nature reviews earth & environment

https://doi.org/10.1038/s43017-023-00472-3

Review article

Global river water quality under climate change and hydroclimatic extremes

Michelle T. H. van Vliet [1] ✉, **Josefin Thorslund** [1,2], **Maryna Strokal** [3], **Nynke Hofstra** [3], **Martina Flörke** [4], **Heloisa Ehalt Macedo** [5], **Albert Nkwasa** [6,7], **Ting Tang** [8], **Sujay S. Kaushal** [9], **Rohini Kumar** [10], **Ann van Griensven** [6], **Lex Bouwman** [11,12] & **Luke M. Mosley** [13]

Abstract

Climate change and extreme weather events (such as droughts, heatwaves, rainstorms and floods) pose serious challenges for water management, in terms of both water resources availability and water quality. However, the responses and mechanisms of river water quality under more frequent and intense hydroclimatic extremes are not well understood. In this Review, we assess the impacts of hydroclimatic extremes and multidecadal climate change on a wide range of water quality constituents to identify the key responses and driving mechanisms. Comparison of 965 case studies indicates that river water quality generally deteriorates under droughts and heatwaves (68% of compiled cases), rainstorms and floods (51%) and under long-term climate change (56%). Also improvements or mixed responses are reported owing to counteracting mechanisms, for example, increased pollutant mobilization versus dilution during flood events. River water quality responses under multidecadal climate change are driven by hydrological alterations, rises in water and soil temperatures and interactions among hydroclimatic, land use and human drivers. These complex interactions synergistically influence the sources, transport and transformation of all water quality constituents. Future research must target tools, techniques and models that support the design of robust water quality management strategies, in a world that is facing more frequent and severe hydroclimatic extremes.

Sections

A full list of affiliations appears at the end of the paper. ✉e-mail: m.t.h.vanvliet@uu.nl

Key points

- River water quality is generally deteriorating under droughts and heatwaves (68% of case studies), rainstorms and floods (51%) and multidecadal historical and future climate change (56%), although improvements and mixed responses are also reported.
- Droughts and heatwaves result in lower dissolved oxygen and increased river temperature, algae, salinity and concentrations of pollutants (such as pharmaceuticals) from point sources owing to lower dilution. By contrast, low flow during these events leads to reduced pollutant transport from agricultural and urban surface runoff, contributing to lower concentrations.
- Rainstorms and floods generally increase the mobilization of plastics, suspended solids, absorbed metals, nutrients and other pollutants from agricultural and urban runoff, although high flow can dilute concentrations for salinity and other dissolved pollutants. The sequence of extreme events (such as droughts followed by floods) also impacts the magnitude and drivers of river water quality responses.
- Multidecadal climate change is causing water temperatures and algae to generally increase, partly causing a general decrease in dissolved oxygen concentrations. Nutrient and pharmaceutical concentrations are mostly increasing under climate change, whereas biochemical oxygen demand, salinity, suspended sediment, metals and microorganisms show a mixture of increasing and decreasing trends.
- The main driving mechanisms for multidecadal water quality changes in response to climate change include hydrological alterations, rises in water and soil temperatures and interactions of hydroclimatic drivers with land use. These impacts are compounded with other human-induced drivers.
- Our findings stress the need to improve understanding of the complex hydroclimatic–geographic–human driver feedbacks; water quality constituent fate, transport, interactions and thresholds; and to develop technologies and water quality frameworks that support the design of robust water quality management strategies under increasing hydroclimatic extremes.

Introduction

Good water quality is vital for healthy ecosystems and safe human water use. Although no common definition for water quality exists, overall it refers to a measure of water composition in terms of its suitability for a particular function or use[1]. Water quality is determined by a large set of constituents (or parameters) representing the physical, biological and chemical aspects of water[2]. When water does not meet quality requirements, it can drive higher water scarcity for both human needs and ecosystems[3–5].

Hydroclimatic drivers (for example, precipitation, evapo(transpi) ration and runoff)[6,7], geographic factors (land use, geology and soil characteristics)[8,9] and human activities (sectoral water use, (un)treated wastewater and fertilizer use)[10–12] all impact river water quality (Fig. 1a). These drivers can be interrelated. For instance, warmer, drier climate conditions impact land use and can increase irrigation water use, which in turn might contribute to increased salinization in several river basins worldwide[9,13]. In addition, hydrological events can amplify contaminant pulses (large changes in concentrations over a short period) from land to rivers and impact the potential for water uses downstream[6]. Hence, there are complex water quantity and quality responses to climate change and weather extremes.

Water quality is also impacted by the interactions between different water types (rivers, lakes, reservoirs, soil and groundwater) and its propagation in time (legacy impacts)[14] and space (upstream versus downstream impacts)[15] within river basins. Furthermore, interactions exist between different water quality constituents[10], which further adds to the complexity (Fig. 1b). For instance, water temperature strongly influences other water quality constituents by impacting the rate of biochemical processes[16], algae growth[17,18], dissolved oxygen saturation[19–22] and decay of chemical substances[23,24] and microorganisms[25,26] in rivers. Algal blooms are also strongly driven by water temperature and the synergistic effects of nutrient supply[17,18]. In addition, higher temperatures and associated evaporation contribute to freshwater salinization[9,13], whereas salinity changes influence the growth of microorganisms[27] and metal contaminant mobilization from soil and sediment[28]. Microplastics have high absorption and carrying capacities[29] and can increase transport of other constituents such as metals[30], organic compounds[31] and antibiotics[32] (Fig. 1b).

Although weather extremes and climate change impacts on water quality are increasingly recognized, there is a stark contrast compared with the volume of research into impacts on water quantity (such as river discharge), as also highlighted in the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report[33]. Major droughts, heatwaves, rainstorms and floods have shown distinct challenges for both water quantity and quality management (drinking water, irrigation and ecosystems)[7], bringing these issues to the forefront of research attention. With climate change and the associated increase in hydroclimatic extremes[34–41], there is an urgent need to improve understanding of water quality responses and mechanisms to extreme weather events and over multidecadal climate change to support water management and decision-making. Although several reviews on this topic exist[6,42–44], there are limited systematic assessments of the impacts of climate change and extreme weather events on river water quality at regional-to-global scales.

In this Review, we synthesize advances on the main responses, mechanisms and interactions impacting river quality under hydroclimatic extremes (such as droughts, heatwaves, rainstorms and floods) and multidecadal historical and future climate change. We consider a wide range of water quality constituents, responses and mechanisms from a compilation of 965 literature case studies published between 2000 and 2022 (Box 1, Supplementary Note 1, Supplementary data). There is a deterioration in reported water quality under climate change and hydroclimatic extremes in most cases, although improvements and mixed responses are also reported. We identify regional-scale and global-scale knowledge gaps and give guidance for future water quality research to support robust water quality management strategies under changing climate and extremes.

Water quality responses to weather extremes

In this section, we briefly synthesize the main responses and driving mechanisms of river water quality under hydroclimatic extremes, including hydrological droughts, heatwaves, compound drought–heatwave events, rainstorms and floods. Additional supporting details for each water quality constituent are described in Supplementary Notes 2–12.

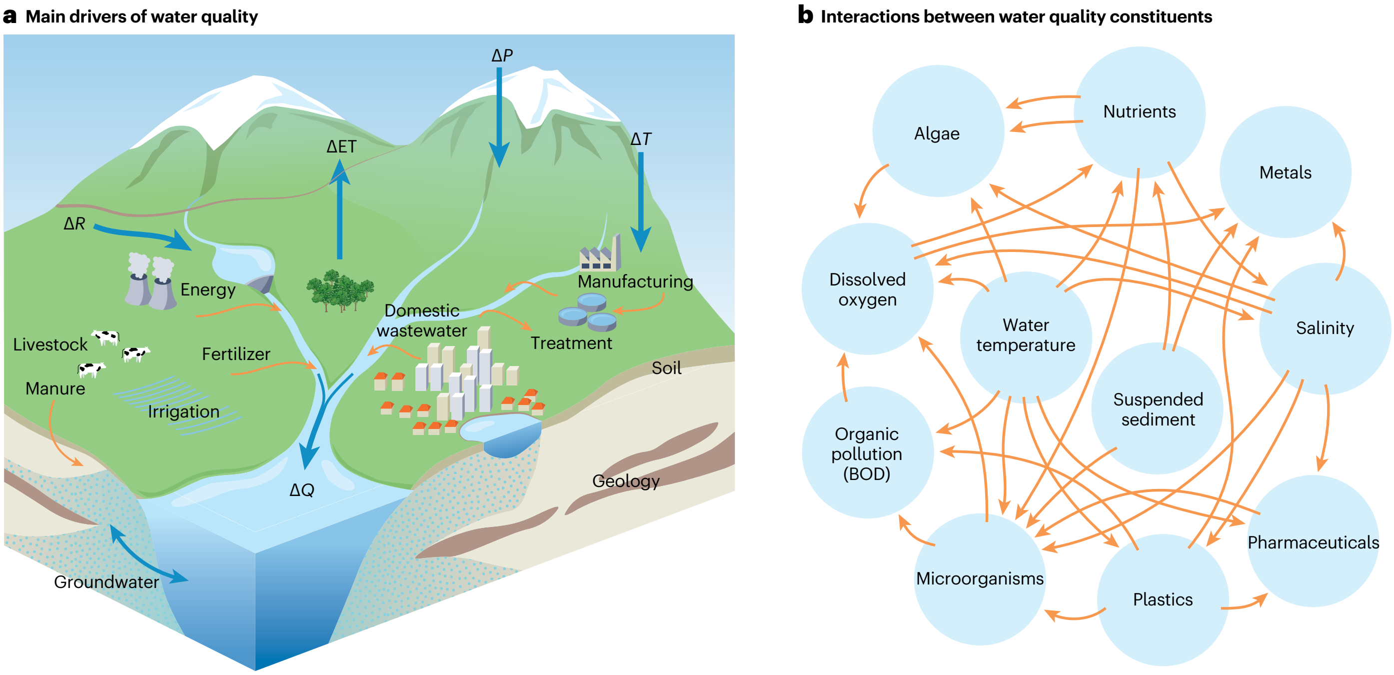


Fig. 1 | Hydroclimatic drivers, geographic factors and human activities impacting river water quality. a, Hydroclimatic drivers mainly include changes in precipitation (Δ*P*), temperature (Δ*T*), evapotranspiration (ΔET), surface runoff (Δ*R*) and discharge (Δ*Q*). Examples of geographic factors include geology, soil characteristics (including weathering products) and land use (urban versus rural). Examples of human activities include polluted wastewater flows from agriculture, domestic, manufacturing (including mining) and energy sector activities. **b**, Examples of the main interactions between different water quality constituents to highlight the complexity of water quality responses under changing climate and hydroclimatic extremes. Water temperature and suspended sediment have important impacts on many other water quality constituents, which in turn lead to other various interactions, for example, (micro)plastics impacting microorganisms, metals and pharmaceuticals. BOD, biochemical oxygen demand.

Hydrological droughts and heatwaves

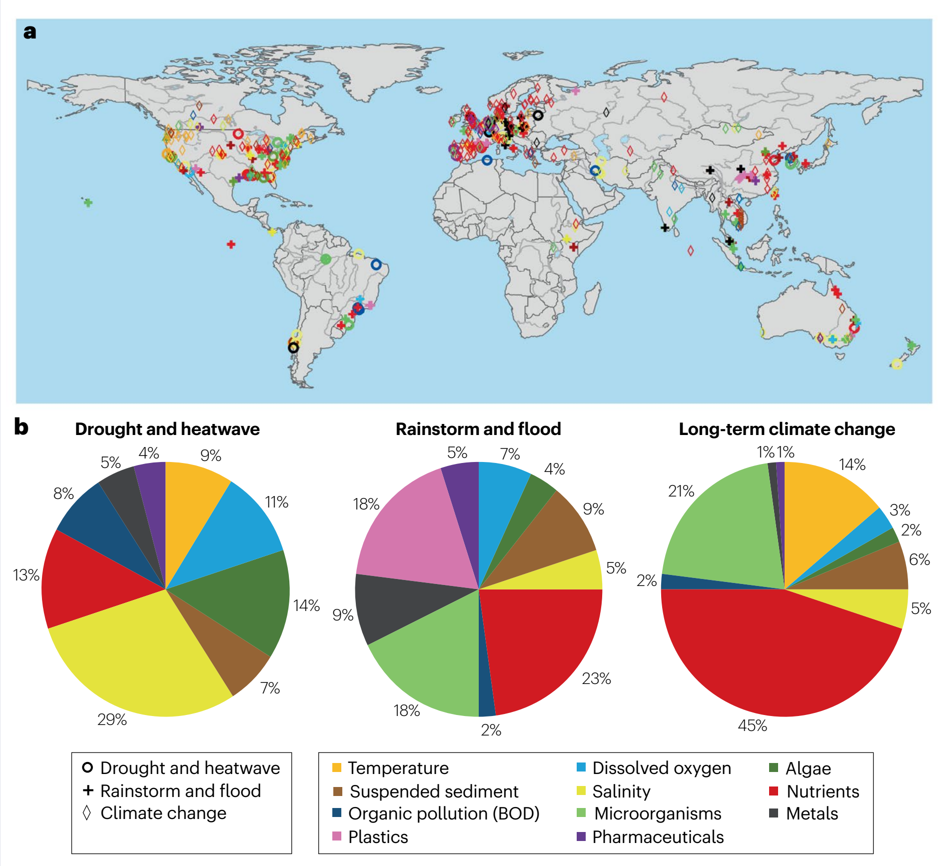
Hydrological droughts are prolonged periods of abnormally low river flows and/or water levels. Hydrological droughts are often but not always related to meteorological drought (extended periods of dryness or rainfall deficit) as they can also be induced by anthropogenic pressures such as excessive sectoral water withdrawals and diversion[45]. Hydrological droughts occur more frequently in polar, cold and temperate climate zones, where they are typically of moderate duration and severity[46]. By contrast, drought frequency is lower in arid and tropical regions, but these droughts are overall more prolonged and severe. Heatwaves are short-term (multiday) periods with excessively high temperatures relevant to the typical weather conditions in a particular location. The occurrence of severe heatwaves is expected to increase in several regions, particularly the arctic and tropical regions but also large parts of the temperate zone[47,48]. Climatic heatwaves can also translate to extreme heat events in rivers[49] and lakes[50], strongly increasing water temperatures.

A water quality deterioration was found for 68% of the case studies under droughts, heatwaves and compound drought–heatwave events (Fig. 2a). Water quality deterioration typically occurs in rivers receiving point source pollutant inputs (which are maintained during drought). Here, lower dilution capacities under low flow and continued point source inputs of pollutants result in higher concentrations[6,42,51]. Increased concentration levels have been reported for salts, pharmaceuticals and for some nutrients, metals (Fig. 2a) and other chemicals that are predominantly transported in dissolved phase (low adsorption to suspended sediment) in rivers and streams[23,24,42,51,52]. Next to lower dilution capacities, salinity levels also increase owing to increased evapo-concentration[42,53] or owing to a relative increase in the contribution of higher-saline groundwater flow under droughts[54]. Furthermore, in delta and estuarine regions, salinity levels also increase under lower flow owing to increased seawater intrusion as observed, for instance, in the Mekong (Asia), Rhine (Europe), Valdivia (South America), Euphrates and Tigris (Middle East)[55]. These salinity increases can also affect other water quality constituents and sectoral uses such as drinking water supply[56]. Increasing salinity levels in rivers during droughts can be substantial; for example, median increases of 21% are reported for rivers and streams in the southern USA[53]. This can result in exceeding salinity standards for irrigation water use as shown for a river in Texas as an example (Fig. 3a). When water quality standards are exceeded, this can increase quality-induced water scarcity, for instance, for municipal water supply[53], manufacturing uses and for irrigation, depending also on the salinity tolerances of crops[57].

Suspended sediment concentrations show mostly lower concentrations during droughts (Fig. 2a) owing to the reduced sediment erosion rates and lower transport capacity under low-flow conditions[58]. This can also lower concentrations of pollutants with high adsorption capacities to suspended sediment, for example, some metals[51]. In addition, droughts reduce the transport of contaminants from diffuse sources (for example, fertilizer and manure from agricultural land) to streams by leaching and runoff[6,42,44]. Nutrients and other water quality constituents can therefore be retained in the landscape

Box 1

Compilation of river water quality responses and their global distribution



The impacts of hydroclimatic extremes (droughts, heatwaves, rainstorms and floods) occurring on daily-to-monthly timescales and multidecadal historical and future climate change impacts on river quality were compiled from 965 published case studies. We define 'case studies' as locations (for example, monitoring stations or (sub)basins) or events or time periods (years) for which water quality responses under climate change or extremes are reported in the literature. River water quality responses, in terms of concentrations and water temperature, were compiled for a set of 11 major water quality constituents (see the figure). We reviewed literature using the ISI Web of Sciences database for 2000–2022 using a consistent selection of search terms for defining climate change and hydroclimatic extremes combined with various terms specifying different water quality constituents, which resulted in 389 scientific publications (details provided in Supplementary Note 1). The majority of water quality constituent responses were reported through changes in concentration, excluding water temperature. Impacts on pollution loads and river export are covered for only some water quality constituents, namely, for nutrients, suspended sediment and microorganisms.

Collected responses in water quality (concentrations) mainly focus on multidecadal impacts from climate change (70%, *n*=680), which are mostly (process-based) modelling studies for historic and future periods (up to the year 2100). For the extreme weather events, most case studies report concentration impacts derived from in situ monitoring data focusing on rainstorms and floods (18%, *n*=180), followed by droughts and heatwaves (11%, *n*=105). Although some case studies focused on solely heatwaves, the majority of case studies in the compilation consider compound events, which are the concurrence of both drought and heatwave. Global spatial patterns clearly show that the highest number of reported river water quality impacts was from North America and Europe (see the figure, part **a**). This spatial pattern strongly corresponds with the distribution of observed water quality monitoring data in the world[12] and should be considered in the interpretation of the results.

For droughts, heatwaves and compound drought–heatwave events, the majority of the compiled case studies reported changes in salinity (29%), followed by algae, nutrients, dissolved oxygen and water temperature. For rainstorms and/or floods, a diverse set of water quality constituents are reported, dominated by nutrients (23%), plastics and microorganisms. For long-term climate change, most cases focused on water quality model projections dominated by nutrients (45%), microorganisms (21%) and water temperature (14%) (see the figure, part **b**).

during drought[59]. This can temporarily decrease pollutant mobilization and delivery and concentrations in streams and rivers[42]. Although groundwater inputs of nutrients, salt and bedrock-derived constituents might remain similar during drought in absolute terms[60,61], their relative influence on surface water quality might increase when surface runoff is low[59,62,63]. In most cases, a larger relative groundwater contribution results in better water quality; however, in areas with, for example, nutrient-rich or saline groundwater, the river water quality can deteriorate. Overall mixed or no marked responses in nutrient concentrations under droughts are reported (Fig. 2a) owing to the combination of limited dilution, reduced delivery from diffuse sources, enhanced retention owing to longer residence time and changes in water temperature impacting biochemical process rates[64].

Hydrological droughts, particularly when combined with heatwaves (compound events), can create favourable conditions for the development of algal blooms (increased chlorophyll *a* concentrations) owing to higher water temperatures, increased stratification and longer water residence times, impairing the water quality under low flow[42,51,65] (Fig. 2a). Dissolved oxygen can become depleted in the bottom waters under these conditions owing to water and sediment oxygen demand for organic matter mineralization and limited resupply from the atmosphere (low re-aeration). Dissolved oxygen concentrations are also strongly controlled by temperature with approximately $1\ \mathrm{mg\ l^{-1}}$ decrease with every 5 °C temperature rise[66]. If accompanied by additional oxygen-consuming biochemical reactions, rise of water temperature can result in hypoxia or even anoxia[67]. This can result in strong reductions, particularly in daily minimum dissolved oxygen concentrations during a heatwave, with values below the ecological threshold as found, for instance, in the Meuse River (western Europe) (Fig. 3b). Strong reductions in dissolved oxygen concentrations with, for instance, minimum values decreasing to $<2\ \mathrm{mg\ l^{-1}}$ can result in fish kills and have detrimental impacts on aquatic ecosystems[68]. Decreased dissolved oxygen concentrations under high water temperatures and low flow are found for several rivers, particularly when organic pollutant levels are high[19–22], whereas some studies report increased dissolved oxygen with peak concentrations (supersaturation) owing to strong photosynthesis from algal bloom[42,51] (Fig. 2a). Next from water temperature rises, lower flow under drought can also promote lower dissolved oxygen just via decreasing water velocity and reaeration and reduced upstream dissolved oxygen replenishment[69]. For instance, an estimated 5 million fish died in the Darling River between 2018 and 2019, mainly owing to low dissolved oxygen during a hydrological drought[70].

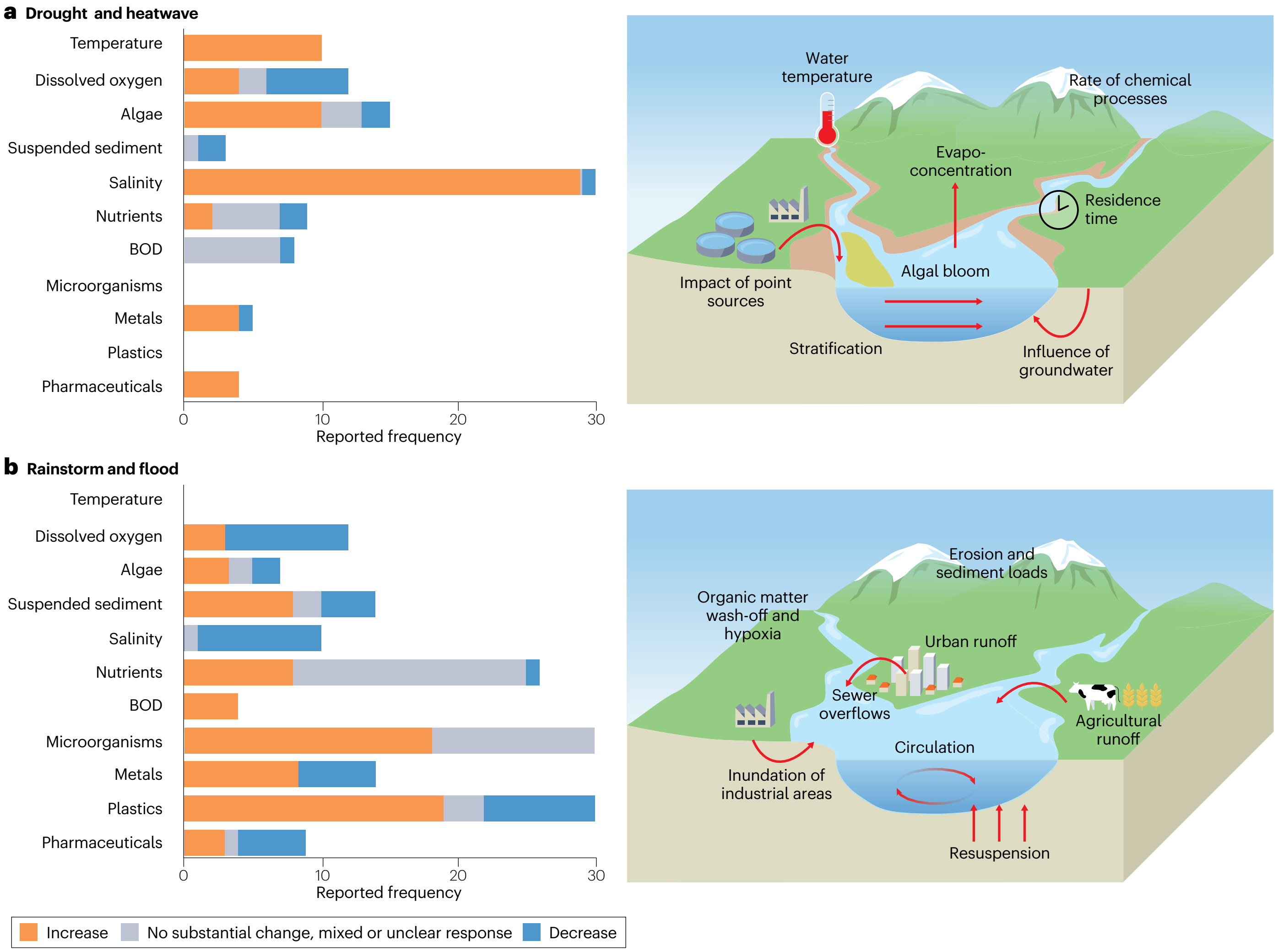


Fig. 2 | Responses and mechanisms impacting river water quality. The two left-hand plots show the reported frequency of responses in water quality on the basis of the compilation of literature case studies (Supplementary Data): during droughts, heatwaves and compound events (part **a**) and under rainstorms and floods (part **b**). An increase in a water quality constituent is shown in orange, a decrease is shown in blue and no marked change, mixed or unclear responses are in grey. Focus is on case studies that reported concentration responses (except for water temperature). The schematic diagrams show a selection of key processes and main driving mechanisms that impact river water quality during hydroclimatic extremes. BOD, biochemical oxygen demand.

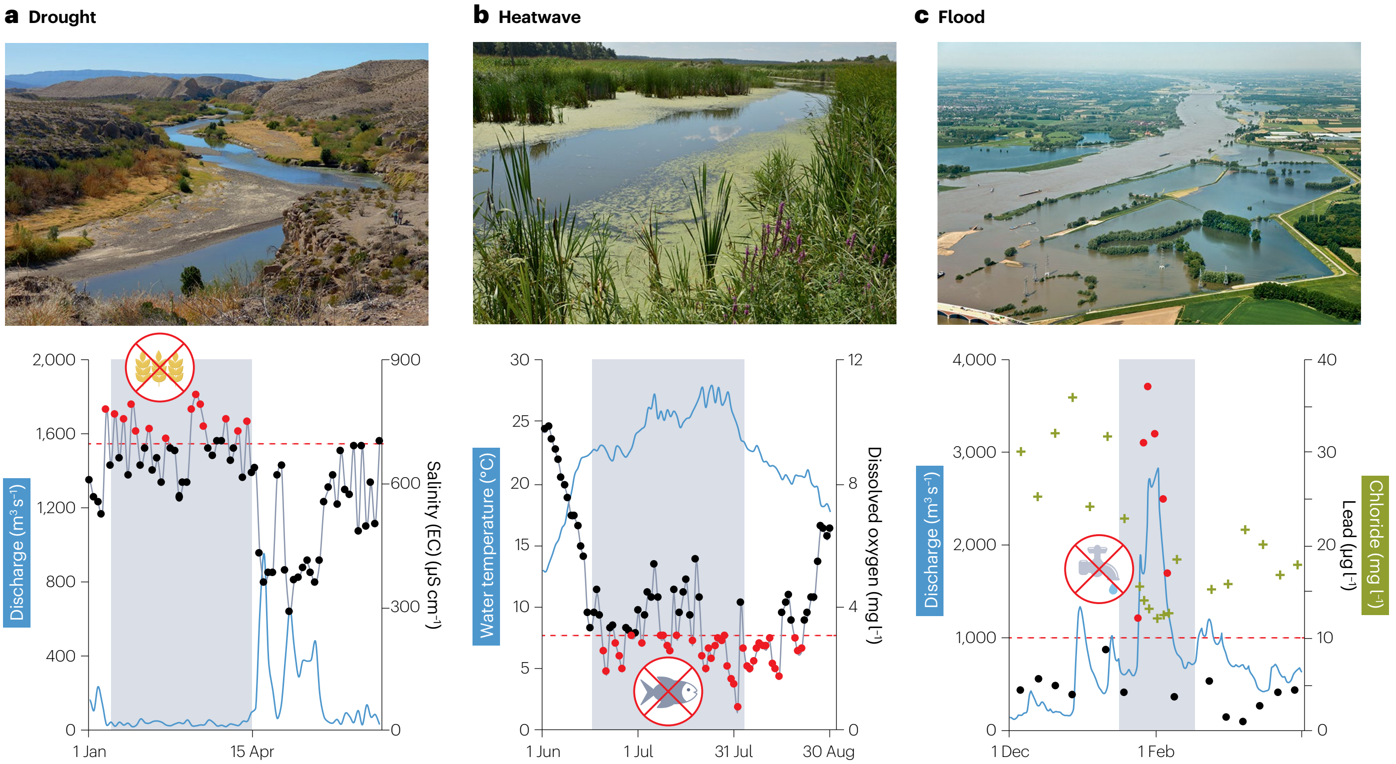


Fig. 3 | Examples of water quality responses during drought, heatwave and flood events. a, Top, a photo of a drained river and, bottom, a plot of observed river salinity increase during a drought in TX, USA in 2012. The salinity exceeded the threshold for irrigation water use (dashed line). **b**, Top, a photo of a river during heatwave. Bottom, a plot shows decreases in daily minimum dissolved oxygen concentrations during a heatwave in western Europe in July 2006. Dissolved oxygen values fell below the ecological threshold (dashed line). **c**, Top, a photo of a river with overflown banks, flooding the neighbouring fields. Bottom, a plot of lead concentrations during the 1995 flood event in the Meuse, western Europe. Lead concentrations exceeded the safe drinking water threshold (dashed line). The corresponding decrease in chloride concentrations (green crosses) indicates the impact of higher dilution during the flood event. Examples were selected on the basis of the availability of detailed water quality monitoring data and were produced on the basis of online data from USGS and Rijkswaterstaat Dutch Ministry of Infrastructure and Water. Values in black indicate concentrations that are meeting water quality requirements, whereas values in red do not meet the user requirements. Extreme events can cause exceedance of water quality standards for sectoral use and ecosystem health. EC, electrical conductance. Image credits for photos: Keith's Color Photography via Getty Images (part **a**), Oleg Prokopenko via Getty Images (part **b**) and Frans Lemmens via Getty Images (part **c**).

Algal blooms and eutrophication issues have been observed in several river systems[71,72], although rivers and streams are considered to be less prone to algal blooms than lakes and reservoirs under heatwaves. Construction of dams and reservoirs, transverse structures in rivers and associated impacts on reducing flow velocities can strongly affect nutrients, dissolved oxygen and algae dynamics and aquatic ecosystem health in general[73]. High water temperature during heatwaves boosts algal growth rates[17] (Fig. 2a). This can promote the growth of cyanobacteria as harmful algal blooms, which have optimum water temperatures for growth that vary between 25 °C and 35 °C (ref. 74). Some cyanobacteria produce toxins, which can cause human health issues and threaten aquatic ecosystems[17,65,75]. Thermal stratification and increased water column stability during heatwaves, combined with low flow conditions, also provide a competitive advantage for many harmful cyanobacteria, which have buoyancy control mechanisms[76].

Temperature increases under heatwaves also impact the mineralization and leaching of particulate and dissolved organic matter, mediated by microorganisms, which often show an exponential increase along with higher temperature[69,77]. In addition, biogeochemical process rates influencing water quality, such as nitrification and denitrification, are strongly related to water temperature[78]. For instance, analyses for streams in the Netherlands have shown that a water temperature increase of 3 °C can double denitrification rates[78].

Rainstorms and floods

Rainstorms and associated flood events have major impacts on various water quality constituents and are also changing in their frequency and intensity in several regions owing to climate change[79,80]. In small river basins, short-duration, high-intensity rainstorms tend to increase with expected increases in flood hazard in a warmer climate[81]. For larger river basins, both increases and decreases in flood hazards have been observed around the world[81].

We found an overall deterioration in river water quality under rainstorms and floods for 51% of the case studies in terms of concentration responses ($n = 157$) (Fig. 2b), and this percentage is the same when we also include case studies that consider impacts on pollutant loadings and export in rivers ($n = 180$). Overall, increased concentrations are found for suspended sediment, plastics, nutrients (mainly in particulate forms), some metals, biochemical oxygen demand (BOD) and microorganisms under rainstorms and floods (Fig. 2b).

In terms of the main mechanisms driving these water quality responses, high-intensity rainfall events and floods result in increased erosion, mobilization and resuspension of in-stream, floodplain and catchment sources, resulting in increased nutrients and other water quality constituents that have been accumulated in the river bed and retained in the landscape during preceding low-flow periods[60] (Fig. 2b). For example, a single major flood event was responsible for nearly 87% of the total mass of sediment eroded in the Carson River (NV, USA) during the entire period of 1991–1997 (ref. 82).

The increased mobilization and resuspension of sediment during rainstorms and floods also result in higher concentrations of contaminants with high adsorption capacities to suspended sediment, such as some metals[83,84]. For instance, peak concentrations of lead were found in the Meuse River (western Europe) during the 1995 flood (Fig. 3c). These peak concentrations during flood events resulted in temporal exceedance of water quality standards for intake for drinking water production. By contrast, lower concentrations of metals adsorbed to sediment (lead, copper and zinc) were also observed owing to increased mixing of contaminated sediment with less-contaminated sediment transported during floods[85,86].

Plastics in rivers also show strong increases during floods (Fig. 2b) owing to increased mobilization and transport capacity of plastic particles[87,88]. High increases in microplastic loads are particularly reported for rivers in the USA (Mississippi, Santa Cruz River)[89,90], Brazil (Paraibo do Sul)[91], France (Rhone, Garonne, Seine)[92–94], the Netherlands (Meuse)[87], Russia (Northern Dvina)[95], China (Yangtze[96,97]) and Australia (Cooks River[98]). Particularly, microplastics show strong interactions with and contribute to increases in other pollutants (for example, metals) owing to their absorption and carrying capacities[29,30]. Strong increases in nutrients, organic pollutants and pharmaceuticals concentrations (Fig. 2b) and loads are mainly caused by sewer overflows and increased runoff from farming sites during periods with excessive precipitation[99–101].

Concentrations of dissolved constituents (for example, salts and dissolved nutrients) can initially also increase as material is mobilized when catchment runoff increases, but in general concentrations are low at very high flows owing to high dilution rates[102]. These processes of increased mobilization and transport and dilution under floods can thus have opposite impacts on the concentration levels. However, consistently reduced salinity levels, driven by increased dilution capacities under floods, are reported for almost all case studies (Fig. 2b). Strong impacts of increased dilution during floods resulting in lower salinity (chloride concentrations) are presented as an example for the Meuse River (western Europe) during the 1995 flood (Fig. 3c, green plus symbols). Increased dilution also contributed to lower concentrations of some other pollutants; for instance, pharmaceuticals and some metals that are mainly in the dissolved phase (Fig. 2b).

The hydrological sequence of transitions from drought to flood events has a profound impact on the quality of river water. Several studies reported on increases in microorganism concentrations during floods, but particularly after dry periods, potentially because of increased runoff of faecal material that has been accumulating during dry periods[103]. Large amounts of plant litter build up in floodplains during dry periods, and subsequent flooding can increase rapid decomposition and oxygen consumption[69]. This explains the strong decline in dissolved oxygen concentrations during and directly after flood events, which are often referred to as hypoxic blackwater events (Fig. 2b) and can have severe and large-scale environmental impacts[104]. For example, a severe hypoxic blackwater event occurred affecting 2,000 km of river channels and persisted for 6 months during a series of spring and summer flood events in 2010–2011 after a decade-long drought in south-eastern Australia[104]. The sequence of droughts and floods is also very important for nutrient export dynamics. For example, mineral fertilizers (nitrogen and phosphorous) that are not taken up by plants during dry periods can accumulate in soils and can be mobilized by leaching or runoff during the subsequent wet (heavy rainfall) period, leading to high nutrient concentrations in receiving water bodies[105,106].

Land use and floods can interact to amplify pulses of contaminants from watersheds[107]. Developed landscapes affect the template upon which floods and rainstorms interact with pollution sources, impacting downstream river water quality. Many urban environments and agricultural watersheds have artificial drainage networks that quickly drain and convey water and pollution sources more efficiently downstream than natural landscapes. This amplifies pulses of contaminants under rainstorms and floods in both agricultural and urban areas[108]. In addition, sewer overflows and inundation or overload of wastewater treatment plants and stormwater infrastructure can lead to the flushing of various contaminants including nutrients (nitrogen and phosphorus), microorganisms, metals, plastics and pharmaceuticals[88,101,109,110] (Fig. 2b). This can result in increased concentrations of these pollutants owing to enhanced mobilization and transport, whereas dilution results in lower concentrations.

To summarize, hydroclimatic extremes such as droughts, heatwaves, rainstorms and floods show in most cases a deterioration of river water quality, but improvements or mixed responses are also reported owing to counteracting mechanisms (such as pollutant mobilization versus dilution). Furthermore, the sequence of different extreme events (such as droughts followed by floods) also impacts the magnitude of river water quality responses and their driving mechanisms.

Climate change impacts on water quality

Several mechanisms impacting water quality that occur on daily, weekly or monthly timescales under hydroclimatic extremes are also prevalent when considering more gradual, multidecade changes in climate conditions. Reported water quality impacts under long-term climate change include diverse responses, resulting in a general deterioration (56% of case studies), improvement (31%) or no substantial or mixed responses (13%). Overall, most of the analysed case studies report increasing trends in water temperature and algae and a decrease in dissolved oxygen concentrations, partly driven by increasing water temperature (Fig. 4a). Nutrients and pharmaceuticals show mostly increasing concentrations, whereas concentrations of BOD, salinity, suspended sediment, metals and microorganisms show a mixture of increasing and decreasing trends under long-term climate change. The main driving mechanisms for multidecadal water quality changes in response to climate change include hydrological alterations (surface runoff, leaching and streamflow), long-term rises in water, sediment and soil temperatures and the long-term interactions of hydroclimatic drivers with land use and other human-induced drivers in the coming decades.

Hydrological change

Several mechanisms induce river water quality changes under changing climate. First of all, there are substantial alterations in hydrological processes, such as surface runoff and leaching, which affect the mobilization and transport of contaminants from diffuse sources (for example, fertilizer and manure from agricultural land) to streams, and associated in-stream concentrations of nutrients and other pollutants[111,112]. In addition, concentrations of water quality constituents are largely driven by changes in streamflow and flow variability at different temporal scales (for example, short-term extremes, seasonality and multiyear changes), which directly impact the dilution capacity for contaminants of both point and diffuse sources[6].

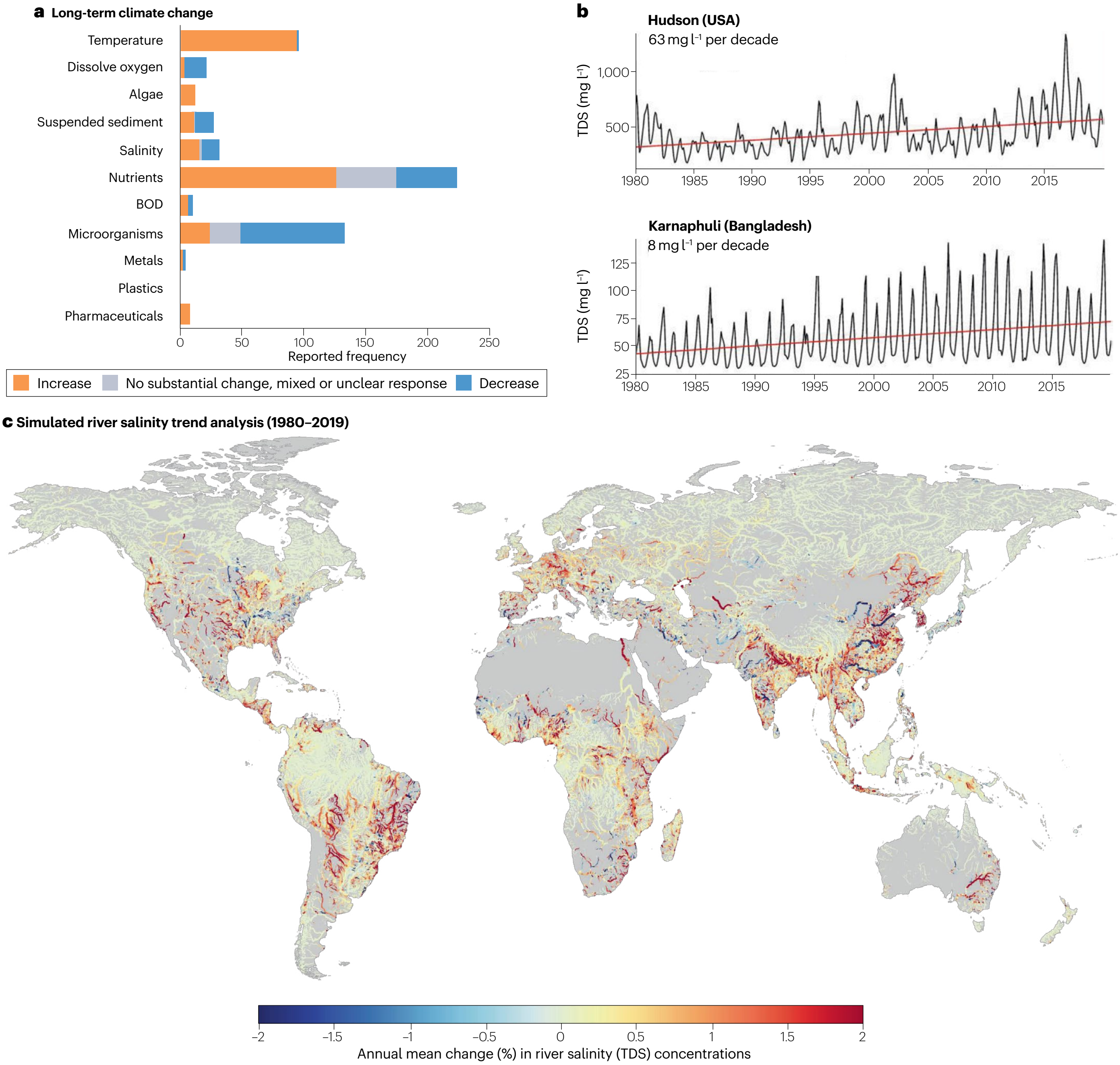


Fig. 4 | Multidecadal water quality responses under climate change. a, The reported frequency of responses to climate change in various water quality components based on the compilation of published case studies (Supplementary Data). **b**, Examples of simulated salinity (total dissolved solids (TDS)) trends in the Hudson (USA) and Karnaphuli (Bangladesh) rivers based on data of Jones et al.[15]. The black line shows the monthly mean simulated TDS concentrations, and the red line shows the long-term linear trend for 1980–2019. **c**, Simulated historical trends in annual mean river salinity for 1980–2019, based on global surface water quality model simulations of DynQual[15], including hydroclimatic and human driver interactions. TDS concentrations in most regions are either relatively constant (high northern latitude region and large parts of tropical region) or show gradual increasing trends, which are most prevalent for Southeast Asia, USA, Mexico, southern South America, parts of Sub-Saharan Africa and south-eastern Australia. Only small areas show decreasing river salinity (TDS concentration) trends, which can be explained by increasing streamflow and dilution of salts. River water quality (salinity) trends are not homogeneous, but show large spatial variability depending on the interactions of hydroclimatic, land use and human-induced driver changes over the study period. BOD, biochemical oxygen demand.

Increases in river flow seasonality with a lower river discharge during the low flow season and higher discharge during the high flow season under future climate are reported[113,114]. Changes in the rain-fed versus snowmelt-fed contribution could also affect river water quality[23]. Increases in annual high flows can amplify pulses of suspended sediment of contaminants (for example, metals) adsorbed onto sediment surfaces in rivers and streams[6]. Moreover, changes in river flow seasonality will have major impacts on dilution rates and in-stream concentrations of many water quality constituents[115]. Also, changes in concentration–discharge relationships are expected owing to climate change[116].

Both increases and decreases in river salinity levels, driven by local or regional specific hydrological changes, are found from the compilation (Fig. 4a). Long-term increasing trends in river salinity are mainly explained by reduced dilution capacity for salts under lower streamflow and increased evapo-concentration, combined with land-use changes and increased human activities (for example, irrigation and resource extraction), and in delta regions also by seawater intrusion[9,15,117]. Distinct increasing salinity trends are found specifically for rivers in Southeast Asia (for example, Mekong, Ganges–Brahmaputra), USA (Mississippi, Hudson), Southern Europe (Ebro), central South America and south-eastern Australia (Murray–Darling)[9,15,117] (Fig. 4b,c).

Water, sediment and soil temperature rises

Next to these hydrological changes, a direct consequence of climate change is a general rise in the water temperatures of rivers and streams (Fig. 4a). Large-scale increasing trends for water temperature since the 1970s (or earlier) have been reported on the basis of monitoring records mainly for rivers in North America[118,119], Europe[120,121] and Eurasian Arctic rivers[122,123], for which most long-term water temperature records are available. These increasing water temperature trends have been confirmed by global-scale water temperature modelling, showing a global average water temperature increase of 0.16 °C per decade over the 1960–2014 period[124]. Future projections for the twenty-first century also show distinct increasing trends for the full range of climate scenarios considered and an intensification of thermal regimes with the largest increases in high (summer) river temperature[113,125]. Largest water temperature increases are projected for the south-eastern USA, southern Europe, eastern Asia and southern parts of Africa and Australia, where declining low river flow during summer can contribute to stronger water temperature rises owing to a lower thermal capacity and therefore higher sensitivity of rivers to atmospheric warming[113].

Future water temperature rises can result in the deterioration of water quality, for instance, owing to reduced dissolved oxygen saturation rates and concentrations, increases in algal blooms and eutrophication issues[19–22] (Fig. 4a). However, water temperature increases can improve impacts on water quality owing to increased decay and transformation rates of nutrients and other pollutants[6,23,126,127] and increased inactivation rates of microorganisms[25], resulting in lower pollutant concentrations.

Next to water temperature, increasing temperatures of soil and sediment in a warmer climate[128] also impacts water quality owing to increased microbial activities[129–131], leading to changes in biogeochemical processes related to the carbon and nutrient cycles (mineralization, nitrification and denitrification)[132,133]. This can promote increased availability of soluble nutrients (such as nitrate), which can enhance leaching from land to water systems, influencing nutrient concentrations in rivers and streams[134]. In addition, climate change can increase risks for wildfires, which destabilize soil storage of nutrients, organics and metals, bring large amounts of suspended particles, chemical and microbial contaminants in post-fire runoff and substantially impact water quality (for instance, nutrients and microorganisms) in rivers and streams in those regions[44,135–137].

Interactions with land use and other drivers

Future river water quality trends are driven not only by long-term hydroclimatic changes but also by their complex interactions with land use and other human-induced (for example, population growth and economic development) drivers[138], which should also be considered in future water quality projections and management[108,139]. There have been mostly increasing trends in nitrogen in global rivers over the past century[8,140,141], but some rivers in the USA and Europe are showing declines owing to the effects of pollution management[142,143]. Although global nitrogen fluxes in rivers have doubled with changes in fertilization of agricultural lands, urbanization, industrialization and wastewater discharges[140,142], also temperature increases and hydrological changes impacting residence times and retention exert an important influence[8,140].

In addition, land use, climate change and variability interact to amplify pulses of contaminants from watersheds to streams and rivers[6,107,108]. Increased rainstorms under climate change can increase pulses of contaminants from agricultural and urban areas and can result in sewer overflows, leading to flushing of nutrients, plastics, microorganisms, pharmaceuticals and other contaminants[26,144,145]. Increasing urbanization puts additional pressure on drainage networks upon which floods and rainstorms interact with pollution sources to convey flood and contaminant pulses from watersheds to streams and rivers[144,146]. Population and aquatic ecosystems residing around urban areas in developing countries with limited wastewater treatment facilities and infrastructure and with rapid urban growth are particularly vulnerable to increased pulses of contaminants under climate change and increased hydroclimatic variability[147,148].

Changes in rainfall intensity and variability, increased temperatures and land-use changes will affect also the fate and transport of agricultural pollutants, such as nutrients, but, for instance, also pesticides, for which concentration responses can be variable and difficult to predict[149]. Future river water quality will thus be driven by the complex interactions that exist among hydroclimatic, land-use change and human (for example, wastewater management) drivers, all of which synergistically influence the sources, transport and transformation of entire groups of water quality constituents.

In brief, multidecadal climate change is causing increases in water temperatures, algae and a general decrease in dissolved oxygen concentrations. However, several pollutants show a mixture of increasing and decreasing trends depending on the main driving mechanisms such as hydrological alterations, rises in water and soil temperatures and interactions among hydroclimatic, land use and other human drivers.

Summary and future perspectives

In this Review, we explore the potential impacts of both hydroclimatic extremes (drought, heatwave, rainstorm and flood events) and longer-term (historic and future) climate change on river water quality, considering a wide range of water quality constituents. There is a general deterioration of river water quality under droughts and heatwaves (68% of compiled case studies), rainstorms and floods (51%) and under long-term climate change (56%), but in some cases also water quality improvements or mixed responses. The direction and magnitude of water quality changes are strongly driven by hydrological (for example,

Table 1 | Responses and mechanisms in different water quality constituents under various extreme weather events and climate change

	Droughts and heatwaves		Rainstorms and floods		Long-term climate change	
	Overall response	**Mechanisms**	**Overall response**	**Mechanisms**	**Overall response**	**Mechanisms**
Temperature	↑	Increased atmospheric warming; lower thermal capacity; lower dilution capacity for thermal pollution under low flow	?	Not described in literature	↑	Increased atmospheric warming; changes in river flow and variability
Dissolved oxygen	↓(↑)	Lower dissolved oxygen solubility under higher water temperature (↓); algal blooms (↑day, ↓night); increased stratification (↓); lower reaeration rates under low flow (↓)	↓(↑)	Higher reaeration rates under higher flow (↑); large supply of oxygen-depleted discharge and floodplain water (↓); increased intensity of heterotrophic microbial activities owing to organic and nutrient inputs after rainfall events (↓); hypoxic black water impacts (↓)	↓	Water temperature rises (↓); changing reaeration under changing river flow (↑↓); increased decay of organic matter (↓); risk of hypoxia under high flow/floods (↓)
Algae	↑	Increased water temperature; increased stratification; longer residence times; increase in light availability owing to high solar radiation or lower turbidity	↓↑	Increases in nutrient inputs (↑); increases in dilution (↓)	↑(↓)	Increased water temperature (↑); increased stratification (↑); shift of phytoplankton composition (↑↓); increase in light availability owing to high solar radiation or lower turbidity (↑)
Suspended sediment	↓	Less sediment erosion; lower mobilization, resuspension and sediment transport capacity	↑(↓)	Increased sediment erosion (↑); increased mobilization, resuspension and transport capacity (↑); increased dilution (↓)	↓↑	Changes in river flow variability (↑↓); changes in sediment pulses (↑↓)
Salinity	↑	Less dilution under low flow; increased evapo-concentration; increased seawater intrusion	↓	More dilution under high flow	↓↑	Changes in dilution patterns (↑↓); increased evapo-concentration (↑); increased seawater intrusion under lower flow and sea level rise (↑)
Nutrients	↓↑	Reduced nutrient inputs by runoff and leaching (↓); lower velocity, longer residence times and increased retention (↓); increased denitrification under higher water temperature (↓); less dilution under low flow (↑)	↑(↓)	Increased mobilization in soils and leaching (↑); increased runoff and mobilization (↑); increased resuspension (↑); increased sewer overflows (↑); less retention by soil and sediment (↑); more dilution (↓)	↑↓	Changes in runoff and leaching impacting mobilization and transport (↑↓); river flow induced changes in dilution (↑↓); increased sewer overflows under increasing rainstorms and floods (↑); water temperature increases (↓)
Organic pollution (BOD)	↓↑	Less dilution under low flow (↑); increased decay under longer residence time and higher water temperature (↓)	↑(↓)	Increased runoff from agricultural and urban wastewater (↑); increased dilution under higher flow (↓)	↓↑	Less dilution under low flow (↑); increased decay under longer residence time and higher water temperature (↓)
Microorganisms	?	Not described in literature	↑(↓)	Increased wash-off from upstream sources (↑); increased sewer overflows (↑); increased dilution (↓)	↓↑	Changes in runoff and leaching (↑↓); river flow induced changes in dilution (↓); increased sewer overflows (↑); water temperature increases (↑↓)
Metals	↓↑	Less dilution of metals in dissolved phase (↑); lower suspended sediment and reduced sediment-adsorbed metals (↓)	↓↑	Increased resuspension of sediment-adsorbed metals (↑); increased dilution of metals in dissolved phase (↓)	↓↑	River flow changes impacting mobilization and transport of sediment-adsorbed metals (↑↓); river flow changes impacting dilution of metals mainly in dissolved phase (↑↓)

Table 1 (continued) | Responses and mechanisms in different water quality constituents under various extreme weather events and climate change

	Droughts and heatwaves		Rainstorms and floods		Long-term climate change	
	Overall response	**Mechanisms**	**Overall response**	**Mechanisms**	**Overall response**	**Mechanisms**
Plastics	?	Not described in literature	↓↑	Increased inundation of contaminated industrial and/or urban areas (↑); increased transport capacity and dynamics (↑); increased dilution under high flow (↓)	?	Not described in literature
Pharmaceuticals	↑(↓)	Lower flow, less dilution (↑); increased decay under higher water temperature for less-persistent pharmaceuticals (↓)	↓↑	Increased dilution under high flow (↓); increased resuspension of (sediment) adsorbed pharmaceuticals (↑)	↑(↓)	River flow changes impacting dilution (↑↓); increased decay under water temperature rises (↓)

Summary of overall responses, such as predominant increase (↑) or decrease (↓) or mixed response (↑↓), in concentrations for different water quality constituents under various event types. The main driving mechanisms for each response are listed. For mixed responses (↑↓), the individual trends are shown for each mechanism to show where they differ. In the overall trend for mixed responses cases, an arrow between brackets represents a response that is less important than the arrow that is not in brackets for that case. See Supplementary Notes 2–12 for reports on more detailed water quality responses, mechanisms and impacts for sectors and ecosystems and associated literature. BOD, biochemical oxygen demand.

surface runoff, discharge) and water, sediment and soil temperature changes and the complex interactions with geographic factors (land use, geology and soil characteristics) and human activities (sectoral water use and wastewater management).

Increasing water temperature, suspended sediment, salinity, algae and dissolved oxygen concentrations are overall consistently reported across the compilation under climate change and extreme weather events (Table 1). Mixed responses (both increase and decrease in concentration) are reported for nutrients, BOD, microorganisms, metals, plastics and pharmaceuticals owing to different constituent behaviours and counteracting mechanisms during extreme weather events. For instance, the initial increase of mobilization and transport of these contaminants by high surface runoff during floods can counteract increased dilution under wet periods, and the opposite occurs under droughts (Table 1).

With the compilation and associated discussion, we aim to provide insights into the main water quality responses and their driving mechanisms, which are key in identifying suitable water quality solutions. However, we acknowledge that each case study included in the compilation might have used different definitions and approaches for identifying hydroclimatic extremes (droughts, heatwaves, rainstorms and floods) and climate change. These varying definitions complicate systematic categorization and quantitative comparisons of river water quality responses under these events. Nevertheless, our compilation of water quality responses from local and regional case studies across the globe corresponds well with the findings of global-scale analyses of future surface water quality under the impacts of long-term climate change[111,150].

This Review focuses on a set of 11 water quality constituents for which responses and driving mechanisms under climate change and extremes are most widely covered in the literature. We acknowledge that there are many other water quality constituents, for example, pesticides, polycyclic aromatic hydrocarbons, polyfluoroalkyl substances and other chemicals of emerging concern, which are also highly relevant owing to their potential human health risks and threats to the biodiversity[151]. For these relatively new substances and chemicals of emerging concern, we have overall limited understanding of their fate and transport in water systems, their complex interactions with other water quality constituents (such as demonstrated in Fig. 1b) and risks of increased concentration levels for ecosystem health and water use for different sectors (such as irrigation and drinking water)[61]. More scientific evidence and an improved understanding of the fate and transport, interactions and threshold levels of these substances in water systems is therefore a main priority for future research so that potential water quality risks can be assessed.

In addition, the complex interactions that exist among hydroclimatic drivers, land-use change and human activities (such as sectoral water use and wastewater management) need to be disentangled, as they all synergistically influence the sources, transport and transformation of nearly all water quality constituents. These compounding interactions between different drivers should provide a basis for developing robust water quality management strategies under climate change and extreme events, for example, by upgrading sanitary sewer infrastructure. Also treated wastewater reuse provides a key option to fulfil the increase in irrigation water demands under climate change and increasing droughts and heatwaves and shows a strong potential to alleviate water scarcity globally[5]. However, pollutants can still enter the environment and adequate care should be taken to avoid secondary risks.

Furthermore, there is a need to further develop tools, data-driven and process-based models and technologies for monitoring and predicting regional or global water quality hotspots and bright spots (Box 2) that are undergoing either a deterioration or improvements in river water quality under hydroclimatic, land use and other human-induced changes. Most river water quality case studies considered in this Review focus on rivers and streams in North America and Europe, and this causes a geographic bias in our literature review. Existing water quality monitoring data are highly fragmented in several regions of the world (most of Africa and parts of Asia) both in space and in time (large data gaps in monitoring time series). This complicates the analyses of long-term water quality trends[12] under climate change and short-term (daily and weekly) responses under hydroclimatic extremes. There is a need to compile local or regional water quality monitoring data to large data sets and also use (large-scale) water

Box 2

Tools and techniques for assessing river water quality at local-to-global scales

Remote sensing: Global satellite remote-sensing data sets of river and lake water quality[167,168] show promise for monitoring spatial surface water quality patterns[169,170], particularly owing to advances in space information science and increasing computer power. For instance, these data sets can provide opportunities for identifying driver-pressure–impact relationships of surface water quality with climatic change[171] and land-use change[172], given that spatially explicit water quality data sets are currently available for multidecadal periods. So far, chlorophyll *a*[173], turbidity[174,175], suspended sediment[170], water temperature and thermal pollution[176–178], coloured dissolved organic matter[175], nutrients and eutrophication levels[175] in lakes and rivers have been estimated through satellite remote sensing, although uncertainties differ depending on the complexity of the water systems and water quality constituents[173]. Use of remote sensing can particularly be valuable in regions of the world, where in situ water quality monitoring is scarce. However, remote sensing is limited to selected water quality constituents and some local in situ data are always still needed for mapping relations between remote sensing multispectral signatures and ground truth data (such as pollution concentration).

Internet of things, high-frequency water quality monitoring and citizen science: The use of innovative measuring techniques, including internet of things-solutions and use of high-frequency water quality monitoring (sensors), allows for high frequency, continuous water quality monitoring. This type of monitoring could also be incorporated in novel early warning systems for water quality[179] and is particularly important to capture the impact of short-term hydroclimatic extremes, which are often missed in conventional water quality monitoring. Citizen science[180] also offers opportunities for measuring and sharing river water quality data. For instance, a nitrate app for smartphones has been developed to enable farmers and citizens in the Netherlands, Denmark and the USA to measure and share water quality measurement (nitrate and salinity) levels with the aim to establish the relationship between different agricultural practices and water quality[181].

Process-based water quality models: Process-based surface water quality models describe the main water quality processes through a set of physical principles and mechanistic insights. They have been developed to gain insight into the state (for example, pollution hotspots and their causes) and trends in river water quality in different regions of the world. These types of models have been applied at local-to-global scales and are particularly suitable for scenario analyses, such as climate change and the interactions with land use and human drivers because they describe the dominant water quality processes in a mechanistic way[182]. Combination of process-based models with high-resolution input data sets (for example, wastewater treatment[183,184]) and increased computer power will allow for high spatiotemporal resolution model simulations (at daily time steps[12,15]), which show promise for capturing short-term (daily to weekly) water quality responses under hydroclimatic extreme events at the continental-to-global scale.

Data-driven water quality models and machine learning: The use of machine learning (ML) techniques in water quality research and prediction is increasing, both at local-to-global scales[185]. These methods show particular promise for capturing the impact of hydroclimatic extremes on water quality. High-performance ML techniques are advantageous for mimicking water quality responses at high-spatiotemporal resolution (daily or even hourly level) and revealing complex patterns between river water quality observations and drivers that are not well represented in process-based models[186] (for example, impacts of sewer overflows on water quality during floods). ML techniques used in water quality research include, among others, artificial neural networks[186–188], least-square support vector machine[189,190], fuzzy inference system[188] and random forest[191] techniques.

quality models, tools and techniques to strategically select streams and rivers that should be prioritized in expanding in situ water quality monitoring campaigns[152].

Most research on long-term climate change impacts focuses on projections for (part of) the twenty-first century by using climate scenarios, and in several cases, also combined with socio-economic (population growth and wastewater treatment) scenarios to force water quality models. Although trends in river water quality are presented specifically with climate change[153], limited work so far has focused on projecting and attributing the occurrence of hydroclimatic extremes[154–156]. Climate attribution could be an important way forward to relate water-quality extremes, their causes, occurrence and severity directly to changes in climate[155,157]. For a comprehensive assessment of water quality under climate change and extremes, different water quality models may show different responses for a certain climate scenario. We therefore need consistent multimodel and multidata source assessment frameworks considering ensembles of various water quality models to better account for model uncertainties in future water quality projections[158]. Examples have been envisaged by World Water Quality Alliance[159] and ISIMIP[160] initiatives to provide robust water quality changes under climate and socio-economic changes, which are needed to support large-scale water management and decision-making.

The era of multiple pollutants, scales, sectors and sources[10,161–163] requires integrated, synergetic solutions that are more cost-effective[164] and can mitigate trade-offs between pollutants, considering multiple Sustainable Development Goal (SDG) targets[165]. In terms of water quality solutions, we should consider focusing on nature-based solutions[166] and pollutant emission reduction measures in addition to improving clean water infrastructure and technology (such as expanding wastewater treatment plants). Current wastewater treatment targets (in line with SDG 6.3) are still insufficient to achieve water quality targets in most regions worldwide, especially developing countries[11]. These pollution control measures should explicitly consider the increase in frequency and intensity of hydroclimatic extremes. For instance, permits for pollutant emissions should not only consider average river discharges to calculate dilution capacities for effluents but also future changes in extremes such as droughts and floods. To achieve clean water for all (SDG6), we need an improved understanding of the feedbacks among hydroclimatic drivers, land-use change and human activities to design suitable water quality management strategies in a world facing more intense and frequent hydroclimatic extremes.

Data availability

Details on the literature review and reports for each water quality constituent (group) are given in Supplementary Notes 1–12. The Supplementary Data file includes a spreadsheet with collected meta-data of all literature case studies in the compilation. River water quality monitoring data for Fig. 3 were retrieved from the USGS Water-Quality Data for the Nation database (https://waterdata.usgs.gov/nwis/qw) and Rijkswaterstaat Dutch Ministry of Infrastructure and Water database (https://waterinfo.rws.nl/#!/nav/expert/).

References

1. Johnson, D. L. et al. Meanings of environmental terms. *J. Environ. Qual.* **26**, 581–589 (1997).
2. Boyd, C. E. Water quality: an introduction. *Water Quality: An Introduction* 1–357 (Springer, 2015); https://doi.org/10.1007/978-3-319-17446-4.
3. van Vliet, M. T. H., Flörke, M. & Wada, Y. Quality matters for water scarcity. *Nat. Geosci.* **10**, 800–802 (2017).
4. Ma, T. et al. Pollution exacerbates China's water scarcity and its regional inequality. *Nat. Commun.* **11**, 650 (2020).
5. van Vliet, M. T. H. et al. Global water scarcity including surface water quality and expansions of clean water technologies. *Environ. Res. Lett.* **16**, 24020 (2021).
6. Whitehead, P. G., Wilby, R. L., Battarbee, R. W., Kernan, M. & Wade, A. J. A review of the potential impacts of climate change on surface water quality. *Hydrol. Sci. J.-J. Des. Sci. Hydrol.* **54**, 101–123 (2009).
7. Hrdinka, T., Novický, O., Hanslík, E. & Rieder, M. Possible impacts of floods and droughts on water quality. *J. Hydro-Environ. Res.* **6**, 145–150 (2012).
8. Beusen, A. H. W., Bouwman, A. F., Van Beek, L. P. H., Mogollón, J. M. & Middelburg, J. J. Global riverine N and P transport to ocean increased during the twentieth century despite increased retention along the aquatic continuum. *Biogeosciences* **13**, 2441–2451 (2016).
9. Thorslund, J., Bierkens, M. F. P., Oude Essink, G. H. P., Sutanudjaja, E. H. & van Vliet, M. T. H. Common irrigation drivers of freshwater salinisation in river basins worldwide. *Nat. Commun.* **12**, 4232 (2021).
10. Strokal, M. et al. Global multi-pollutant modelling of water quality: scientific challenges and future directions. *Curr. Opin. Environ. Sustain.* **36**, 116–125 (2019).
11. Jones, E. R. et al. Current wastewater treatment targets are insufficient to protect surface water quality. *Commun. Earth Environ.* **3**, 221 (2022).
12. UNEP. *A Snapshot of the World's Water Quality — Towards a Global Assessment* (United Nations Environment Programme, 2016).
13. Kaushal, S. S. et al. Five state factors control progressive stages of freshwater salinization syndrome. *Limnol. Oceanogr. Lett.* https://doi.org/10.1002/LOL2.10248 (2022).
14. Bouwman, A. F. et al. Lessons from temporal and spatial patterns in global use of N and P fertilizer on cropland. *Sci. Rep.* **7**, 40366 (2017).
15. Jones, E. R. et al. DynQual v1.0: a high-resolution global surface water quality model. *Geosci. Model Dev.* **16**, 4481–4500 (2023).
16. Gervasio, M. P., Soana, E., Granata, T., Colombo, D. & Castaldelli, G. An unexpected negative feedback between climate change and eutrophication: higher temperatures increase denitrification and buffer nitrogen loads in the Po River (Northern Italy). *Environ. Res. Lett.* **17**, 84031 (2022).
17. Paerl, H. W. & Huisman, J. Climate: blooms like it hot. *Science* **320**, 57–58 (2008).
18. Conley, D. J. et al. Controlling eutrophication: phosphorus and nitrogen. *Science* **323**, 1014–1015 (2009).
19. Cox, B. A. & Whitehead, P. G. Impacts of climate change scenarios on dissolved oxygen in the river Thames, UK. *Hydrol. Res.* **40**, 138–152 (2009).
20. Ficklin, D. L., Stewart, I. T. & Maurer, E. P. Effects of climate change on stream temperature, dissolved oxygen, and sediment concentration in the Sierra Nevada in California. *Water Resour. Res.* **49**, 2765–2782 (2013).
21. Diamantini, E. et al. Driver detection of water quality trends in three large European river basins. *Sci. Total. Environ.* **612**, 49–62 (2018).
22. Chapra, S. C., Camacho, L. A. & McBride, G. B. Impact of global warming on dissolved oxygen and bod assimilative capacity of the world's rivers: modeling analysis. *Water (Switzerland)* **13**, 2408 (2021).
23. Sjerps, R. M. A., ter Laak, T. L. & Zwolsman, G. J. J. G. Projected impact of climate change and chemical emissions on the water quality of the European rivers Rhine and Meuse: a drinking water perspective. *Sci. Total Environ.* **601–602**, 1682–1694 (2017).
24. Wolff, E. & van Vliet, M. T. H. Impact of the 2018 drought on pharmaceutical concentrations and general water quality of the Rhine and Meuse rivers. *Sci. Total Environ.* **778**, 146182 (2021).
25. Hofstra, N. Quantifying the impact of climate change on enteric waterborne pathogen concentrations in surface water. *Environ. Sustain.* **3**, 471–479 (2011).
26. Hunter, P. R. Climate change and waterborne and vector-borne disease. *J. Appl. Microbiol.* **94**, 37S–46S (2003).
27. DeVilbiss, S. E., Steele, M. K., Krometis, L. A. H. & Badgley, B. D. Freshwater salinization increases survival of *Escherichia coli* and risk of bacterial impairment. *Water Res.* **191**, 116812 (2021).
28. Leyden, E., Farkas, J., Hutson, J. & Mosley, L. M. Short-term seawater inundation induces metal mobilisation in freshwater and acid sulfate soil environments. *Chemosphere* **299**, 134383 (2022).
29. Zhang, Y. et al. How climate change and eutrophication interact with microplastic pollution and sediment resuspension in shallow lakes: a review. *Sci. Total Environ.* **705**, 135979 (2020).
30. Naqash, N., Prakash, S., Kapoor, D. & Singh, R. Interaction of freshwater microplastics with biota and heavy metals: a review. *Environ. Chem. Lett.* **18**, 1813–1824 (2020).
31. Mei, W. et al. Interactions between microplastics and organic compounds in aquatic environments: a mini review. *Sci. Total Environ.* **736**, 139472 (2020).
32. Wang, Y. et al. Interaction of microplastics with antibiotics in aquatic environment: distribution, adsorption, and toxicity. *Environ. Sci. Technol.* **55**, 15579–15595 (2021).
33. Caretta, M. A. et al. *Water*. in *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/9781009325844.006.552 (2022).
34. Prudhomme, C. et al. Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proc. Natl Acad. Sci. USA* **111**, 3262–3267 (2014).
35. Trenberth, K. E. et al. Global warming and changes in drought. *Nat. Clim. Change* **4**, 17–22 (2014).
36. Christidis, N., Jones, G. S. & Stott, P. A. Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. *Nat. Clim. Change* **5**, 46–50 (2015).
37. Perkins-Kirkpatrick, S. E. & Lewis, S. C. Increasing trends in regional heatwaves. *Nat. Commun.* **11**, 3357 (2020).
38. Ye, L., Shi, K., Xin, Z., Wang, C. & Zhang, C. Compound droughts and heat waves in china. *Sustainability* **11**, 3270 (2019).
39. Dankers, R. & Feyen, L. Flood hazard in Europe in an ensemble of regional climate scenarios. *J. Geophys. Res.* https://doi.org/10.1029/2008JD011523 (2009).
40. Tabari, H. Climate change impact on flood and extreme precipitation increases with water availability. *Sci. Rep.* **10**, 13768 (2020).
41. Blöschl, G. et al. Changing climate both increases and decreases European river floods. *Nature* **573**, 108–111 (2019).
42. Mosley, L. M. Drought impacts on the water quality of freshwater systems; review and integration. *Earth-Sci. Rev.* **140**, 203–214 (2015).
43. Murdoch, P. S., Baron, J. S. & Miller, T. L. Potential effects of climate chance on surface-water quality in North America. *J. Am. Water Resour. Assoc.* **36**, 347–366 (2000).
44. Mishra, A., Alnahit, A. & Campbell, B. Impact of land uses, drought, flood, wildfire, and cascading events on water quality and microbial communities: a review and analysis. *J. Hydrol.* **596**, 125707 (2021).
45. Wada, Y., van Beek, L. P. H., Wanders, N. & Bierkens, M. F. P. Human water consumption intensifies hydrological drought worldwide. *Environ. Res. Lett.* **8**, 34036 (2013).
46. Gu, L. et al. Intensification of global hydrological droughts under anthropogenic climate warming. *Water Resour. Res.* **59**, e2022WR032997 (2023).
47. Fischer, E. M. & Schär, C. Consistent geographical patterns of changes in high-impact European heatwaves. *Nat. Geosci.* **3**, 398–403 (2010).
48. Arias, P.A. et al in *Climate Change 2021: The Physical Science Basis* (eds. Masson-Delmotte, V. et al.) 33–144 (Cambridge Univ. Press, 2021).
49. Tassone, S. J. et al. Increasing heatwave frequency in streams and rivers of the United States. *Limnol. Oceanogr. Lett.* **8**, 295–304 (2022).
50. Woolway, R. I. et al. Lake heatwaves under climate change. *Nature* **589**, 402–407 (2021).
51. van Vliet, M. T. H. & Zwolsman, J. J. G. Impact of summer droughts on the water quality of the Meuse river. *J. Hydrol.* **353**, 1–17 (2008).
52. Hellwig, J., Stahl, K. & Lange, J. Patterns in the linkage of water quantity and quality during low-flows. *Hydrol. Process.* **31**, 4195–4205 (2017).
53. Jones, E. & van Vliet, M. T. H. Drought impacts on river salinity in the southern US: implications for water scarcity. *Sci. Total Environ.* **644**, 844–853 (2018).

54. Anderson, T. T. et al. Catchment-scale groundwater-flow and recharge paradox revealed from base flow analysis during the Australian Millennium Drought (Mt Lofty Ranges, South Australia). *Hydrogeol. J.* **29**, 963–983 (2021).
55. Abdullah, A. D. et al. Predicting the salt water intrusion in the Shatt al-Arab estuary using an analytical approach. *Hydrol. Earth Syst. Sci.* **20**, 4031–4042 (2016).
56. Garcés-Vargas, J. et al. Tidally forced saltwater intrusions might impact the quality of drinking water, the Valdivia River (40° S), Chile Estuary Case. *Water* **12**, 1 (2020).
57. Thorslund, J., Bierkens, M. F. P., Scaini, A., Sutanudjaja, E. H. & van Vliet, M. T. H. Salinity impacts on irrigation water-scarcity in food bowl regions of the US and Australia. *Environ. Res. Lett.* **17**, 84002 (2022).
58. Méndez-Freire, V., Villaseñor, T. & Mellado, C. Spatial and temporal changes in suspended sediment fluxes in Central Chile induced by the mega drought: the case of the Itata River Basin (36°–37°S). *J. South Am. Earth Sci.* https://doi.org/10.1016/j/jsames.2022/103930 (2022).
59. Mosley, L. M. et al. The impact of extreme low flows on the water quality of the Lower Murray River and lakes (South Australia). *Water Resour. Manag.* **26**, 3923–3946 (2012).
60. Murphy, S. F., McCleskey, R. B., Martin, D. A., Writer, J. H. & Ebel, B. A. Fire, flood, and drought: extreme climate events alter flow paths and stream chemistry. *J. Geophys. Res. Biogeosci.* **123**, 2513–2526 (2018).
61. Scanlon, B. R., Fakhreddine, S., Reedy, R. C., Yang, Q. & Malito, J. G. Drivers of spatiotemporal variability in drinking water quality in the United States. *Environ. Sci. Technol.* **2022**, 12965–12974 (2022).
62. Rozemeijer, J. et al. Climate variability effects on eutrophication of groundwater, lakes, rivers, and coastal waters in the Netherlands. *Sci. Total Environ.* **771**, 145366 (2021).
63. Yu, L. et al. Groundwater impacts on surface water quality and nutrient loads in lowland polder catchments: monitoring the greater Amsterdam area. *Hydrol. Earth Syst. Sci.* **22**, 487–508 (2018).
64. Zhou, X. et al. Exploring the relations between sequential droughts and stream nitrogen dynamics in central Germany through catchment-scale mechanistic modelling. *J. Hydrol.* **614**, 128615 (2022).
65. Huisman, J. et al. Cyanobacterial blooms. *Nat. Rev. Microbiol.* **16**, 471–483 (2018).
66. Cox, B. A. A review of dissolved oxygen modelling techniques for lowland rivers. *Sci. Total Environ.* **314–316**, 303–334 (2003).
67. Paerl, H. W. Mitigating harmful cyanobacterial blooms in a human- and climatically-impacted world. *Life* **4**, 988–1012 (2014).
68. Chen, Y. J., Nicholson, E. & Cheng, S. T. Using machine learning to understand the implications of meteorological conditions for fish kills. *Sci. Rep.* **10**, 17003 (2020).
69. Mosley, L. M., Wallace, T., Rahman, J., Roberts, T. & Gibbs, M. An integrated model to predict and prevent hypoxia in floodplain-river systems. *J. Environ. Manage.* **286**, 112213 (2021).
70. Koehn, J. D. & Koehn, J. D. Key steps to improve the assessment, evaluation and management of fish kills: lessons from the Murray–Darling river system, Australia. *Mar. Freshw. Res.* **73**, 269–281 (2021).
71. Cheng, B. et al. Characterization and causes analysis for algae blooms in large river system. *Sustain. Cities Soc.* **51**, 101707 (2019).
72. Xia, R. et al. River algal blooms are well predicted by antecedent environmental conditions. *Water Res.* **185**, 116221 (2020).
73. Yang, N. et al. Dam-induced flow velocity decrease leads to the transition from heterotrophic to autotrophic system through modifying microbial food web dynamics. *Environ. Res.* **212**, 113568 (2022).
74. Lürling, M., Eshetu, F., Faassen, E. J., Kosten, S. & Huszar, V. L. M. Comparison of cyanobacterial and green algal growth rates at different temperatures. *Freshw. Biol.* **58**, 552–559 (2013).
75. Hallegraeff, G. M. et al. Perceived global increase in algal blooms is attributable to intensified monitoring and emerging bloom impacts. *Commun. Earth Environ.* **2**, 1–10 (2021).
76. Johnk, K. D. et al. Summer heatwaves promote blooms of harmful cyanobacteria. *Glob. Change Biol.* **14**, 495–512 (2008).
77. Whitworth, K. L. & Baldwin, D. S. Improving our capacity to manage hypoxic blackwater events in lowland rivers: the Blackwater Risk Assessment Tool. *Ecol. Modell.* **320**, 292–298 (2016).
78. Veraart, A. J., de Klein, J. J. M. & Scheffer, M. Warming can boost denitrification disproportionately due to altered oxygen dynamics. *PLoS ONE* **6**, e18508 (2011).
79. Hirabayashi, Y., Kanae, S., Emori, S., Oki, T. & Kimoto, M. Global projections of changing risks of floods and droughts in a changing climate. *Hydrol. Sci. J.-J. Des. Sci. Hydrol.* **53**, 754–772 (2008).
80. Breinl, K., Di Baldassarre, G., Mazzoleni, M., Lun, D. & Vico, G. Extreme dry and wet spells face changes in their duration. *Environ. Res. Lett.* **15**, ab7d05 (2020).
81. Blöschl, G. Three hypotheses on changing river flood hazards. *Hydrol. Earth Syst. Sci.* **26**, 5015–5033 (2022).
82. Carroll, R. W. H., Warwick, J. J., James, A. I. & Miller, J. R. Modeling erosion and overbank deposition during extreme flood conditions on the Carson River, Nevada. *J. Hydrol.* **297**, 1–21 (2004).
83. Dennis, I. A., Macklin, M. G., Coulthard, T. J. & Brewer, P. A. The impact of the October–November 2000 floods on contaminant metal dispersal in the River Swale catchment, North Yorkshire, UK. *Hydrol. Process.* **17**, 1641–1657 (2003).
84. Milačič, R., Zuliani, T., Vidmar, J., Oprčkal, P. & Ščančar, J. Potentially toxic elements in water and sediments of the Sava River under extreme flow events. *Sci. Total Environ.* **605–606**, 894–905 (2017).
85. Nábělková, J., Šťastná, G. & Komínková, D. Flood impact on water quality of small urban streams. *Water Sci. Technol.* **52**, 267–274 (2005).
86. Saha, A. et al. Impacts of a massive flood event on the physico-chemistry and water quality of River Pampa in Western Ghats of India. *Int. J. Environ. Anal. Chem.* **102**, 7969–7987 (2020).
87. van Emmerik, T. et al. Hydrology as a driver of floating river plastic transport. *Earth's Future* **10**, e2022EF002811 (2022).
88. Roebroek, C. T. J. et al. Plastic in global rivers: are floods making it worse? *Environ. Res. Lett.* **16**, 25003 (2021).
89. Scircle, A., Cizdziel, J. V., Missling, K., Li, L. & Vianello, A. Single-pot method for the collection and preparation of natural water for microplastic analyses: microplastics in the Mississippi River System during and after historic flooding. *Environ. Toxicol. Chem.* **39**, 986–995 (2020).
90. Eppehimer, D. E. et al. Impacts of baseflow and flooding on microplastic pollution in an effluent-dependent arid land river in the USA. *Environ. Sci. Pollut. Res. Int.* **28**, 45375–45389 (2021).
91. Costa, I. Dda et al. Is the Paraíba do Sul river colourful? Prevalence of microplastics in freshwater, south-eastern Brazil. *Mar. Freshw. Res.* **73**, 1439–1449 (2022).
92. Constant, M. et al. Microplastic fluxes in a large and a small Mediterranean river catchments: the Têt and the Rhône, Northwestern Mediterranean Sea. *Sci. Total Environ.* **716**, 136984 (2020).
93. de Carvalho, A. R., Riem-Galliano, L., ter Halle, A. & Cucherousset, J. Interactive effect of urbanization and flood in modulating microplastic pollution in rivers. *Environ. Pollut.* https://doi.org/10.2139/ssrn.4045864 (2022).
94. Treilles, R. et al. Microplastic and microfiber fluxes in the Seine River: flood events versus dry periods. *Sci. Total Environ.* **805**, 150123 (2022).
95. Zhdanov, I. et al. Assessment of seasonal variability of input of microplastics from the Northern Dvina river to the Arctic Ocean. *Mar. Pollut. Bull.* **175**, 113370 (2022).
96. Xu, D., Gao, B., Wan, X., Peng, W. & Zhang, B. Influence of catastrophic flood on microplastics organization in surface water of the Three Gorges Reservoir, China. *Water Res.* **211**, 118018 (2022).
97. Han, N., Ao, H., Mai, Z., Zhao, Q. & Wu, C. Characteristics of (micro)plastic transport in the upper reaches of the Yangtze river. *Sci. Total Environ.* **855**, 158887 (2023).
98. Hitchcock, J. N. Storm events as key moments of microplastic contamination in aquatic ecosystems. *Sci. Total Environ.* **734**, 139436 (2020).
99. Yang, C. P., Yu, Y. T. & Kao, C. M. Impact of climate change on Kaoping river water quality. *Appl. Mech. Mater.* **212–213**, 137–140 (2012).
100. Krein, A. et al. Concentrations and loads of dissolved xenobiotics and hormones in two small river catchments of different land use in Luxembourg. *Hydrol. Process.* **27**, 284–296 (2013).
101. Zouboulis, A. & Tolkou, A. Effect of climate change in wastewater treatment plants: reviewing the problems and solutions. *Manag. Water Resour. Under Clim. Uncertain.* https://doi.org/10.1007/978-3-319-10467-6_10/FIGURES/10 (2015).
102. Biswas, T. K. & Mosley, L. M. From mountain ranges to sweeping plains, in droughts and flooding rains; river Murray water quality over the last four decades. *Water Resour. Manag.* **33**, 1087–1101 (2019).
103. Rodrigues, M. T. et al. Human adenovirus spread, rainfalls, and the occurrence of gastroenteritis cases in a Brazilian basin. *Environ. Monit. Assess.* **187**, 720 (2015).
104. Whitworth, K. L., Baldwin, D. S. & Kerr, J. L. Drought, floods and water quality: drivers of a severe hypoxic blackwater event in a major river system (the southern Murray–Darling Basin, Australia). *J. Hydrol.* **450–451**, 190–198 (2012).
105. Lee, M., Shevliakova, E., Malyshev, S., Milly, P. C. D. & Jaffé, P. R. C. G. L. Climate variability and extremes, interacting with nitrogen storage, amplify eutrophication risk. *Geophys. Res. Lett.* https://doi.org/10.1002/2016gl069254 (2016).
106. Lee, M., Stock, C. A., Shevliakova, E., Malyshev, S. & Milly, P. C. D. Globally prevalent land nitrogen memory amplifies water pollution following drought years. *Environ. Res. Lett.* **16**, 014049 (2021).
107. Kaushal, S. S. et al. Interaction between urbanization and climate variability amplifies watershed nitrate export in Maryland. *Environ. Sci. Technol.* **42**, 5872–5878 (2008).
108. Kaushal, S. S. et al. Land use and climate variability amplify carbon, nutrient, and contaminant pulses: a review with management implications 1. *J. Am. Water Resour. Assoc.* **50**, 585–614 (2014).
109. Zhou, M. et al. Dilution or enrichment: the effects of flood on pollutants in urban rivers. *Environ. Sci. Eur.* **34**, 61 (2022).
110. Pailler, J. Y. et al. Behaviour and fluxes of dissolved antibiotics, analgesics and hormones during flood events in a small heterogeneous catchment in the grand Duchy of Luxembourg. *Water Air Soil Pollut.* **203**, 79–98 (2009).
111. Xie, H. & Ringler, C. Agricultural nutrient loadings to the freshwater environment: the role of climate change and socioeconomic change. *Environ. Res. Lett.* **12**, 104008 (2017).
112. Wang, M., Kroeze, C., Strokal, M., van Vliet, M. T. H. & Ma, L. Global change can make coastal eutrophication control in China more difficult. *Earth's Future* **8**, e2019EF001280 (2020).
113. van Vliet, M. T. H. et al. Global river discharge and water temperature under climate change. *Glob. Environ. Change Policy Dimens.* **23**, 450–464 (2013).
114. Eisner, S. et al. An ensemble analysis of climate change impacts on streamflow seasonality across 11 large river basins. *Clim. Change* **141**, 401–417 (2017).
115. Abily, M. et al. Climate change impact on EU rivers' dilution capacity and ecological status. *Water Res.* **199**, 117166 (2021).

116. Knapp, J. L. A., Von Freyberg, J., Studer, B., Kiewiet, L. & Kirchner, J. W. Concentration–discharge relationships vary among hydrological events, reflecting differences in event characteristics. *Hydrol. Earth Syst. Sci.* **24**, 2561–2576 (2020).
117. Kaushal, S. S. et al. Freshwater salinization syndrome on a continental scale. *Proc. Natl Acad. Sci. USA* **115**, E574–E583 (2018).
118. Bartholow, J. M. Recent water temperature trends in the lower Klamath river, California. *North Am. J. Fish. Manag.* **25**, 152–162 (2005).
119. Kaushal, S. S. et al. Rising stream and river temperatures in the United States. *Front. Ecol. Environ.* **8**, 461–466 (2010).
120. Pekarova, P. et al. Long-term trend and multi-annual variability of water temperature in the pristine Bela River basin (Slovakia). *J. Hydrol.* **400**, 333–340 (2011).
121. Webb, B. W. & Nobilis, F. Long-term changes in river temperature and the influence of climatic and hydrological factors. *Hydrol. Sci. J.-J. Des. Sci. Hydrol.* **52**, 74–85 (2007).
122. Lammers, R. B., Pundsack, J. W. & Shiklomanov, A. I. Variability in river temperature, discharge, and energy flux from the Russian pan-Arctic landmass. *J. Geophys. Res.* **112**, 1–15, G04S59 (2007).
123. Liu, B. Z., Yang, D. Q., Ye, B. S. & Berezovskaya, S. Long-term open-water season stream temperature variations and changes over Lena River basin in Siberia. *Glob. Planet. Change* **48**, 96–111 (2005).
124. Wanders, N., van Vliet, M. T. H., Wada, Y., Bierkens, M. F. P. & van Beek, L. P. H. High-resolution global water temperature modeling. *Water Resou. Res.* **55**, 2760–2778 (2019).
125. Bosmans, J. et al. FutureStreams, a global dataset of future streamflow and water temperature. *Sci. Data* **9**, 307 (2022).
126. Punzet, M., Voß, F., Voß, A., Kynast, E. & Bärlund, I. A global approach to assess the potential impact of climate change on stream water temperatures and related in-stream first-order decay rates. *J. Hydrometeorol.* **13**, 1052–1065 (2012).
127. Delpla, I., Jung, A.-V., Baures, E., Clement, M. & Thomas, O. Impacts of climate change on surface water quality in relation to drinking water production. *Environ. Int.* **35**, 1225–1233 (2009).
128. Soong, J. L., Phillips, C. L., Ledna, C., Koven, C. D. & Torn, M. S. CMIP5 models predict rapid and deep soil warming over the 21st century. *J. Geophys. Res. Biogeosci.* **125**, e2019JG005266 (2020).
129. Zhang, Q., Qin, W., Feng, J. & Zhu, B. Responses of soil microbial carbon use efficiency to warming: review and prospects. *Soil. Ecol. Lett.* **4**, 307–318 (2022).
130. Melillo, J. M. et al. Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. *Science* **358**, 101–105 (2017).
131. Koch, O., Tscherko, D. & Kandeler, E. Temperature sensitivity of microbial respiration, nitrogen mineralization, and potential soil enzyme activities in organic alpine soils. *Glob. Biogeochem. Cycles* **21**, 4017 (2007).
132. Hicks Pries, C. E., Castanha, C., Porras, R. C. & Torn, M. S. The whole-soil carbon flux in response to warming. *Science* **355**, 1420–1423 (2017).
133. Bai, E. et al. A meta-analysis of experimental warming effects on terrestrial nitrogen pools and dynamics. *N. Phytol.* **199**, 441–451 (2013).
134. Turner, M. M. & Henry, H. A. L. Net nitrogen mineralization and leaching in response to warming and nitrogen deposition in a temperate old field: the importance of winter temperature. *Oecologia* **162**, 227–236 (2010).
135. Valenca, R., Ramnath, K., Dittrich, T. M., Taylor, R. E. & Mohanty, S. K. Microbial quality of surface water and subsurface soil after wildfire. *Water Res.* **175**, 115672 (2020).
136. Abbott, B. W. et al. Tundra wildfire triggers sustained lateral nutrient loss in Alaskan Arctic. *Glob. Change Biol.* **27**, 1408–1430 (2021).
137. Santos, R. M. B., Sanches Fernandes, L. F., Pereira, M. G., Cortes, R. M. V. & Pacheco, F. A. L. Water resources planning for a river basin with recurrent wildfires. *Sci. Total Environ.* **526**, 1–13 (2015).
138. Sterling, S. M., Ducharne, A. & Polcher, J. The impact of global land-cover change on the terrestrial water cycle. *Nat. Clim. Change* **3**, 385–390 (2012).
139. Cao, Q., Sun, N., Yearsley, J., Nijssen, B. & Lettenmaier, D. P. Climate and land cover effects on the temperature of puget sound streams. *Hydrol. Process.* **30**, 2286–2304 (2016).
140. Green, P. et al. Pre-industrial and contemporary fluxes of nitrogen through rivers: a global assessment based on typology. *Biogeochemistry* **68**, 71–105 (2004).
141. Meybeck, M. Global analysis of river systems: from Earth system controls to Anthropocene syndromes. *Philos. Trans. R. Soc. B Biol. Sci.* **358**, 1935–1955 (2003).
142. Stets, E. G. et al. Landscape drivers of dynamic change in water quality of U.S. rivers. *Environ. Sci. Technol.* **54**, 4336–4343 (2020).
143. Bouraoui, F. & Grizzetti, B. Long term change of nutrient concentrations of rivers discharging in European seas. *Sci. Total Environ.* **409**, 4899–4916 (2011).
144. Miller, J. D. & Hutchins, M. The impacts of urbanisation and climate change on urban flooding and urban water quality: a review of the evidence concerning the United Kingdom. *J. Hydrol. Reg. Stud.* **12**, 345–362 (2017).
145. Marlow, T., Elliott, J. R. & Frickel, S. Future flooding increases unequal exposure risks to relic industrial pollution. *Environ. Res. Lett.* **17**, 074021 (2022).
146. Ntelekos, A. A., Oppenheimer, M., Smith, J. A. & Miller, A. J. Urbanization, climate change and flood policy in the United States. *Clim. Change* **103**, 597–616 (2010).
147. Koop, S. H. A. The challenges of water, waste and climate change in cities. *Environ. Dev. Sustain.* **19**, 385–418 (2017).
148. Strokal, M. et al. Urbanization: an increasing source of multiple pollutants to rivers in the 21st century. *npj Urban Sustain.* **1**, 24 (2021).
149. Bloomfield, J. P., Williams, R. J., Gooddy, D. C., Cape, J. N. & Guha, P. Impacts of climate change on the fate and behaviour of pesticides in surface and groundwater — a UK perspective. *Sci. Total Environ.* **369**, 163–177 (2006).
150. Jones, E. R. et al. Sub-Saharan Africa will increasingly become the dominant hotspot of surface water pollution. *Nat. Water* **1**, 602–613 (2023).
151. Morin-Crini, N. et al. Emerging contaminants: analysis, aquatic compartments and water pollution. Emerging Contaminants Vol. 1 https://doi.org/10.1007/978-3-030-69079-3_1 (2021).
152. Pérez, C. J., Vega-Rodríguez, M. A., Reder, K. & Flörke, M. A multi-objective artificial bee colony-based optimization approach to design water quality monitoring networks in river basins. *J. Clean. Prod.* **166**, 579–589 (2017).
153. Ryberg, K. R. & Chanat, J. G. Climate extremes as drivers of surface-water-quality trends in the United States. *Sci. Total Environ.* **809**, 152165 (2022).
154. Mengel, M., Treu, S., Lange, S. & Frieler, K. ATTRICI v1.1 — counterfactual climate for impact attribution. *Geosci. Model Dev.* **14**, 5269–5284 (2021).
155. Michalak, A. M. Study role of climate change in extreme threats to water quality. *Nature* **535**, 349–350 (2016).
156. Sinha, E., Michalak, A. M. & Balaji, V. Eutrophication will increase during the 21st century as a result of precipitation changes. *Science* **357**, 405–408 (2017).
157. Sinha, E. et al. Modeling perennial bioenergy crops in the E3SM land model (ELMv2). *J. Adv. Model. Earth Syst.* https://doi.org/10.1029/2022MS003171 (2023).
158. van Vliet, M. T. H. et al. Model inter-comparison design for large-scale water quality models. *Curr. Opin. Environ. Sustain.* **36**, 59–67 (2019).
159. WWQA. *A Partnership Effort*. https://www.unep.org/explore-topics/water/what-we-do/improving-and-assessing-world-water-quality-partnership-effort (accessed 2023).
160. ISIMIP. *Inter-Sectoral Impact Model Intercomparison Project*. https://www.isimip.org/ (accessed 2023).
161. Chen, X. et al. Multi-scale modeling of nutrient pollution in the rivers of China. *Environ. Sci. Technol.* **53**, 9614–9625 (2019).
162. Tang, T. et al. Bridging global, basin and local-scale water quality modeling towards enhancing water quality management worldwide. *Curr. Opin. Environ. Sustain.* **36**, 39–48 (2019).
163. Hofstra, N., Kroeze, C., Flörke, M. & van Vliet, M. T. H. Editorial overview: water quality: a new challenge for global scale model development and application. *Curr. Opin. Environ. Sustain.* **36**, A1–A5 (2019).
164. Strokal, M. et al. Cost-effective management of coastal eutrophication: a case study for the Yangtze River basin. *Resour. Conserv. Recycl.* **154**, 104635 (2020).
165. Wang, M. et al. Accounting for interactions between sustainable development goals is essential for water pollution control in China. *Nat. Commun.* **13**, 730 (2022).
166. Jarosiewicz, P., Fazi, S. & Zalewski, M. How to boost ecohydrological nature-based solutions in water quality management. *Ecohydrol. Hydrobiol.* **22**, 226–233 (2022).
167. *Copernicus Global Land Surface — Lake Water Quality* (Copernicus, 2023); https://land.copernicus.eu/global/products/lwq.
168. *IIWQ World Water Quality Information and Capacity Building Portal* (UNESCO & EOMAP, 2023); http://www.worldwaterquality.org/.
169. Dekker, A. & Hestir, E. *Evaluating the Feasibility of Systematic Inland Water Quality Monitoring with Satellite Remote Sensing, CSIRO: Water for a Healthy Country National Research Flagship* (CSIRO, 2012).
170. Lymburner, L. et al. Landsat 8: providing continuity and increased precision for measuring multi-decadal time series of total suspended matter. *Remote Sens. Environ.* **185**, 108–118 (2016).
171. Mi, H., Fagherazzi, S., Qiao, G., Hong, Y. & Fichot, C. G. Climate change leads to a doubling of turbidity in a rapidly expanding Tibetan lake. *Sci. Total Environ.* **688**, 952–959 (2019).
172. Baltodano, A., Agramont, A., Reusen, I. & van Griensven, A. Land cover change and water quality: how remote sensing can help understand driver–impact relations in the Lake Titicaca basin. *Water* **14**, 1021 (2022).
173. Odermatt, D., Giardino, C. & Heege, T. Chlorophyll retrieval with MERIS Case-2-Regional in perialpine lakes. *Remote Sens. Environ.* **114**, 607–617 (2010).
174. Heege, T., Kiselev, V., Wettle, M. & Hung, N. N. Operational multi-sensor monitoring of turbidity for the entire Mekong Delta. *Int. J. Remote Sens.* **35**, 2910–2926 (2014).
175. Lisle, S., D, P. J. & H, M. W. An evaluation of nitrate, fDOM, and turbidity sensors in New Hampshire streams. *Water Resour. Res.* **54**, 2466–2479 (2018).
176. Handcock, R. N. et al. Accuracy and uncertainty of thermal-infrared remote sensing of stream temperatures at multiple spatial scales. *Remote Sens. Environ.* **100**, 427–440 (2006).
177. Chen, C. Q., Shi, P. & Mao, Q. W. Application of remote sensing techniques for monitoring the thermal pollution of cooling-water discharge from nuclear power plant. *J. Environ. Sci. Heal. A* **38**, 1659–1668 (2003).
178. Ling, F. et al. Monitoring thermal pollution in rivers downstream of dams with Landsat ETM+ thermal infrared images. *Remote Sens.* **9**, 1175 (2017).
179. Luo, L. et al. A novel early warning system (EWS) for water quality, integrating a high-frequency monitoring database with efficient data quality control technology at a large and deep lake (Lake Qiandao), China. *Water* **14**, 602 (2022).
180. Kirschke, S. et al. Citizen science projects in freshwater monitoring. From individual design to clusters? *J. Environ. Manage* **309**, 114714 (2022).
181. Deltares. Nitrate App. https://publicwiki.deltares.nl/display/wqapp (2023).
182. Beusen, A. H. W. et al. Exploring river nitrogen and phosphorus loading and export to global coastal waters in the shared socio-economic pathways. *Glob. Environ. Change* **72**, 102426 (2022).
183. Jones, E. R., van Vliet, M. T. H., Qadir, M. & Bierkens, M. F. P. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. *Earth Syst. Sci. Data* **13**, 237–254 (2021).

184. Ehalt Macedo, H. et al. Distribution and characteristics of wastewater treatment plants within the global river network. *Earth Syst. Sci. Data* **14**, 559–577 (2022).
185. Desbureaux, S. et al. Mapping global hotspots and trends of water quality (1992–2010): a data driven approach. *Environ. Res. Lett.* **17**, 114048 (2022).
186. Hameed, M. et al. Application of artificial intelligence (AI) techniques in water quality index prediction: a case study in tropical region, Malaysia. *Neural Comput. Appl.* **28**, 893–905 (2017).
187. Chau, K. A review on integration of artificial intelligence into water quality modelling. *Mar. Pollut. Bull.* **52**, 726–733 (2006).
188. Khan, Y. & Chai, S. S. Ensemble of ANN and ANFIS for water quality prediction and analysis — a data driven approach. *J. Telecommun. Electron. Comput. Eng.* **9**, 117–122 (2017).
189. Heddam, S. & Kisi, O. Modelling daily dissolved oxygen concentration using least square support vector machine, multivariate adaptive regression splines and M5 model tree. *J. Hydrol.* **559**, 499–509 (2018).
190. Wang, X., Zhang, F. & Ding, J. Evaluation of water quality based on a machine learning algorithm and water quality index for the Ebinur Lake Watershed, China. *Sci. Rep.* **7**, 12858 (2017).
191. Yajima, H. & Derot, J. Application of the random forest model for chlorophyll-*a* forecasts in fresh and brackish water bodies in Japan, using multivariate long-term databases. *J. Hydroinformatics* **20**, jh2017010 (2017).

Acknowledgements

The authors kindly acknowledge J. Banken of Wageningen University and K. Schweden of Ruhr University Bochum for their assistance with collecting water quality literature. The authors thank M. Stoete of Utrecht University for her assistance in designing some figures. The authors also acknowledge the World Water Quality Alliance (WWQA), ISI-MIP and EU COST-Action PROCLIAS initiatives. M.T.H.v.V. was financially supported by the European Union (ERC Starting Grant, B-WEX, Project 101039426) and Netherlands Scientific Organisation (NWO) by a VIDI grant (VI.Vidi.193.019). M.S. was supported by the Netherlands Scientific Organisation (NWO) by a VENI grant (016.Veni.198.001). J.T. was financially supported by The Swedish Research Council Formas (Project No. 2018-00812).

Author contributions

M.T.H.v.V. designed and led the study and manuscript effort. J.T. contributed to the design of the literature review. J.T., M.S., N.H., M.F., H.E.M., A.N., T.T. and M.T.H.v.V. collected literature for the analyses and wrote reports for specific water quality constituents for the supplementary information. L.M.M., S.S.K. and R.K. contributed to the writing of specific sections. All authors contributed to the writing of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43017-023-00472-3.

Peer review information *Nature Reviews Earth & Environment* thanks J. Rozemeijer, D. Barceló, E. Douglas and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

[1]Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands. [2]Department of Physical Geography and the Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden. [3]Water Systems and Global Change Group, Wageningen University, Wageningen, The Netherlands. [4]Institute of Engineering Hydrology and Water Resources Management, Ruhr University Bochum, Bochum, Germany. [5]Department of Geography, McGill University, Montréal, Quebec, Canada. [6]Vrije Universiteit Brussel, Brussels, Belgium. [7]Directorate of Water Resources Management, Ministry of Water and Environment, Kampala, Uganda. [8]International Institute for Applied Systems Analysis, Laxenburg, Austria. [9]Department of Geology and Earth System Science Interdisciplinary Center, University of Maryland, UMD, College Park, MD, USA. [10]Helmholtz Centre for Environmental Research — UFZ, Leipzig, Germany. [11]Department of Earth Sciences — Geochemistry, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands. [12]PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands. [13]School of Biological Sciences, Faculty of Science, Engineering and Technology, University of Adelaide, Adelaide, SA, Australia.

https://doi.org/10.1038/s44221-023-00158-6

Complex interplay of water quality and water use affects water scarcity under droughts and heatwaves

Michelle T. H. van Vliet

Droughts and heatwaves amplify water scarcity by decreasing water availability, worsening water quality and increasing sectoral water use. These three driving mechanisms interact strongly, but insights into this complex interplay, particularly between water quality and sectoral water use, are urgently needed to unravel the drivers of water scarcity and to identify robust solutions for sustainable water management.

Droughts and heatwaves pose serious challenges for water management by drastically increasing water scarcity in many regions of the world[1]. These events are marked by high associated economic losses. For instance, the 2022 droughts in Europe, the USA and China were among the ten costliest disasters, resulting in economic losses of at least US$22 billion, US$16 billion and US$7.6 billion, respectively[2]. With droughts and heatwaves occurring more frequently, younger people will nowadays be exposed to more of these hydroclimate extremes over their lifetimes[3]. There is an urgent need to improve our water management to alleviate severe water scarcity and the number of affected people.

Water scarcity has traditionally been estimated by focusing solely on water quantity[1], but the useability of water for different sectoral uses also depends on suitable water quality. Water scarcity thus represents more than the physical lack of water, taking into account the imbalance between the supply and demand of water resources of suitable quality for various sectoral uses[1,4,5].

Water-scarcity drivers under droughts and heatwaves

Both changes in climate (precipitation, temperature and evaporation) and changes in socioeconomic systems (population and GDP) drive the availability, use and quality of water resources (Fig. 1a), directly affecting water scarcity[1,4,5]. Hence, water scarcity increases when one or more of the following three driving mechanisms intensify: decreasing water availability; increasing sectoral water use, and worsening water quality.

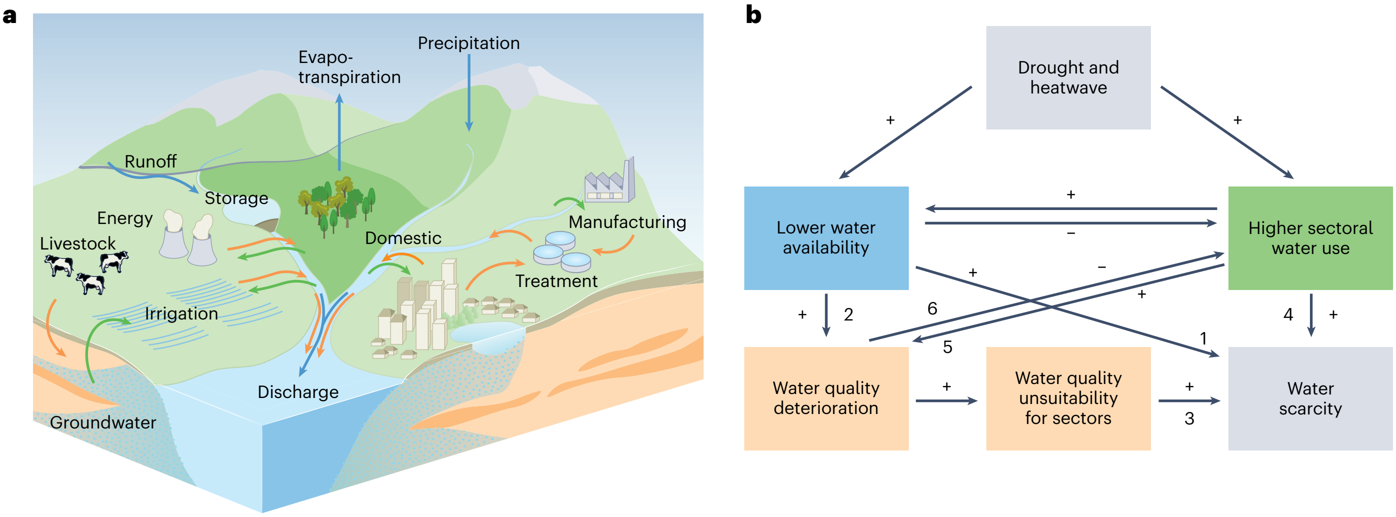


Fig. 1 | Water-source, water-pollution and water-use interactions, leading to higher water scarcity under droughts and heatwaves. a, Water-use (green arrows) and pollutant-loading (orange arrows) pathways are indicated for the agriculture (irrigation, livestock), domestic, energy and manufacturing sectors and along with main hydrological fluxes driving the availability of water resources (blue arrows). There are multiple water-quality constituents of sectoral water use, such as water temperature in the thermoelectric power sector; salinity, nutrients and pesticides in agricultural use; and pharmaceuticals, pathogenic and organic pollution in domestic use. **b**, Complex interplay of lower water availability (blue), higher sectoral water use (green) and deterioration of water quality (orange). Positive and negative responses are indicated by + and −, respectively, and numbered arrows refer to the descriptions of driving mechanisms in the main text.

Droughts and heatwaves are particularly critical, because they adversely affect all three mechanisms, which are also highly interrelated. Declines in water availability during these extreme events increase water scarcity directly (arrow 1; Fig. 1b), but also indirectly by degrading surface water quality (arrow 2; Fig. 1b), for instance, by reducing the capacity of rivers to dilute pollutants. The effects on water quality of droughts and heatwaves can be substantial and show a deterioration in 68% of analysed case studies (105) for rivers and streams globally[6]. This deterioration in water quality aggravates water scarcity when water-quality requirements for certain sectoral uses are not met, for instance if the salinity levels for irrigation water use are exceeded[7] or if the water temperature limits for cooling of thermoelectric power plants are exceeded[8] (arrow 3; Fig. 1b). Droughts and heatwaves also increase sectoral water demands, such as for domestic use and irrigation[9], resulting in higher water scarcity directly, from a water-quantity perspective (arrow 4; Fig. 1b). Indirectly, pollutant emissions from increasing sectoral water uses may increase water scarcity further by worsening water quality, particularly in regions with limited (waste) water treatment capacity[4] (arrow 5; Fig. 1b).

Water-use sectors depend strongly on clean water, but contribute to water pollution by its use, resulting in a complex, paradoxical interplay (arrows 5 and 6; Fig. 1b). For instance, increased water temperatures severely constrain the use of cooling water and thermoelectric power supply, particularly during warm dry spells[8], but the thermoelectric power sector is also itself the dominant source of thermal pollution in rivers globally[10]. Elevated freshwater salinity levels during droughts severely constrain irrigation water use and crop production[7], but irrigation itself has been shown to be the main human driver of freshwater salinization of river systems globally[11]. Similarly, high concentrations of pathogens, pharmaceuticals, organic pollution and various other pollutants adversely affect the domestic use of water, particularly when (waste)water treatment levels and capacities are low. However, the domestic sector is also the major contributing sector and source for most of these pollutants globally[12].

Water quality can potentially constrain sectoral water use when its thresholds in surface waters are exceeded. This, in turn, exacerbates water scarcity. Global and regional studies have shown that water scarcity is strongly driven by water-quality issues, particularly in the water-scarcity hotspot regions[4,5]. In such hotspots, excessive sectoral water withdrawals not only contribute to water scarcity from a water-quantity perspective, but also polluted return flows degrade water quality downstream.

Identifying suitable solutions for sustainable water management requires more than knowledge of these driving mechanisms. A better understanding of the exact contribution of these mechanisms and their complex interplay is crucial. We need to develop tools and assessment frameworks to unravel the drivers of water scarcity. Such tools must enable us to account for the complex interactions and feedbacks between the availability, quality and sectoral use of water; to provide daily/weekly and high-spatial-resolution quantifications of water scarcity and its driving mechanisms under hydroclimatic extremes; and to allow for the implementation of suitable water-management options towards the alleviation of water scarcity.

Interplay of water quality and sectoral water use

To improve our understanding of water scarcity and its driving mechanisms under hydroclimatic extremes such as droughts and heatwaves, we need to develop integrated water-scarcity assessment frameworks that account for the full coupling between water availability, sectoral water use and water quality. Although the interactions between sectoral water use and surface/groundwater availability are studied widely[13,14], their interplay and feedbacks with water quality have in general not been studied. Water-quality models are usually run offline from hydrological and water-resources models, and if they are coupled, there is normally only a one-directional flow of hydrological and sectoral water-use data into the water-quality models[12]. The interplay of how water-quality constraints (that is, exceeded water-quality thresholds for sectoral use) reduce water-use potentials is overall disregarded. Fully coupled modelling frameworks representing the two-way interplay of water quality and sectoral use could help us to obtain more realistic estimates of competition for water resources (in terms of both quantity and water quality in different sectors) and of water scarcity (particularly during critical events such as droughts and heatwaves).

High-spatiotemporal-resolution estimates under hydroclimatic extremes

Large-scale water-scarcity studies have so far focused mainly on average conditions by using monthly or annual estimates of water availability and sectoral water use[1], and in some cases also of water quality[4,5]. However, this generally results in ignorance of the impacts of hydroclimatic extremes (droughts, heatwaves and compound drought–heatwave events) on water-scarcity levels. Higher-temporal-resolution simulations, either daily or weekly, of water availability, sectoral water use and water quality are therefore key to capturing these impacts of hydroclimatic extremes.

With increasing computational power and rapid developments in high-performance computing, there are opportunities for higher-spatiotemporal-resolution simulations of both the quantity and quality of water resources[12,15]. Although high-frequency water-quality monitoring records are sparse and the quantification of temporally detailed pollution loading in water systems remain challenging, new high-resolution datasets (such as for wastewater treatment) have supported the development of high-spatiotemporal-resolution water-quality modelling globally (with daily and 5-arcminute resolution)[12]. These model developments can help us to account for water-quality responses and interactions with sectoral water use and water availability under droughts and heatwaves at regional to global levels.

Implementing water-management options for water-scarcity alleviation

Understanding the interactions between the quality, availability and sectoral use of water resources during present and future droughts and heatwaves is paramount when searching for suitable water-management options aimed at alleviating water scarcity. We thus need to unravel the drivers of water scarcity under these hydroclimatic extremes to develop suitable solutions in the major water-scarcity hotspots of the world. Water-scarcity alleviation options traditionally focus on increasing freshwater availability (such as increasing reservoir storage[14] and desalination of seawater[4]) or increasing water-use efficiencies (such as shifting to higher-efficiency irrigation techniques[7] or changing the type of power-plant cooling system[8]). Recently, there has been a growing focus on options that contribute to water-quality improvements (such as reducing pollutant emissions or expanding wastewater treatment and reuse[4]). Water-scarcity assessment frameworks should account for the implementation of synergistic combinations of solutions, including the synergies, trade-offs and cost-effectiveness of these options. These could include sectoral water-use reductions, water-quality improvements and increases in clean water availability to achieve the all-encompassing goal of sufficient clean water for all – including future generations, which will face more intense and more frequent droughts and heatwaves.

Michelle T. H. van Vliet
Department of Physical Geography, Faculty of Geosciences,
Utrecht University, Utrecht, The Netherlands.
e-mail: m.t.h.vanvliet@uu.nl

References

1. Liu, J. et al. *Earth's Future* **5**, 545–559 (2017).
2. *Weather, Climate and Catastrophe Insight 2022* (AON, 2023).
3. Thiery, W. et al. *Science* **374**, 158–160 (2021).
4. van Vliet, M. T. H. et al. *Environ. Res. Lett.* **16**, 024020 (2021).
5. Ma, T. et al. *Nat. Commun.* **11**, 650 (2020).
6. van Vliet, M. T. H. et al. *Nat. Rev. Earth Environ.* **4**, 687–702 (2023).
7. Assouline, S., Russo, D., Silber, A. & Or, D. *Water Resour. Res.* **51**, 3419–3436 (2015).
8. Miara, A. et al. *Nat. Clim. Change* **7**, 793–798 (2017).
9. Cárdenas Belleza, G. A. et al. *Environ. Res. Lett.* **18**, 104008 (2023).
10. Raptis, C. E. et al. *Environ. Res. Lett.* **11**, 104011 (2016).
11. Thorslund, J. et al. *Nat. Commun.* **12**, 4232 (2021).
12. Jones, E. R. et al. *Geosci. Model Dev.* **16**, 4481–4500 (2023).
13. Haddeland, I. et al. *Proc. Natl Acad. Sci. USA* **111**, 3251–3256 (2014).
14. Di Baldassarre, G. et al. *Nat. Sustain.* **1**, 617–622 (2018).
15. Bierkens, M. F. P. et al. *Hydrol. Process.* **29**, 310–320 (2015).

Acknowledgements

The author was financially supported by the European Union (ERC Starting Grant, B-WEX, Project 101039426) and The Netherlands Scientific Organisation (NWO) by a VIDI grant (VI.Vidi.193.019).

Competing interests

The author declares no competing interests.