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Current wastewater treatment targets are insufficient to protect surface water quality

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The quality of global water resources is increasingly strained by socio-economic developments and climate change, threatening both human livelihoods and ecosystem health. With inadequately managed wastewater being a key driver of deterioration, Sustainable Development Goal (SDG) 6.3 was established to halve the proportion of untreated wastewater discharged to the environment by 2030. Yet, the impact of achieving SDG6.3 on global ambient water quality is unknown. Addressing this knowledge gap, we develop a high-resolution surface water quality model for salinity as indicated by total dissolved solids, organic pollution as indicated by biological oxygen demand and pathogen pollution as indicated by fecal coliform. Our model includes a novel spatially-explicit approach to incorporate wastewater treatment practices, a key determinant of in-stream pollution. We show that achieving SDG6.3 reduces water pollution, but is still insufficient to improve ambient water quality to below key concentration thresholds in several world regions. Particularly in the developing world, reductions in pollutant loadings are locally effective but transmission of pollution from upstream areas still leads to water quality issues downstream. Our results highlight the need to go beyond the SDG-target for wastewater treatment in order to achieve the overarching goal of clean water for all.

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Compared to water availability (e.g. river discharge), few observations and large-scale modelling assessments exist for understanding global surface water quality[1]. Inadequate water quality for different sectoral purposes poses a variety of constraints across the water-food-energy-ecosystem nexus[2]: organic and pathogen pollution causes risks to human health[3], increased salinity levels threaten agricultural productivity[4] and increased water temperatures can disrupt thermoelectric power plants that depend on surface water resources for cooling[5,6]. Moreover, all these pollutants can adversely affect the aquatic environment[7]. Improving our ability to accurately simulate in-stream pollutant concentrations is therefore key to improved understanding of the threats to global clean water resources and to devise management options that safeguard clean water for all[8,9].

Sectoral activities artificially increase surface water pollutant concentrations by discharging polluted water back to the environment, particularly in regions with limited wastewater treatment[8–10]. The existence of and degree to which treatment practices reduce contaminant levels[11] and the proportion of (treated) wastewater relative to streamflow[12] are crucial determinants of the quality of receiving waters[11,13]. The importance of wastewater management practices is recognised in Sustainable Development Goal (SDG) target 6.3[14], which sets the target of halving the proportion of untreated wastewater released to the environment by 2030. With inadequately managed wastewater being the key driver of water pollution, this target represents the principal action for achieving the overarching goal of improved ambient water quality. Yet, no study has quantitatively assessed the effectiveness of achieving SDG6.3 on global ambient water quality.

Here we develop a high-resolution surface water quality model (henceforth *DynQual*) that is essential for addressing this knowledge gap. DynQual simulates surface water temperature (Tw), salinity as indicated by total dissolved solids (TDS), organic pollution as indicated by biological oxygen demand (BOD) and pathogen pollution as indicated by faecal coliform (FC) concentrations (Fig. S1). The model is unique in that it operates at an unprecedented spatial resolution of 5×5 arc-minutes (~10 km at the equator) and simulates water quality dynamically at daily temporal resolution globally. Water temperature (Tw) is simulated using a heat-advection approach[15,16] with thermoelectric powerplant effluents added as an additional point source of advected heat (Fig. S2). Pollutant loadings of TDS, BOD and FC are calculated per sector following previous approaches[8,9] (Supplementary Notes 1). The high spatial resolution of our model allows for meaningful inclusion of a novel spatially explicit wastewater treatment dataset[11], further disaggregated by treatment level (Supplementary Notes 4 and Fig. S12), that is more representative of the real-world situation compared to existing approaches. Pollutant loadings are subsequently routed through the global stream network to calculate in-stream concentrations at the daily timestep. The model accounts for both the dilution capacity of the rivers and natural degradation processes (see Methods and Supplementary Notes 2).

Results

Global surface water quality. Modelled water temperature (Tw) and in-stream concentrations of TDS, BOD and FC show overall good agreement with the observed data (Supplementary Notes 3). Global patterns in salinity, organic and pathogen pollution at the high spatial resolution (Fig. 1) are consistent with previous work[8,9]. While TDS concentrations are strongly influenced by geological factors, hotspots of high salinity pollution (>2100 mg l^{-1} TDS) correspond to heavily industrialised regions, such as north-eastern China and the contiguous United States, and to heavily irrigated regions such as northern India (Fig. 1a; Figs. S3 and S6). Exceedance of the salinity threshold in these regions tends to occur for more than half the year (>6 months) and occasionally year-round. More localised salinity pollution is also common in the tributaries to some major European rivers, before dissipating due to the increased dilution capacity of the main stream. Exceedance of the salinity threshold between 1–3 months per year occur in the Mediterranean and across large swathes of Africa. Exceedance of salinity thresholds are relatively low across South America, although some seasonal exceedances do occur in the more populated and industrialised regions.

Global patterns in the exceedance of BOD (8 mg l^{-1}) and FC (1000 cfu 100 ml^{-1}) thresholds follow similar patterns, attributed to the pollutant loadings originating from similar sectoral sources (Fig. 1b, c; Figs. S4–S6). However, both the frequency and magnitude of FC threshold exceedances are larger than for TDS and BOD. Modelled FC concentrations can occasionally exceed 10,000 cfu 100 ml^{-1}, with the most polluted river stretches having FC concentrations surpassing 1 million cfu 100 ml^{-1}. Exceedances of BOD and FC thresholds are typically very low in sparsely populated locations, such as in northern high-latitudes and wet-tropical rainforests. In most other world regions, exceedance of organic and pathogen pollution thresholds are commonplace for at least some part of the year. Across East and Southern Asia, in-stream concentrations of BOD and FC that exceed quality thresholds are occurring both frequently and across many streams irrespective of river discharge (i.e. dilution capacity). Year-round exceedances of thresholds, especially for FC, are very high across China. Frequent exceedances are also widespread across Africa, such as in the tributaries of the Nile and the Niger, with typically more seasonal exceedances in the main channels of these rivers. BOD and FC thresholds are also exceeded across many parts of Western Europe, Japan and the Eastern Seaboard of the USA, despite wastewater treatment rates already being high. However, exceedances in these regions tend to be more seasonal and do not typically occur in rivers with large year-round discharges. Statistics aggregated by geographical region are displayed in Fig. S7.

Figure 1d displays the incidences of threshold exceedance in any month of the year aggregated across multiple water quality constituents. Thus, a value of 2 denotes that 2 out of 3 of the water quality constituent thresholds are jointly exceeded in at least 1 month, with monthly concentrations averaged over 2006–2015. In line with the analysis of individual water quality constituents, no exceedances in any of the water quality thresholds considered are found for large portions of the high-latitude and wet-tropical regions. Conversely, in most other populated regions, one or more water quality thresholds are exceeded in at least 1 month per year. Simultaneous exceedances of all three water quality constituents (i.e. TDS, BOD, FC) mostly occur where large seasonal variations in river discharge (e.g. Africa, India) exist. High TDS loadings can be mostly attributed to either large scale irrigation systems (e.g. North India) or manufacturing activities (e.g. East China). Exceedances in BOD and FC concentrations are commonplace both where wastewater treatment rates are low (e.g. East Asia and Pacific, Southern Asia) and high (e.g. Western Europe, Northern America). This demonstrates the importance of dilution (i.e. river discharge) in determining in-stream concentrations. Incidences where only one water quality constituent shows exceeded concentrations are mostly attributed to FC, and mostly during low-flow seasons.

Halving the proportion of untreated wastewater (SDG6.3). Expansions in wastewater treatment to achieve SDG6.3 are designated at the country-level and delineated to gridcells based
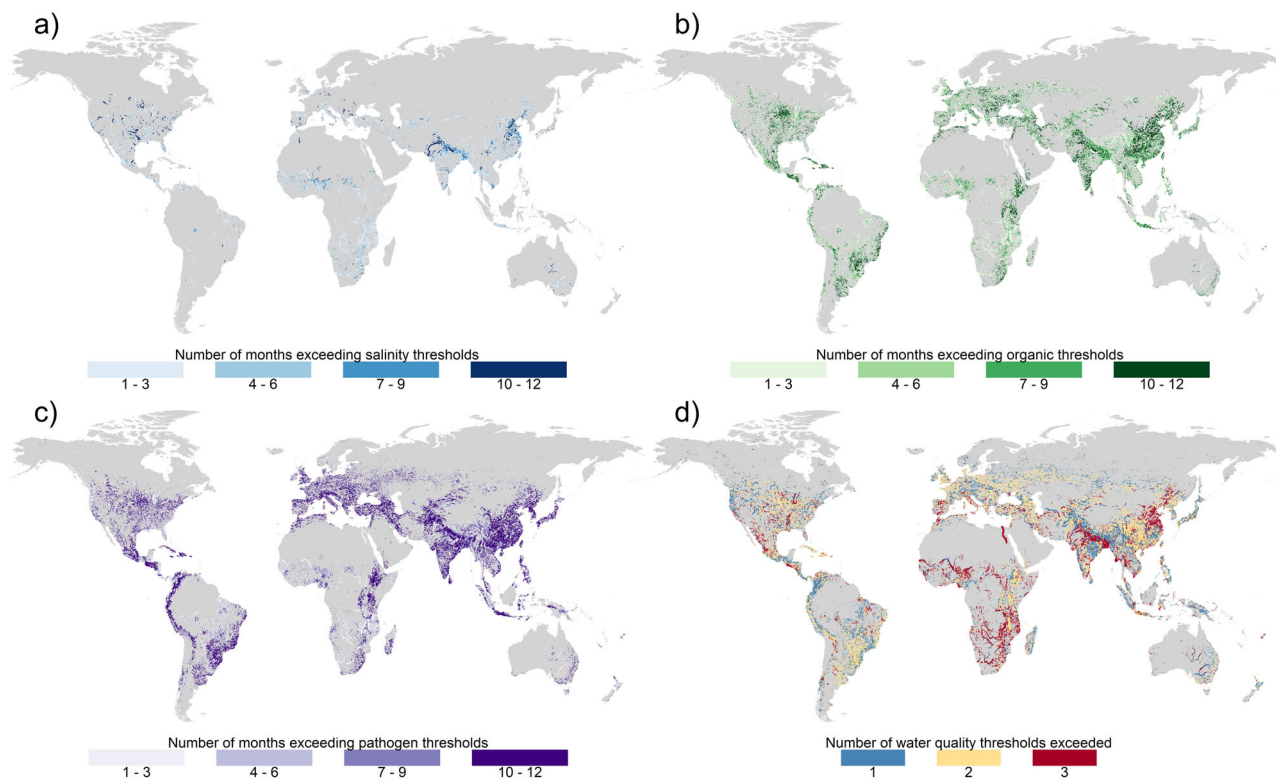
Fig. 1 Historical exceedances of key water quality thresholds for sectoral water use. Number of months per year exceeding key water quality thresholds for **a** total dissolved solids (TDS) (2100 mg l^{-1}); **b** biological oxygen demand (BOD) (8 mg l^{-1}); and **c** faecal coliform (FC) (1000 cfu 100 ml^{-1}), averaged over 2006–2015. **d** The combined number of water quality thresholds (i.e. TDS, BOD and FC) exceeded in any month of the year, averaged over 2006-2015. Only streams with an average annual discharge >1 m s^{-1} are displayed.

upon where pollutant loadings are highest (Supplementary Notes 5 and Figs. S14–15). Figure 2a displays the top 30 countries with the largest required expansions in wastewater treatment. Together, these 30 countries account for ~87% of the total required expansions to achieve SDG6.3. The largest expansions required before 2030 are in China (40 billion m^3 yr^{-1}), the USA (16 billion m^3 yr^{-1}) and India (15 billion m^3 yr^{-1}), with these three countries alone accounting for ~45% of the required expansions. Expansions are required across many regions in the populated areas of North America and Europe, particularly where (a proportion of) the collected wastewater is still released to the environment without treatment. Conversely, in world regions with little or no wastewater treatment in 2015, the expansions required to achieve SDG6.3 are fulfilled by establishing wastewater treatment in only a few, densely populated locations. While high percentage reductions in pollutant loadings are achieved in these specific locations, achieving SDG6.3 in these regions has a more limited impact on pollutant loadings across geographical space (Fig. S16).

As we assume that secondary wastewater treatment practices do not influence TDS loadings[9], the expansions in wastewater treatment influence BOD and FC loadings and concentrations only. This assumption also means that reductions in gridded pollutant loadings are capped at 85% and 97.5%, which are the assumed pollutant removal efficiencies for secondary wastewater treatment for BOD and FC, respectively (Table S4). Figure 2b and Fig. 2c display the region-aggregated reductions in BOD and FC pollutant loadings relative to loadings without expansions in wastewater treatment. Strong (absolute) reductions are achieved in the East Asia and Pacific and Southern Asia regions. Reductions in total BOD loadings range from 16% to 32% across the different regions; and reductions in total FC loadings from 17% to 43%. While increases in wastewater treatment capacities

reduce point source pollution locally, the benefits to surface water quality also propagate downstream. The average annual reductions in BOD and FC concentrations when achieving SDG6.3 are displayed in Fig. 3a, b, respectively (see Figs. S17 and S18 for zoom-in panels).

While Fig. 3a, b are very similar, variations between BOD and FC reductions occur due to: (1) the different removal efficiencies associated with secondary wastewater treatment; (2) the differences in proportion of loadings originating from sectors influenced by wastewater treatment; and (3) interplay with the decay processes. Reductions in BOD and FC concentrations are particularly large in Northern India, Eastern China and the Eastern Seaboard of the USA, corresponding to the countries requiring the largest volumetric expansions in wastewater treatment (Fig. 2a). SDG6.3 expansions led to very high localised reductions in BOD and FC concentrations, which also translate into substantial improvements in the river water quality of the regions' major rivers e.g. Mississippi (US), Ganges (India) and Yellow (China). Improvements in water quality associated with SDG6.3 can be seen in most streams across Europe, with reductions of ~40% for BOD and ~50% for FC concentrations are achieved in the major rivers. The fact that such substantial reductions are achieved in both the tributaries and main channels of European river networks is attributed to the fact that the required increases in wastewater treatment capacities for SDG6.3 are widespread in space, following the extensive treatment capacity currently in place.

Conversely, in regions where SDG6.3 can be achieved by expanding wastewater treatment capacities at a small number of locations—particularly Africa—reductions in BOD and FC concentrations are less ubiquitous. Here, the concentrations in a greater proportion of stream segments are unaffected by
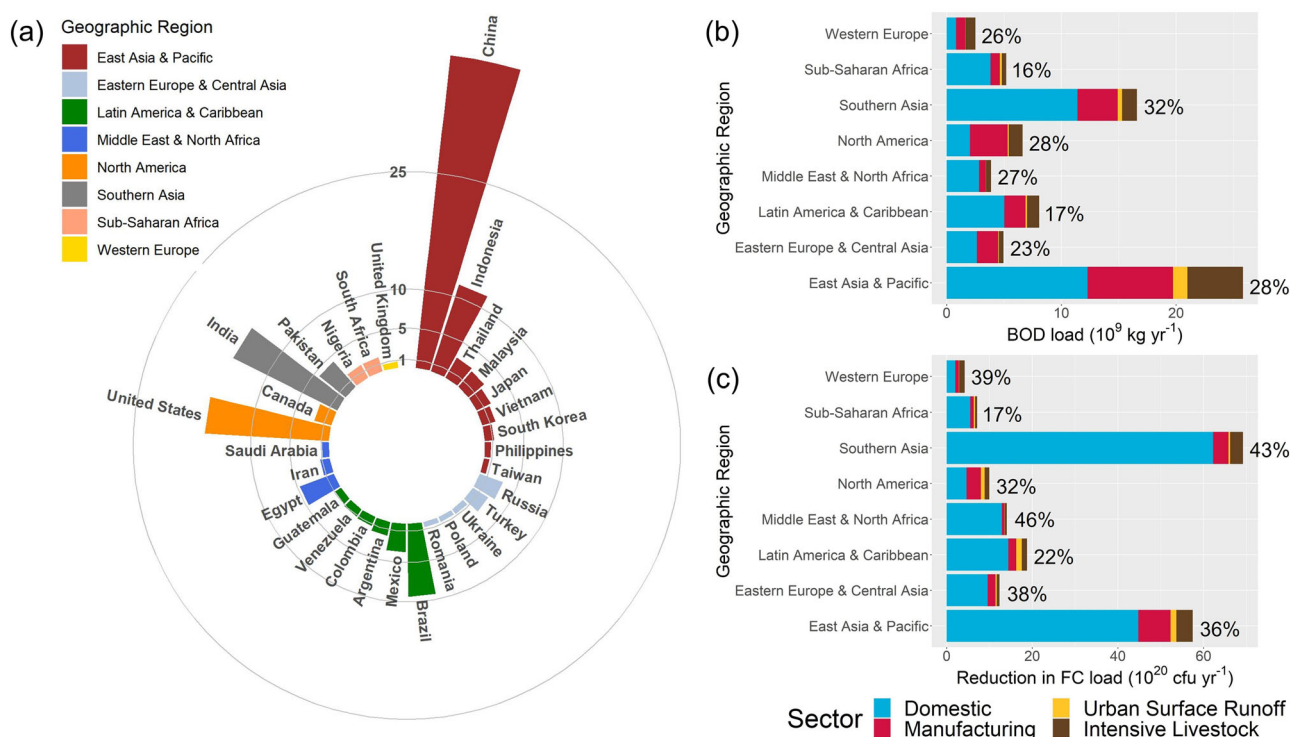
Fig. 2 Required expansions in wastewater treatment capacities to achieve Sustainable Development Goal (SDG) 6.3 and the associated impact on pollutant loadings. a Expansions in wastewater treatment capacity (10^9 m^3 yr^{-1}) required by 2030 to achieve SDG6.3 for the top 30 countries; and the associated absolute and percentage reductions in **b** biological oxygen demand (BOD) and **c** faecal coliform (FC) pollutant loadings per sector aggregated per geographical region.

achieving SDG6.3. Nevertheless, the benefit of achieving SDG6.3 on BOD and FC concentrations can still be seen in both localised stream segments (where expansions are occurring) and also for major rivers, such as the lower Nile and parts of the Niger. In countries with highly concentrated populations, such as Australia, SDG6.3 expansions in wastewater treatment are also confined to a small number of locations. Thus, very high localised reductions in BOD and FC concentrations are achieved, but only in the major urban settlements.

Time-series of in-stream concentrations at selected locations (Fig. 3c and Fig. S19) show that SDG6.3 can drastically reduce in-stream concentrations and reduce the frequency and magnitude of water quality threshold exceedance. For example, BOD concentrations in the Citarum River, Indonesia can be reduced to below the 8 mg l^{-1} threshold in almost all months of the year under SDG6.3, whereas year-round exceedance is commonplace under current wastewater treatment levels. Similarly, without expansions in wastewater treatment, FC concentrations in the Hudson River, USA begin to frequently exceed the 1000 cfu 100 ml^{-1} threshold (typically 4–6 months per year), whereas these exceedances are entirely prevented under SDG6.3. Such exceedances of water quality thresholds are important as they may result in the surface water being unsuitable for sectoral uses, or threaten environmental health.

The percentage reductions in BOD (Fig. 3a and Fig. S17) and FC (Fig. 3b and Fig. S18) also translate into changes in the frequency and magnitude of water quality threshold exceedances. We demonstrate these changes with respect to the percentage of surface water abstractions that exceed quality thresholds under historical, no expansion and SDG6.3 conditions (Fig. 4 and Figs. S20–S21). With no reductions in TDS loadings assumed with secondary wastewater treatment, no variation in TDS exceedances under the two scenarios are found. Furthermore,

only small changes are found in these scenarios relative to the historical conditions.

In terms of BOD and FC threshold exceedance, reductions in the proportion of surface water extractions exceeding quality thresholds are highest in developed regions of Northern America, Western Europe and Eastern Europe and Central Asia. In these regions, expansions in wastewater treatment for SDG6.3 are widespread in space, achieved through a combination of expanding wastewater treatment in gridcells where wastewater treatment is already present ('collected, untreated', Fig. S13) and establishing wastewater treatment facilities in new locations. Furthermore, in-stream concentrations of BOD and FC are typically lower in these regions attributed to the wastewater collection and treatment infrastructure that is already established. Thus, SDG6.3 expansions in wastewater treatment are more frequently sufficient for achieving reductions beneath quality thresholds. Conversely, in world regions with more limited existing wastewater treatment (e.g. Sub-Saharan Africa), achieving SDG6.3 leads to relatively fewer changes in threshold exceedances. While wastewater treatment expansions in these regions causes substantial reductions in localised pollutant loadings, these are often insufficient to reduce in-stream concentrations to levels beneath quality thresholds. This primarily occurs due to the propagation of pollution originating in upstream areas where expansions in wastewater treatment are not allocated.

Conclusions

Our findings show that substantial reductions in organic and pathogen pollution, as indicated by BOD and FC concentrations in surface waters, are achieved under SDG6.3. The achieved water quality improvements, to differing extents across regions, reduce
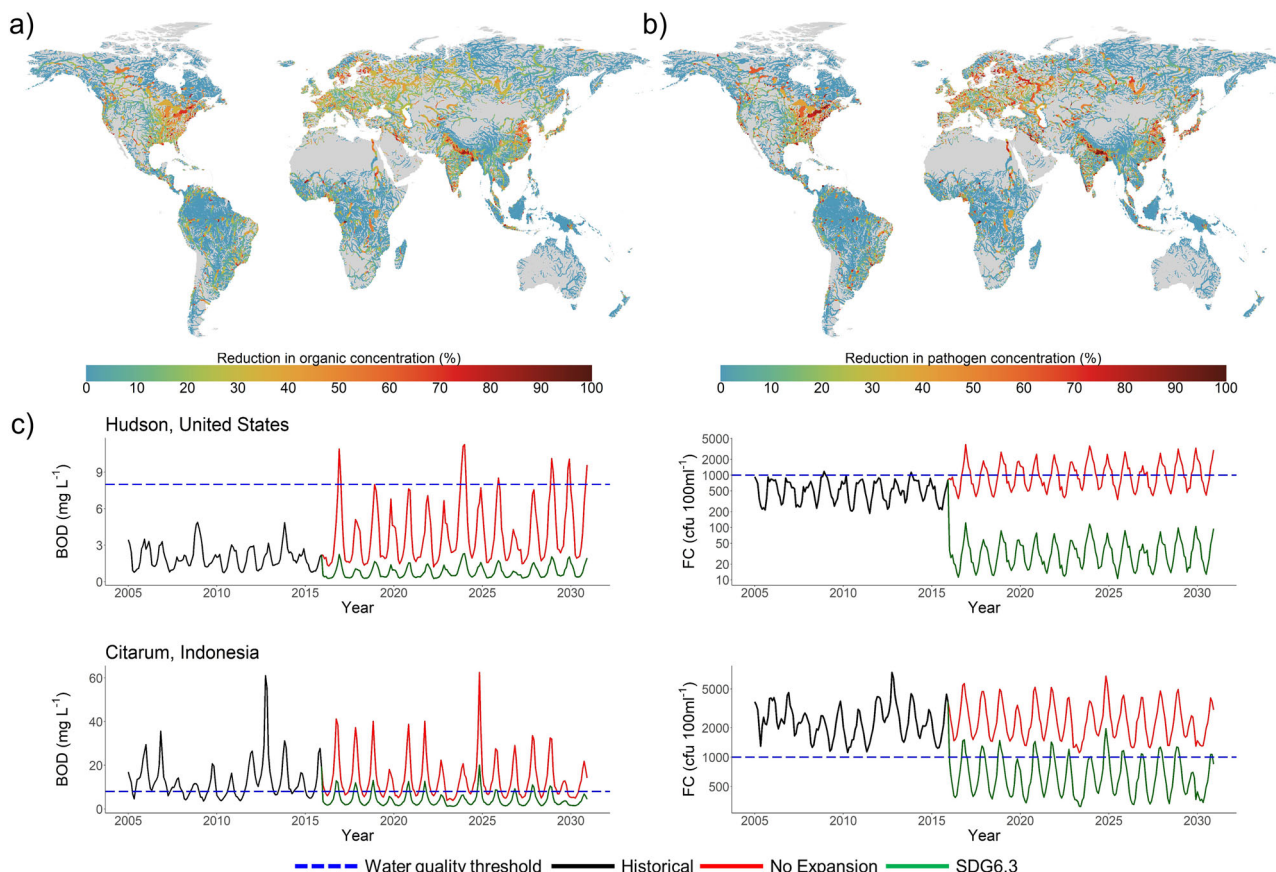
Fig. 3 The impact of achieving Sustainable Development Goal (SDG) 6.3 on surface water quality. Average annual percentage reductions in **a** organic pollution as indicated by biological oxygen demand (BOD) concentrations and **b** pathogen pollution as indicated by faecal coliform (FC) concentrations, assuming no expansions in wastewater treatment vs. achieving SDG6.3. Percentage reductions displayed in **a** and **b** are averaged over multiple general circulation models (GCMs) for the time period 2021–2030 and are only displayed for streams with an average annual discharge >10 m s^{-1}. More detailed maps displaying percentage reductions in BOD and FC concentrations in key world regions are available Figs. S17 and S18, respectively. **c** In-stream BOD (left) and FC (right) concentrations under historical, no expansion and SDG6.3 conditions. Additional time-series plots across more world regions are displayed in Fig. S19.

the frequency and magnitude of water quality threshold exceedances for sectoral uses and aquatic ecosystem health (Fig. 4 and Fig. S20). Reductions in threshold exceedances are typically largest where wastewater treatment rates are already high, such as Northern America and Western Europe. Conversely, in world regions with limited existing wastewater treatment, the impact of achieving SDG6.3 on threshold exceedance is more modest. This occurs due to SDG6.3 being met by expanding wastewater treatment in a relatively limited number of locations. Furthermore, volumes of untreated wastewater (and the associated pollutant loadings) can still be very large under SDG6.3—in a country without any existing wastewater treatment facilities, 50% of the total produced wastewater is still released to the environment untreated. With propagation of pollution from upstream areas still resulting in widespread exceedances of key water quality thresholds, the suitability of SDG6.3 as a global sustainability target for improving ambient water quality must be considered. Based on our study, it can be concluded that SDG6.3 can substantially improves ambient water quality worldwide, but that in many world regions improvements are still insufficient to meet water quality requirements for human use and aquatic ecosystem health.

As we enter the "Decade of Action (2021–2030)" for achieving the Sustainable Development Agenda, now is the time to renew global efforts to go above and beyond the wastewater treatment target stipulated by SDG6.3. While achieving the required

expansions in wastewater treatment will poses serious economic challenges, extracting the economic value inherent within wastewater flows (e.g. water, nutrients and energy recovery) can provide funding opportunities compatible with a circular economy. Yet, our results also demonstrate that in addition to expanding and improving our 'hard-infrastructure' (i.e. sewer networks and wastewater treatment facilities), a strong focus on reducing pollutant emissions at source will also be required to achieve the overarching goal of SDG6—*clean water and sanitation for all*.

Materials and methods

Wastewater treatment and pollutant loadings. Pollutant loadings are considered from six distinct sources, namely from the domestic, manufacturing, irrigation, livestock and thermoelectric power sectors, and from urban surface runoff (Fig. S1). Pollutant loadings of water temperature (Tw), total dissolved solids (TDS), biochemical oxygen demand (BOD) and faecal coliform (FC) are calculated at a gridcell resolution of 5 × 5 arc-minutes (~10 km at the equator) with a monthly timestep. Socio-economic and hydroclimatic data are used as basis from 1980–2015 (historical), with data for 2016–2030 based on future projections associated with RCP 7.0 and SSP3[17]. This combination represents an intermediate-high emissions and development scenario (CMIP6), characterised by regional rivalry[18]. Loadings from the domestic and livestock sectors are estimated by multiplying the gridded population[19] with a pollutant-specific per capita excretion rate[8,9]. Conversely, loadings from the manufacturing and irrigation sectors, and from urban surface runoff, are estimated by multiplying a return flow volume, simulated with the global hydrology and water resources model PCR-GLOBWB2[20], with a pollutant-specific mean effluent concentration[8,9]. Heat dumps from the power sector are estimated by multiplying the associated return flows with an estimated difference in water temperature between the return flows and the receiving waters[6,9]. More
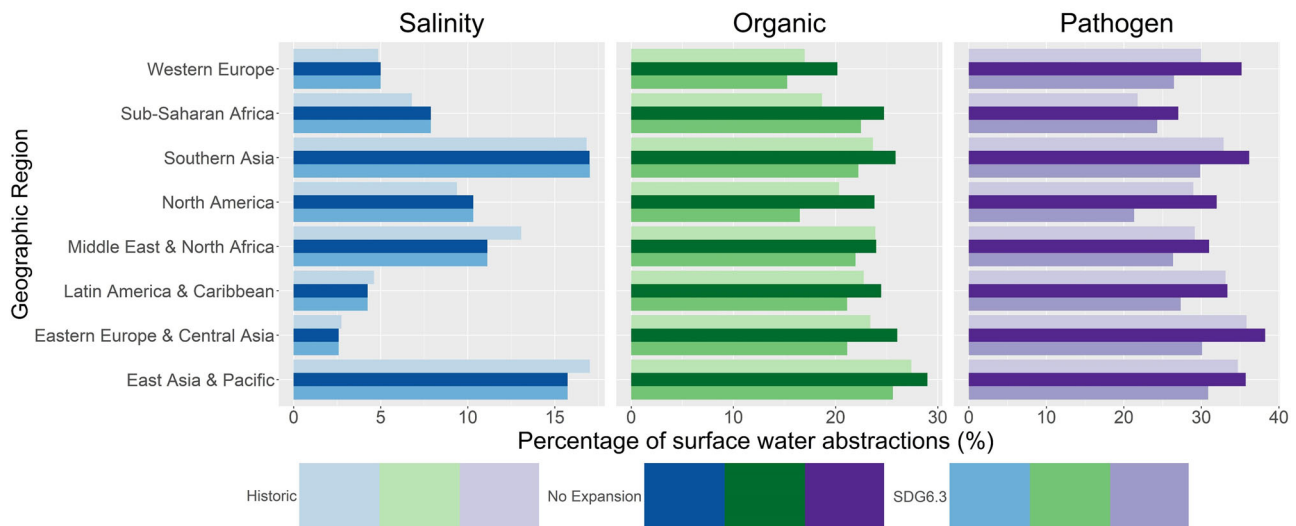
Fig. 4 Impact of achieving Sustainable Development Goal (SDG6.3) on the quality of surface water abstractions for sectoral water use. Percentage of surface water abstractions exceeding critical water quality thresholds for salinity pollution as indicated by total dissolved solids (TDS) concentrations (2100 mg l^{-1}), organic pollution as indicated by biological oxygen demand (BOD) concentrations (8 mg l^{-1}) and pathogen pollution as indicated by faecal coliform (FC) concentrations (1000 cfu 100 ml^{-1}) under historical and near-future (no expansions and SDG6.3) conditions. Water quality threshold exceedance and surface water abstractions are assessed at monthly temporal resolution, and subsequently aggregated per geographic region across all months. Results are averaged across multiple general circulation models (GCMs) using 2005–2014 as the historical and 2021–2030 as the future time period.

information on the datasets used and methodology for calculating pollutant loadings per sector are presented in Supplementary Notes 1 (Figs. S2–S6).

Sector-specific pollutant loadings can be abated based upon their transmission paths to receiving waters (Fig. S1 and Supplementary Notes 4). Pollutant loadings from the domestic and manufacturing sectors, and from urban surface runoff, can be heavily influenced by wastewater management plants where wastewater collection (e.g. in sewers) and subsequent treatment (e.g. in sewage treatment works) practices are occurring (Fig. S11). The specific path via which municipal wastewater is disposed, including the treatment level (i.e. removal efficiency) of collected wastewater, is therefore key to determining the resultant pollutant loadings. Previous global water quality studies have used country-level data to represent this process[8,9]. Here, we use a newly developed global wastewater collection and treatment dataset[11], further disaggregated by treatment level (primary, secondary, tertiary+), to delineate these wastewater pathways at 5 arc-minutes (Figs. S12–S13). This is a substantially higher spatial resolution than previously captured. For detailed information on the spatially explicit wastewater dataset, we refer to the original publication[11].

Surface water quality modelling (DynQual). A new surface water quality model, named *DynQual*, has been developed in this study to simulate surface water temperature (Tw), water salinity as indicated by total dissolved solids (TDS), organic pollution as indicated by biological oxygen demand (BOD) and pathogen pollution as indicated by faecal coliform (FC) concentrations at a spatial resolution of 5 × 5 arc-minutes and daily resolution globally. These water quality constituents are selected because they are key in constraining different sector water uses and ecosystem health[21,22]. DynQual has been developed in a flexible way to allow for the addition of more water quality constituents, which could include nutrients, dissolved oxygen and emerging contaminants.

DynQual builds on recent water quality model developments[8–10,23] and the water temperature modelling framework DynWat[15,16]. DynWat solves the surface water energy balance at the daily timestep, while also accounting for surface water abstractions, reservoirs, riverine flooding and the formation of ice, giving Tw at a spatial resolution of 5 × 5 arc-minutes[16]. We further include advected flow from heat effluents of thermoelectric powerplants, following previous work[9,24]. Daily surface water concentrations of TDS [mg l^{-1}], BOD [mg l^{-1}] and FC [cfu 100 ml^{-1}] at 5 × 5 arc-minutes, are simulated by using a mass balance approach, combining the sectoral pollutant loadings routed over the stream network with the dilution capacity of the receiving stream. We assume instantaneous and full mixing of all pollutant loadings in each gridcell. TDS is simulated using conservative substances approach, whereas BOD and FC are simulated using a non-conservative substances approach with first-order decay during downstream water transport[8,9,25]. The decay coefficient for FC is a function of water temperature, solar radiation and the settling rate of bacteria (sedimentation)[8,25], whereas the decay coefficient for BOD is water-temperature dependent only[9,10]. Hydrology (surface runoff, interflow, baseflow, channel storage) and surface water abstractions are simulated by the global hydrology and

water resources model PCR-GLOBWB 2, for which we refer to the original publication[20]. More information on the surface water quality modelling approach is presented in Supplementary Notes 2.

In this study, DynQual is run for a historical time period of 1980–2015 using W5E5 forcing data[26,27] (Supplementary Notes 1–2). DynQual is uncalibrated to facilitate application in ungauged basins (e.g. parts of Africa with limited water quality monitoring availability) without loss of performance[16]. In-stream concentrations for the historical time period are validated against in-situ surface water quality monitoring data from the Global Environment Monitoring System (GEMS)[28] (Table S1). Overall, modelled Tw and in-stream concentrations of TDS, BOD and FC show good agreement with the observed data, as indicated by calculated Kling Gupta Efficiency coefficients. In accordance with the focus of our study—the exceedance of key water quality thresholds under past and near-future conditions—we also present our validation results with respect to pollutant classes[8]. More information on the validation of the water quality model from 1980–2015 is presented in the Supplementary Notes 3 (Figs. S8–S10).

Future projections of water quantity, surface water temperature and pollutant (i.e. TDS, BOD and FC) concentrations are made up to 2030, including the impact of climate change following the representative concentration pathway RCP 7.0[17]. We use bias-corrected CMIP6 forcing data from 5 GCMs[17] for the time period 2006–2030. Future pollutant loadings are simulated following the shared socio-economic pathway SSP3[17,19] under two different assumptions considering (1) no expansion in wastewater treatment ('no expansion'); and (2) expansions to halve the proportion of untreated wastewater globally by 2030 ('SDG6.3'). We compare our water quality simulations under these two assumptions to evaluate the relative impact of halving the proportion of untreated wastewater on global surface water quality. Surface water quality simulations are linked to concentration thresholds relevant for sectoral water use (Table S2)[8] to determine the frequency and magnitude of their exceedance. This allows for evaluation of the constraints posed to sectoral water users from a water quality perspective. Future work should also assess pollution status from an ecological perspective, whereby the assimilative capacity of the receiving waters (aside from just the dilution component) is a key additional consideration.

Halving the proportion of untreated wastewater (SDG6.3). SDG6.3 sets the target of halving the proportion of untreated wastewater that is released to the environment and improve ambient water quality by 2030[14]. We only consider wastewater undergoing secondary or higher treatment practices in 2015 as adequately treated for SDG6.3, as a substantial proportion of pollutant loadings are abated only at these treatment levels. We calculate the volumetric expansion required in domestic and manufacturing sectors to achieve SDG6.3 at the country level using trend analysis, and subsequently delineate these expansions hierarchically to gridcells with the highest pollutant loadings in 2015. We focus our expansions on gridcells with high pollutant loadings as collection and treatment is assumed to be both more desirable and economically feasible (and hence more likely) where the strongest reductions in pollutant loadings are achieved.

Expansions in wastewater treatment are assumed to be at the secondary level. An overarching assumption is that SDG6.3 is met by all countries by 2030. Given current progress towards this target, particularly against the backdrop of financial challenges of COVID-19[29], we acknowledge the likelihood of SDG6.3 achievement to be low. Nevertheless, this assumption allows for quantitative assessment of the suitability of SDG6.3 for improving ambient water quality. Detailed information and results regarding the spatial expansions in wastewater treatment associated with achieving SDG6.3 is presented in Supplementary Notes 5 (Figs. S14–S15).

Data availability

Data used in this study for water quality simulations is primarily available open-access and is accessible from the original sources: climate forcing[17], population[30], livestock numbers[31], powerplants[32] and wastewater collection and treatment[11,33]. Global water quality output data from 1980 to 2015 at 10 km resolution is available at https://doi.org/10.6084/m9.figshare.20486277, while simulated water quality under the two wastewater treatment scenarios for all 5 GCMs is available at https://doi.org/10.6084/m9.figshare.20486310. Further information is available in the Supplementary Information or upon reasonable request.

Code availability

The global hydrological model PCR-GLOBWB2[20], which is used for hydrological simulations, is available at: https://github.com/UU-Hydro/PCR-GLOBWB_model/. The code of the water quality model is available upon request to the corresponding author.

References

1. Alcamo, J., Flörke, M. & Maerker, M. Future long-term changes in global water resources driven by socio-economic and climate changes. *Hydrol. Sci. J.* **52**, 247–275 (2007).
2. Heal, K. V. et al. Water quality: the missing dimension of water in the water–energy–food nexus. *Hydrol. Sci. J.* **66**, 745–758 (2021).
3. Ashbolt, N. J. Microbial contamination of drinking water and disease outcomes in developing regions. *Toxicology* **198**, 229–238 (2004).
4. Rietz, D. N. & Haynes, R. J. Effects of irrigation-induced salinity and sodicity on soil microbial activity. *Soil Biol. Biochem.* **35**, 845–854 (2003).
5. van Vliet, M., Sheffield, J., Wiberg, D. & Wood, E. Impacts of recent drought and warm years on water resources and electricity supply worldwide. *Environ. Res. Lett.* **11**, 124021 (2016).
6. van Vliet, M. et al. Vulnerability of US and European electricity supply to climate change. *Nat. Clim. Change* **2**, 676–681 (2012).
7. Englert, D., Zubrod, J. P., Schulz, R. & Bundschuh, M. Effects of municipal wastewater on aquatic ecosystem structure and function in the receiving stream. *Sci. Total Environ.* **454-455**, 401–410 (2013).
8. UNEP. *A Snapshot of the World's Water Quality: Towards a Global Assessment* (United Nations Environment Programme, 2016).
9. van Vliet, M. T. H. et al. Global water scarcity including surface water quality and expansions of clean water technologies. *Environmental Research Letters* **16**, 024020 (2021).
10. Wen, Y., Schoups, G. & van de Giesen, N. Organic pollution of rivers: combined threats of urbanization, livestock farming and global climate change. *Scientific Reports* **7**, 43289 (2017).
11. 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).
12. 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).
13. Mateo-Sagasta, J., Raschid-Sally, L. & Thebo, A. In *Wastewater: Economic Asset in an Urbanizing World* (eds Drechsel, P. et al.) 15–38 (Springer Netherlands, 2015).
14. UN. *Transforming Our World: the 2030 Agenda for Sustainable Development* (UN Development Programme, 2015).
15. van Beek, L., Eikelboom, T., van Vliet, M. & Bierkens, M. F. P. A physically based model of global freshwater surface temperature. *Water Resources Research* **48**, W09530 (2012).
16. 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 Resources Research* **55**, 2760–2778 (2019).
17. Büchner, S. L. A. ISIMIP3b bias-adjusted atmospheric climate input data. *ISIMIP Repos.* https://doi.org/10.48364/ISIMIP.842396.1 (2021).
18. Fujimori, S. et al. SSP3: AIM implementation of shared socioeconomic pathways. *Global Environmental Change* **42**, 268–283 (2017).
19. Jones, B. & O'Neill, B. C. Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environmental Research Letters* **11**, 084003 (2016).
20. Sutanudjaja, E. et al. PCR-GLOBWB 2: A 5 arcmin global hydrological and water resources model. *Geoscientific Model Development* **11**, 2429–2453 (2018).
21. Damania, R., Desbureaux, S., Rodella, A.-S., Russ, J. & Zaveri, E. *Quality Unknown: The Invisible Water Crises* (World Bank Group, Washington, DC, 2019).
22. Dumont, E., Williams, R., Keller, V., Voß, A. & Tattari, S. Modelling indicators of water security, water pollution and aquatic biodiversity in Europe. *Hydrological Sciences Journal* **57**, 1378–1403 (2012).
23. 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).
24. van Vliet, M. T. H. et al. Coupled daily streamflow and water temperature modelling in large river basins. *Hydrol. Earth Syst. Sci.* **16**, 4303–4321 (2012).
25. Reder, K., Flörke, M. & Alcamo, J. Modeling historical fecal coliform loadings to large European rivers and resulting in-stream concentrations. *Environmental Modelling & Software* **63**, 251–263 (2015).
26. Cucchi, M. et al. WFDE5: bias-adjusted ERA5 reanalysis data for impact studies. *Earth Syst. Sci. Data* **12**, 2097–2120 (2020).
27. Stefan, L. et al. WFDE5 over land merged with ERA5 over the ocean (W5E5 v2.0). *ISIMIP Repos.* https://doi.org/10.48364/ISIMIP.342217 (2021).
28. UNEP. *GEMStat Database of the Global Environment Monitoring System for Freshwater (GEMS/Water) Programme* (UN Environment Programme, 2020).
29. Kantur, Z. & Özcan, G. What pandemic inflation tells: old habits die hard. *Econ. Lett.* **204**, 109907 (2021).
30. O'Neill, B. C. et al. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.* **9**, 3461–3482 (2016).
31. Gilbert, M. et al. Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. *Scientific Data* **5**, 180227 (2018).
32. Lohrmann, A., Farfan, J., Caldera, U., Lohrmann, C. & Breyer, C. Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. *Nature Energy* **4**, 1040–1048 (2019).
33. Jones, E., van Vliet, M. T. H., Qadir, M. & Bierkens, M. F. P. Country-level and gridded wastewater production, collection, treatment and re-use. *PANGAEA*, https://doi.org/10.1594/PANGAEA.918731 (2020).

Author contributions

The research was designed by E.R.J., M.F.P.B. and M.T.H.v.V. The water quality model was developed by E.R.J., with assistance from N.W. and E.H.S. Data analysis and the interpretation of results was led by E.R.J., with guidance and feedback from M.F.P.B., N.W., E.H.S., L.P.H.v.B. and M.T.H.v.V. The manuscript was written by E.R.J. and was approved by all authors.

Competing interests

The authors declare no competing interests.

Additional information

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