive relation with water temperature is also found by others[13,14]. Ochirbold et al.[15] find no significant correlation with temperature.

Most studies find a positive relation between microorganisms concentrations and precipitation and/or discharge and/or runoff[9,12–14,16–26]. A positive link with precipitation, discharge or runoff can lead to high concentrations in different times of the year, depending on the hydrological cycle of the area. Reasons provided for this positive relation include increased disease incidence[20], increasing transport of contaminants by snowmelt and rainfall-induced runoff[18], Combined Sewer Overflows (CSOs)[12,24], and an increase in decay rates in the dry season[21]. Some papers see an indication for first flush[22], while others see prolonged high concentrations after rain events[23]. Several authors see a positive relation, but also note that river water contamination appears year round[24,26]. Two authors find higher viral concentrations in a dry year[27], and a negative relation with rainfall[28], and two authors find no relation with precipitation or discharge[11,29]. Several authors also list factors that have a stronger relation with microorganisms concentrations than precipitation, discharge or runoff, including urban development and population growth[12].

Other potential links with climate variables or impact are decreases found due to solar radiation, in this case during the day[17], and the observation that the presence of wildfire residues influences the concentration of microorganisms by reducing the growth and accelerating the die-off[30].

Unfortunately, a large number of articles that link microorganism concentrations to hydroclimatic variables through correlation or regression analysis were not found in the literature search, because they do not discuss climate or hydroclimatic change, but rather a relationship with weather variables and/or seasonality. However, many of these articles were summarised previously[31]. In this study 34 articles, 13 in temperate and 21 in (sub)tropical regions, were identified to statistically relate microorganism concentrations to hydroclimatic variables. Results were similar to the results from our literature review. All studies showed a positive correlation between microorganism concentrations and rainfall. In temperate regions almost all studies found a negative relation between microorganism concentrations and temperature. In (sub)tropical regions in most cases a positive relation is found instead. The positive relation in (sub)tropical regions can be explained by coinciding high temperatures and precipitation, in addition to some other explanatory factors including potential growth of faecal indicator bacteria in (sub)tropical regions[31].

Extrapolating these relations from our literature review and the correlations from Islam et al[31] between hydroclimatic variables and microorganisms to historical changes in the hydroclimatic variables, with an increase in temperature and strengthening of the hydrological cycle[32], would indicate that areas that have become warmer and drier would have experienced reduced microorganism concentrations, while areas that have become warmer and wetter would have experienced increased microorganism concentrations.

Future water quality trends in relation to hydroclimatic drivers

The future trends and scenario outputs and their mechanisms are very similar to those discussed for the historical situation. In different locations, seasons and wet or dry years these mechanisms play out differently and therefore we see increases[10,12,33–42] and decreases[10,33,35,37,42–44] in microorganism concentrations in rivers.

Projected changes in microorganism concentrations are in many cases small, i.e. some percent. Only increases or decreases of one order of magnitude or more (>90%) actually make a difference when evaluating exceedance of thresholds or health risks and we do not see such big changes in the collected data, unless other variables have been included in scenarios. So, frequently other variables have a much larger impact, such as socio-economic development, including population growth, urbanisation, sanitation improvements, wastewater treatment and improved manure management[40,42,44–46], the type and magnitude and management of contamination sources[34], or land use and management[37].

9.3 Short-term surface water quality processes under hydroclimatic extremes

Drought impacts on river water quality

No articles in the review studied drought impacts by themselves. However, dry periods are relevant, because they influence the impact of high flow or flood events. Many articles refer to this influence and are summarised under flood/heavy rainfall impacts.

Heatwave impacts on river water quality

No papers in this review reported impact of heatwaves on the concentration of microorganisms.

Flood/rainstorm impacts on river water quality

During floods frequently very high concentrations are reported[47–50], but these are not always linked to baseline conditions, and this makes it hard to evaluate the impact of these floods. However, many studies do see strong increases during floods compared to baseline concentrations[17,19,51–60]. These increases can be orders of magnitude increases. The increases are not always the same for all microorganisms and may depend on their mechanism. For instance, Stott et al[61] relate increases in *E. coli* to resuspension or other mobilisation of in-stream sources, while increases in *Campylobacter* occur slightly later and can be linked to wash-in from upstream sources. Also other studies see differences between indicators and human specific markers[62]. Also higher diversity in bacteria is found during flood events[39].

Many studies just report increases during floods, but some also report first flush effects, where concentrations decrease soon after the first occurrence of the flood[63], or sometimes decreases with increases in the height of the flood[29] or simply decreases after some time (weeks – months)[64–67] or after a series of floods[68]. After some time, wash off is not an important factor and dilution seems to play a stronger role. Several studies also determine increases in microorganism concentration during floods particularly after dry periods, potentially because of increased runoff of faecal material[14,69].

9.4 Potential impacts on sectoral uses and ecosystems

River water concentrations can lead to waterborne diseases through exposure, for instance after intake of water through drinking, during bathing, or when eating irrigated vegetables. The current search focused on river water concentrations and not on waterborne disease. However, some studies do link the concentrations in rivers to disease risk, for example through quantitative microbial risk assessment. Some simulate the required reduction in concentration for a specific purpose, such as drinking water. Others compare the river concentrations to thresholds for different purposes, such as bathing water guidelines. Gonzalez-Fernandez et al.[25] find that bathing water thresholds are exceeded in more than 85% of their river samples. Derx et al.[27] and Sterk et al.[33], for example, find that that there is increased risk and increased reductions are required for drinking water when the dilution capacity is low in dry periods, while Demeter et al.[34] find that there is no change in reduction targets when only climate and demography change in Austria. Schijven and de Roda Husman[10] add that the exposure to river water can increase with climate change due to increased recreation, which together with potential growth of pathogens can lead to an increased infection risk. Such analyses also lead to advice on exposure, such as not to go swimming after rainfall[19] or to limit exposure to flood water[55] and to a plea to include health risk in creating awareness about living with floods[70].

Additionally, another body of literature exists that summarises the impacts of climate change on waterborne diseases, taking into account risk factors through water exposure. Examples of studies in this body of literature and that were not included in our review are Levy et al.[71], who find a positive association between temperature and diarrhoeal disease, except for viral diarrhoea, and also an increase in diarrhoeal disease after extreme precipitation and flood events, or Kraay et al.[72], who see an increase in disease cases after extreme rain that followed a dry period. To get a complete overview of climate change impacts on diarrhoeal disease, such studies should also be incorporated.

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10. Metals

10.1 Present state, hotspots and human drivers

Pollution of river systems by heavy metals and metalloids is a major environmental issue due to their potential toxicity, biomagnification and accumulation in the river habitant [1, 2]. Heavy metals and metalloids are elements with an atomic density greater than 4 g cm^{-3} ref[3]. Of the several heavy metal and metalloids elements, the commonly documented and potentially toxic elements include; Cadmium (Cd), Chromium (Cr), Copper (Cu), Mercury (Hg), Nickel (Ni), Lead (Ld), Iron (Fe), Arsenic (As), Tin (Sn) and Zinc (Zn) [4], most of which are preferentially sediment-bound in aquatic ecosystems [5]. In recent decades, anthropogenic activities (e.g. increased industrial, domestic and agricultural wastes) and natural processes (e.g., soil erosion, atmospheric deposition, rock weathering) have gradually redistributed many heavy metals from the Earth's crust to the environment [6, 7], with heavy metal pollution in surface water changing from single metal pollution to mixed metal pollution [2]. From the 1970s to the 2010s, the main sources of heavy metal pollution have changed from mining and manufacturing to waste discharge and rock weathering, with heavy metal concentrations in global rivers currently higher in developing regions (Africa [8], Asia, and South America) than developed regions (Europe and North America) [2]. For instance, in Europe's Elbe River, Cd concentrations downstream decreased by 35 % from 1998 – 2016 [9] while in Africa's Niger River, Cd concentrations increased from 0.01 μg L^{-1} to 21.9 μg L^{-1} from the 1970s to 2010s [10, 11].

10.2 Long-term water quality responses under climate change

Climate change adds another dimension as an influencing factor in heavy metal pollution of rivers. Variations in rainfall have an impact on surface runoff and river discharge which in turn impact the transportation of heavy metal contaminants [12]. On the other hand, rising levels of temperature and CO_2 levels indirectly increase chemical weathering as a result of both temperature and lower pH [13], leading to release of metals in the earth crust and soils [14].
We searched for articles that were published between 1st January 2000 and 1st November 2022 using Web of Science. We identified 7,314 articles from the search, of which 27 articles were selected for this review because of their relevance for climate-related impacts on heavy metals and metalloids in riverine systems. Of the 27 articles, 6 articles (about 22 %) report on the impacts of climate change (2 articles focusing on historical trends and 4 articles focusing on the projected future trends), 17 articles (about 63 %) focusing on flood and or heavy rainfall related events and 4 articles (about 15 %) focusing on drought events.

Historical water quality trends in relation to hydroclimatic drivers
From the reviewed literature, there are strong relationships between heavy metal concentrations in rivers and climatic factors [14, 15]. In Gothenburg in Sweden, Frogner-Kockum et al. [14] reported a correlation between short-term increase in precipitation and an increase in metal contaminant (Cr, Cu, Pb, and Zn) transport in Göta Älv, Säveån and Mölndalsån Rivers within 1961 – 2010

period. The increased metal concentrations were attributed to the increased surface runoff and ground water levels from lasting rainy periods. In another catchment, Iordache et al. [15] also shows that the discrepancies in elemental concentrations (Pb, As, Cd, and Hg) between 2018 and 2019 in Olt river, Romania can be attributed to climate warming. With increased warming in southern Europe between 2018 – 2019 [16, 17], lower river discharge rates and higher temperatures during summer/autumn increased heavy metal levels by limiting the dilution efficiency of the river on the chemical loads [15].

Future water quality trends in relation to hydroclimatic drivers

Reviewed literature shows both increasing trends [18, 19] and decreasing trends [12, 20] of heavy metal pollution in rivers, with the change of trend strongly correlated with the changes in weather variables. For instance, Wijngaard et al. [19] report a projected increase in the order of 50 and 40 % in Zn and Cd concentrations respectively, in Dommel River with future climate (2090 – 2099), mainly attributed to accelerated surface runoff and leaching due to increased projected rainfall. For inflow rivers in Nizhnekamskoe reservoir in Russia, Motovilov and Fashchevskaya [18] report a projected mean increase of 5 % in Mn loads of Belaya river averaged over 7 years under a Delta Change (DC) climatic future scenario. On the contrary, Visser et al. [20] report a projected decrease of Cd and Zn concentrations in Keersop stream (tributary of Meuse River), attributed to lower discharge rates combined with lower groundwater levels from projected future drier conditions (2071 – 2100). Also in Myanmar, heavy metal loads (As, Hg and Fe) in Chindwin River are projected to decrease in a range of (-26 %) – 1770 % within the near (2010 – 2039), mid (2040 – 2069) and far (2070 – 2099) future scenarios [12]. The heavy metal decrease was strongly linked with a decreasing discharge trend following a projected decreasing rainfall regime. In general, future climate change impacts on heavy metal pollution are projected to be different in different riverine systems because of the differences in future climate scenarios for different parts of the world.

10.3 Short-term surface water quality processes under hydroclimatic extremes

Below, we elaborate separately on the impacts of different hydroclimatic extremes on heavy metal river concentrations with examples.

Drought impacts on river water quality

From the reviewed literature, both an increasing concentration[21-24] of heavy metals and metalloids during the drought periods, mainly attributed to lower water levels limiting the dilution effects of the rivers and a decreasing concentration [21] of mostly particle-reactive metals, mainly attributed to lower concentration of suspended solids during drought periods is reported. In Lithuanian rivers, droughts and fires led to an increase in concentrations of heavy metals (Fe, Cu, Zn, Cd, Ni, Mn, Hg, Pb) by changing the pH in the soils (pH values < 6), facilitating the migration from soil to groundwater and from river bottom sediments to the surface water [22]. In the Meuse River, drought periods of 1979 and 2003 led to increased concentrations of Selenium (Se), Barium (Ba) and Nickel (Ni) due to the reduced dilution of the chemical input (point source loading) while concentrations of Pb, Hg, Cr and Cd with a high proportion absorbed to suspended material decreased during the drought period due to lower concentration of suspended solids [21]. Metals with a moderately high partition coefficient property i.e., Cu, Zn and As had no distinct changes during the drought period since neither the effect of less dilution nor the effect of lower suspended solid concentration dictates [21]. Under the 2010 – 2015 unprecedented drought in Chile, Biobío River showed an increase in Cr, Fe and Co concentrations linked to increased evaporation from the river system, increased water residence times and increased interchange between water and sediments in groundwater [23]. Zwolsman and van Bokhoven [24] report a higher concentration of Cd, Cr, Cu, Hg, Ni, Pb and Zn during the 1976 and 2003 droughts in the Rhine River, mainly attributed to a decline in river discharge leading to limited river dilution of chemical loads. Additionally, the heavy metal pollution was higher in the 1976 drought when the river received more pollution loads than in the 2003 drought, signifying that droughts could have greater impacts on already poor water quality [24].

Heatwave impacts on river water quality

Compared to droughts and floods, research on the heat waves' impacts on heavy metal contamination in river systems is very limited and are not included in this literature review.

Flood/rainstorm impacts on river water quality

Reviewed literature shows increases [7, 26 - 34] and decreases [35 - 41] of heavy metal concentrations in different river systems during flood events. For instance; Pattelli et al. [7] reports an increase by an order of magnitude in the Hg concentrations in Paglia River, Italy after the November 2012 flood event indicating that floods prompted Hg mobilisation in the river basin rather than dilution. In the Czech Republic, an increase of heavy content (Cu, Ni, Pb and Zn) in Bílina River was reported after the 2013 flood event, which was attributed to the churning of river sediments as a result of the flood [27]. However, Čmelík et al. [27] further suggest that the effect of floods is only temporal and that anthropogenic pollution e.g. industrial discharge is more important than the flood impact due to a significant increase in anthropogenic heavy metal pollution observed after a longer period of time that was not accompanied by floods. In the Sava river, a tributary of the Danube river, perturbation of sediments during an extremely high river discharge event (September 2014) led to remobilisation and increase of heavy metals associated with particulate and organic matter [28]. For a historically mined catchment such as the Swale in the UK, severe flooding in the autumn of 2000 of River Swale led to elevated levels of Pb, Cd and Zn in the river due to the reworking of the metal-rich floodplain material [31]. This shows that flood events in the coming decades could lead to increased heavy metal contamination of river systems in historically mined catchments.

On the contrary, a flood event in February 1998 led to a decrease of Zn, Cd and Pb concentrations in Biała Przemsza River, Poland due to reworking and dilution of polluted sediments by sediments eroded from the channel bed of the main stream and its tributaries [35]. In Czech Republic, Nábělková et al. [36] report a decrease of heavy metal (Cu, Cr, Ni, Pb and Zn) concentrations in the Botic creek, a tributary of the Vltava River due to sediment remobilisation or mixing of contaminated sediment with less contaminated sediment transported during flood. Also, in India [41], the devastating effects of the August 2018 flood of Pampa River led to a reduced concentration of heavy metals (Cu, Zn, Cd, Pb and Mn), attributed to the dilution effect of the flood. Overall, during flood events, there may be either the dilution of sediment-associated heavy metal concentrations or the mobilisation of stored contaminated sediment, leading to either an increase or decrease in heavy metal concentrations. Additionally, an aspect that still needs to be further explored is the heavy metal mobilisation through surface water-groundwater interactions following flood or drought events.

10.4 Potential impacts on sectoral uses and ecosystems

The occurrence of heavy metals in drinking water beyond the permissible standard levels can cause human health hazards. For example, Ni, Hg and Cr are carcinogenic elements with Ni and Hg causing damage to DNA and Cr causing dermatitis and ulceration of the skin [42]. In the aquatic environment, heavy metals bioaccumulate with increasing trophic levels which could have detrimental effects on the river biota. Through the food chain, heavy metals could be hazardous to animal and human life e.g. recent studies acknowledged high mercury concentrations in Mediterranean fish [43]. Thus, changes in heavy metal concentrations during hydroclimatic extremes such as storms, snowmelt, floods, heatwaves, or drought can cause conditions that exceed thresholds of river ecosystem tolerance, leading to water-quality degradation.

10.5 References

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11. Plastics

11.1 Present state, hotspots and human drivers

Plastics are found in many compartments of the Earth's system including water in different sizes and forms [1]. Based on the size, plastics are often characterised as macro- (>5mm), micro (between 5 mm to 100 nm) and nanoplastics (<100 nm) [2]. Macroplastics in water result from various anthropogenic sources such as mismanaged solid waste [3], agricultural films [4], plastic packaging materials and bottles [5], which are often diffuse sources of water pollution. Microplastics in water result often from sewage systems, which are point sources of water pollution [6,7]. Sewage systems contain microplastics from car tyre wears, personal care products, household dust and laundry. Macroplastics can also be a diffuse source of micro- and nanoplastics in water because of their degradation into smaller particles [7]. The share of the anthropogenic sources in plastic water pollution varies among river basins depending on their socio-economic development and hydro-climatic characteristics. For example, microplastics are often reported in many river basins of Europe and North America mainly from sewage systems [8]. This is because the European and North American basins have large sewage connection rates [9]. Municipal solid waste is well-managed explaining lower amounts of macroplastics in those regions [3,10]. In contrast, macroplastics are largely found in many rivers in Asia, Africa and South America where the production of mismanaged solid water is high [3,11-13]. These regions are poorly developed compared to Europe and North America, which contributes to poor management of solid waste [3]. In addition to those water sources, the recent COVID-19 pandemic may also add plastics to water through national measures (e.g., an increased use of plastic bottles with disinfect and masks) [14,15].

11.2 Long-term water quality responses under climate change

Historical water quality trends in relation to hydroclimatic drivers

Historical long-term water quality responses under climate change are hardly reported for plastics based on the results of our literature review. We reviewed published articles between 1 January 2000 and 1 November 2022 using the Web of Science search. We identified 215 articles from the search, of which 12 articles were selected because of their relevance to climate-related impacts on plastics in the water. Among those articles, 11 articles reported observations of mainly microplastics in individual rivers in Brazil (Paraibo do Sul River [16]), France (River Têt [17], Rhone [17], Garonne [18], Seine [19]), Australia (Cooks River Estuary [20]), Russia (Northern Dvina River [21]), the Netherlands (Meuse River [22]), China (Three Gorges Dam [23] and the Yangtze basin [24]), and the USA (Mississippi River [25] and Santa Cruz River in Arizona [26]). Those observations are related to only floods or rainfall events and focus on their short-term impacts on (micro)plastic pollution.

Future water quality trends in relation to hydroclimatic drivers

Among our reviewed articles, only Roebroek, et al. [27] focused on model-based future trends in relation to floods as the hydroclimatic driver of plastics in global rivers. They analysed the relation between river discharges and plastic transport to identify the role of floods for plastics in rivers worldwide. The focus was on plastic mobilisation in the river system under flood conditions compared to the situation without floods with a 10-year return period. In general, Roebroek, et al. [27] reported an increase in plastic mobilisation due to floods. This implies that rivers may export more plastics because of floods. However, this increase differs per country and is reported as the relative increase with a 10-year return period flood. The ten top countries with the highest plastic mobilisation potential due to floods are China, India, Brazil, Thailand, Egypt, Philippines, Turkey, Congo, Nigeria and Vietnam. For these countries, a relative factor of increase in plastic mobilisation in rivers ranges from 2.16 (Congo) to 27.61 (Vietnam).

11.3 Short-term surface water quality processes under hydroclimatic extremes

All our 12 reviewed articles focus on the impact of floods and rainfall events mainly for microplastics in individual rivers (see Section 2 for references). However, we did not find articles reporting the impact of droughts or/and heatwaves on plastics in the water.

Drought impacts on river water quality
No papers in the review reported on observed or modelled impact of droughts on plastics.

Heatwave impacts on river water quality
No papers in the review reported on observed or modelled impact of heatwaves on plastics.

Flood/rainstorm impacts on river water quality
Most of our reviewed articles (8 out of 12) reported an increase in microplastics in rivers as a result of floods or rainfall events based on observations. This increase was reported for the following rivers: Paraibo do Sul (Brazil [16]), Rhone [17], Garonne [18], Seine [19] (France), Cooks (Australia [20]), Northern Dvina (Russia [21]), Meuse (the Netherlands [22]), and Three Gorges Dam reservoir (China [23]). The magnitude of the increase differs largely among those individual rivers and depends on the considered units (e.g., concentration or particles), location and frequency of water samples, and type of plastics. For example, da Costa, et al. [16] looked at the concentration of microplastics (particles per m^3) in low-water (June 2021) and high-water (February 2021) regimes for the Paraibo do Sul River in Brazil. They concluded that the abundance of microplastics in the river increased to 7-47 particles per m^3 depending on the location of the water samples. Xu, et al. [23] reported around a 60% increase in microplastics in the Three Gorges Dam (China) after one flooding event. van Emmerik, et al. [22] showed that during the Meuse floods of July 2021, the transport of macroplastics increased by a factor 4–6 compared to the yearly means. In contrast, decreases in microplastic particles per dm^3 are reported for most analysed sites of the Mississippi River Basin [25]. These decreases were calculated based on mean concentrations during flooding and post-flood events.

11.4 Potential impacts on sectoral uses and ecosystems

Water quality thresholds for plastics are not well defined [28]. Little is also known about the adverse impact of plastics in water on human and ecosystem health [28-30]. Human health risks associated with plastic pollution depend on exposure. Drinking water is one of the pathways to how humans may be exposed to microplastic pollution[31]. It is known that plastics have the potential to accumulate in the food web and have a toxic effect because of plastic-associated additives[30]. However, more scientific evidence is needed to determine the adverse impacts and the thresholds for macro, micro- and nanoplastics.

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12. Pharmaceuticals

12.1 Present state, hotspots and human drivers

Pharmaceuticals have recently been detected in surface waters across the world. Based on sampling campaigns and simulation models, the most contaminated countries are in Africa and Asia[1,2], mostly due to the lack of sanitation, low water availability, and large population numbers[3]. Urban wastewater discharges are the dominant sources of these contaminants, but discharges from industry, hospitals, and veterinary activities are also important, especially at the local scale[4].

In this report, the impact of climate change on the concentration of pharmaceuticals in rivers is reviewed based on existing literature. Extreme events related to climate change are known to influence flow patterns, which subsequently influence dilution capacities. Droughts cause low flow conditions that directly increase pharmaceutical concentrations. Floods caused by heavy rainfall induce temporary dilution, but they can also mobilise substances previously accumulated in sediments and surfaces during dry periods and cause combined sewer overflows. In future projections, climate change might not be the most influential factor, but the compounding effect of the increased dilution caused by expected low flows with population growth and increase in consumption of pharmaceuticals can lead to the increase of the concentration of these substances in rivers.

Changes of pharmaceutical concentrations due to climate change can have impacts on toxicity, antimicrobial resistance, and reproductive effects in aquatic organisms, humans, and animals.

12.2 Long-term water quality responses under climate change

Historical water quality trends in relation to hydroclimatic drivers

No study on the long-term responses of pharmaceutical concentrations under climate change was found in the literature using the search terms above.

Future water quality trends in relation to hydroclimatic drivers

Projections of pharmaceutical concentrations in surface waters under climate change combine scenarios of reduced flow, temperature increases, population growth, and consumption pattern changes for the year 2050. Green, et al. [5] estimated increases in average estrogen concentrations from 3.7 to 4.9 ng/L on the Erewash River in the United Kingdom and from 2.9 to 6.6 ng/L on the Onkaparinga River in Australia. Results from Sjerps, et al. [6] indicate that peak concentrations of pharmaceuticals could increase up to a factor of two to four in the rivers Rhine and Meuse in the Netherlands. Also for the Rhine River, Schlüsener, et al. [7] predicted an increase of 1.4 times the average concentrations of venlafaxine by 2100.

12.3 Short-term surface water quality processes under hydroclimatic extremes

Drought impacts on river water quality

Palma, et al. [8] found increased pharmaceutical concentrations in a drought year (2017) in comparison to a post-drought year (2018) at the Guadiana Basin, South of Portugal. Wolff and van Vliet [9] also detected increased pharmaceutical concentrations of carbamazepine (average of +10%) and metoprolol (+29%) during the 2018 drought in the rivers Rhine and Meuse. The increase occurred likely due to decreased dilution capacity under low flow conditions, although the changes were not statistically significant. In contrast, the less persistent pharmaceutical ibuprofen showed limited responses under the 2018 drought in the Rhine and Meuse rivers, which is probably due increased decay under higher water temperatures, which compensates for concentration increases driven by reduced dilution[9]. Concentrations of estrogens were measured atypically high in the Douro River Estuary in Portugal possibly due to drought conditions in December 2005 [10].

Heatwave impacts on river water quality

No study on heatwave impacts on pharmaceutical concentrations in rivers was found in the literature using the search terms above.

Flood/rainstorm impacts on river water quality

Concentrations of most analysed pharmaceuticals in the Llobregat River in Spain [11], in the Mess and the Pétrusse catchments in Luxembourg [12], and in the Xiangjiang River in China [13] decreased after flood events due to dilution.

After Hurricane Harvey in 2017 across Galveston Bay, Texas, high concentrations of pharmaceuticals were measured due to flooding. These concentrations decreased after four weeks due the increased dilution [14]. Similar effect was observed by Palma, et al. [8] and Tamtam, et al. [15], highest concentrations of pharmaceuticals in Alamos River (a temporary river in Portugal) and in the Seine river in France were measured after rainfalls, due to the resuspension of substances from sediments. Pailler, et al. [16] found that pharmaceutical concentrations are positively correlated to the number of days since the last flood event, indicating that the substances accumulate during dry periods and are flushed during the initial phase of a flood. The first flush event can also include sewer overflows from combined sewer systems [12].

Flood conditions did not cause significant changes of pharmaceutical concentrations in the South Saskatchewan River, Canada [17].

12.4 Potential impacts on sectoral uses and ecosystems

Increasing pharmaceutical concentrations in surface waters due to climate change can have toxicity, antimicrobial resistance and reproductive effects in aquatic organisms, humans, and animals. Keller, et al. [18] found that the risk of endocrine disruption in fish (e.g., feminization of male fish) due to steroid estrogens could increase by 9 to 11% in rivers in England and Wales by 2050. On the Onkaparinga River in Australia, the total length of the river downstream a

wastewater treatment plant is projected as “at risk” of endocrine disruption in wild fish by 2050 under all three scenarios analysed by Green, et al. [5].
Osorio, et al. [11] examined the behaviour of biofilms to detect the effects of disturbances (such as floods) on the ecosystem. They found that the bacterial compartment of river biofilms was affected by higher levels of antibiotics, i.e., rivers with higher concentrations of antibiotics (as in the first flush of a flood) showed an increase in bacteria mortality. Even if most projected concentrations of pharmaceuticals estimated by Sjerps, et al. [6] remained below thresholds for drinking water quality, some of these thresholds were exceeded in cases of drought periods.
In addition, Lin, et al. [13], Tamtam, et al. [15], and Basiuk, et al. [17] emphasised that continual exposure of the bacteria in aquatic ecosystems to even small concentrations of antibiotics could lead to the emergence and/or intensification of antimicrobial resistance.

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