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Urbanization: an increasing source of multiple pollutants to rivers in the 21st century

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Most of the global population will live in urban areas in the 21st century. We study impacts of urbanization on future river pollution taking a multi-pollutant approach. We quantify combined point-source inputs of nutrients, microplastics, a chemical (triclosan) and a pathogen (*Cryptosporidium*) to 10,226 rivers in 2010, 2050 and 2100, and show how pollutants are related. Our scenarios consider socio-economic developments and varying rates of urbanization and wastewater treatment. Today, river pollution in Europe, South-East Asia and North America is severe. In the future, around 80% of the global population is projected to live in sub-basins with multi-pollutant problems in our high urbanization scenarios. In Africa, future river pollution is projected to be 11–18 times higher than in 2010, making it difficult to meet Sustainable Development Goals. Avoiding future pollution is technically possible with advanced wastewater treatment in many regions. In Africa, however, clean water availability is projected to remain challenging. Our multi-pollutant approach could support effective water pollution assessment in urban areas.

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INTRODUCTION

Urban areas currently accommodate more than half of the global population[1] and generate over two-thirds of the world gross domestic products (GDP)[2,3]. In 2050, more than two-thirds of the global population will live in cities[1,4,5]. Rapid urbanization creates opportunities for economic developments[6], but may also increase the use of freshwater resources[4,6–9]. This will increase competition for water between cities and agriculture[4]. More urban waste is likely to result in contamination of water with multiple pollutants such as nutrients[10] and pathogens[11,12] from human excretion, plastics[13–18], and chemicals[19,20] from personal care products. River pollution poses a threat to the availability of clean water in large parts of the world[7,21], challenging the achievement of Sustainable Development Goal 6 (SDG, clean water for all) and 11 (sustainable cities). Recent studies on impacts of rapid urbanization on water stress or water scarcity worldwide exist[4], but often ignore water quality[7].

Previous global studies likely underestimate the impact of urbanization on water pollution because of their strong focus on single pollutants[10,16,20,22–24] (Fig. 1). Urbanization (e.g., sewer connections in cities) is, however, often a common, point source of multiple pollutants in rivers, contributing to multiple impacts. Examples are eutrophication problems caused by nitrogen (N) and phosphorus (P) in many world regions[25,26], and diarrhea caused by pathogens (e.g., *Cryptosporidium*) especially in developing countries[11,27]. A multi-pollutant approach is, thus, urgently needed to account for interactions between drivers of urbanization (e.g., population, economy) and pressures such as emissions of different pollutants[21]. This can help to identify effective solutions accounting for synergies and trade-offs in pollution control. Furthermore, reducing multiple pollutants in rivers from urban-related sources

might be easier (e.g., improved wastewater treatment) than from diffuse sources such as agricultural runoff (e.g., delay effects of reduction options due to accumulation of substances in soils). This may have a positive effect on the overall water quality status depending on diffuse sources.

In this paper, we study the impacts of urbanization on river pollution in the 21st century, taking a multi-pollutant perspective. We define multi-pollutant problems as increasing levels of more than one pollutant to rivers in future decades. We analyze, simultaneously, the following groups of pollutants: nutrients (N and P), pathogens (such as *Cryptosporidium*), microplastics and chemicals (such as triclosan). These pollutants are selected because of their increasing pollution in many rivers worldwide[18,20,23,28–30]. Yet, these pollutants have common urban sources such as sewer systems (worldwide) and open defecation. We quantify point-source inputs of the pollutants to 10,226 rivers for 2010, 2050 and 2100 associated with urbanization: sewer systems and open defecation. For this, we use a global model of Strokal et al.[31] that takes the sub-basin scale modelling approach of Strokal et al.[32] for nutrients and integrates modelling approaches for other pollutants[18,20,23] (Supplementary Tables 1, 2 and 3). We develop this model further for multiple-pollutants and future analyses based on evaluated, modelling approaches (see the "Methods" section).

To assess the impacts of urbanization, we develop five scenarios with different levels of urbanization and wastewater treatment rates (Fig. 2). The storylines are interpretations of the five Shared Socio-economic Pathways (SSPs)[33–36] (Supplementary Tables 4, 5 and 6). These SSPs are five pathways with different levels of socio-economic challenges for mitigation and adaptation[33–36]. SSP1 is a Green Road pathway with low socio-economic challenges (e.g., low population growth), but with high economic and urbanization

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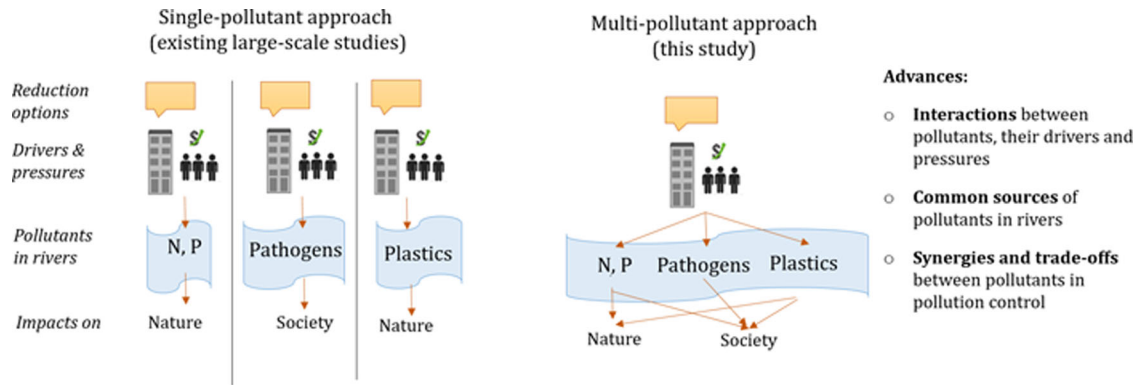
Fig. 1 Multi-pollutant approach in relation to single-pollutant approaches. The figure shows a difference between single-pollutant approaches (most existing studies) and a multi-pollutant approach (this study) to assess the impacts of the rapid urbanization on future global river quality. We take N (nitrogen), P (phosphorus), pathogens and plastics as examples. Advances of the multi-pollutant approach are discussed in the main text.
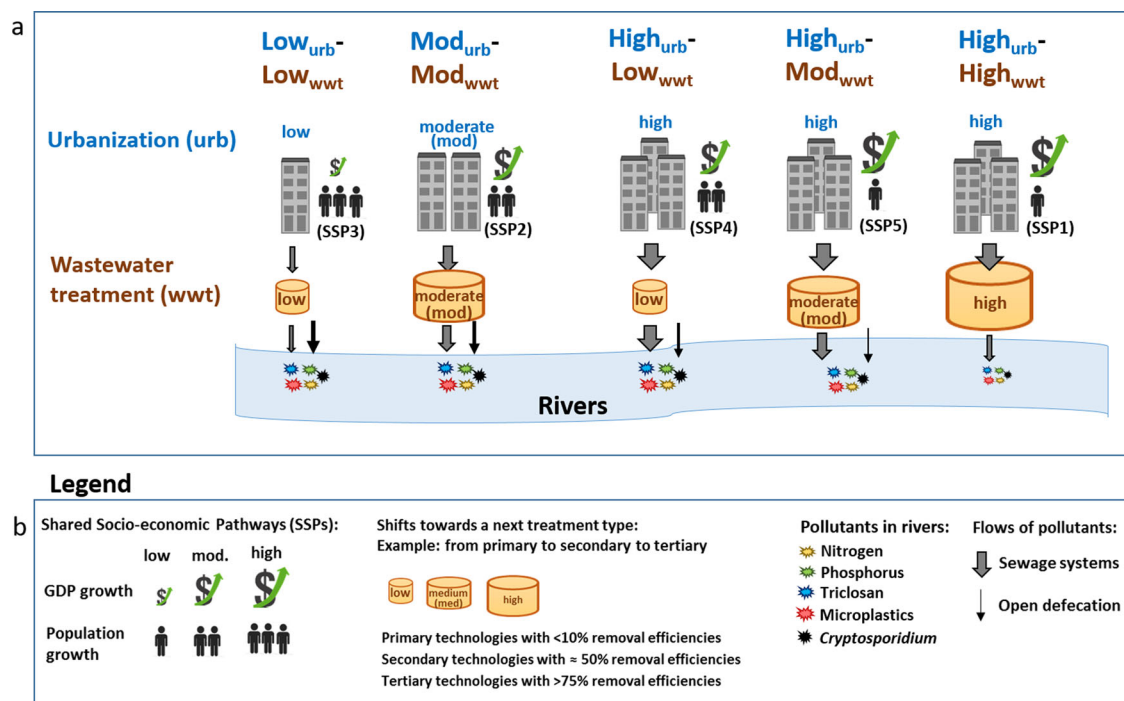

Fig. 2 Storylines of five scenarios to analyze impacts of urbanization on the river quality in the 21st century. Low, moderate and high urbanization is defined here as the increasing number of urban people and total people with sewer connections (see a and b panels and Supplementary Tables 4–6). The number of people opens defecating directly to water is assumed to decrease with sewer connection. Higher sewer connections imply that more wastewater treatment plants will be constructed to maintain the increasing volumes of the waste (see the "Methods" section). Low, moderate and high wastewater treatment levels refer here to a shirt (low, moderate, high) towards a next treatment type: e.g., from primary to secondary to tertiary (**a, b**, Supplementary Tables 4–6). This implies the low, moderate and high ambitions to improve wastewater treatment (**b**). Future years are 2050 and 2100. Supplementary Tables 1–6 give quantitative interpretations of the storylines for our multi-pollutant model (see also the "Methods" section). GDP is the gross domestic product. Sources for the technologies are in the main text and in Supplementary Table 3.

development. It is largely oriented towards achieving sustainable goals (see Supplementary Tables 4, 5 and 6). SSP2 is a middle of the road pathway with medium challenges to mitigation and adaptation. Future trends will not be very different from historical trends. SSP3 is a Rocky Road pathway with high challenges to mitigation and adaptation. It is a world with difficulties to control the population growth and has low economic and urbanization development (see Supplementary Tables 4, 5 and 6). SSP4 is a Road Divided pathway with high challenges to mitigation and low to adaptation. It has a large gap between urban and rural development with the high urbanization rates especially in urban

areas. SSP5 is a taking the highway pathway with high challenges to mitigate, but low challenges to adapt. It is a word with priorities towards economy (see Supplementary Tables 4, 5 and 6).

Our five scenarios incorporate socio-economic pathways of SSPs, but with quantitative interpretations of aspects related to urbanization and wastewater treatment (see the "Methods" section). Our scenarios aim to show the impact of urbanization on multiple pollutants in rivers. Thus, the names of our five scenarios correspond to the different levels of urbanization and wastewater treatment: from low urbanization and low wastewater treatment rates towards high urbanization and high wastewater
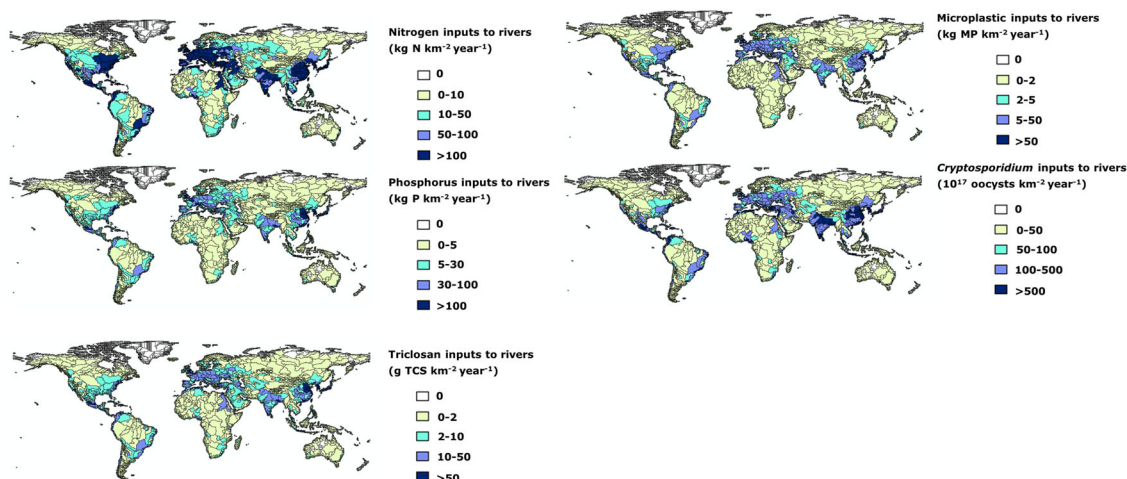
Fig. 3 Inputs of multiple pollutants to rivers in 10,226 sub-basins in 2010. Units are kg km^{-2} of sub-basin area year^{-1} for nitrogen (N), phosphorus (P) and microplastics (MP), g km^{-2} of sub-basin area year^{-1} for triclosan (TCS) and 10^{17} oocysts km^{-2} of sub-basin area year^{-1} for *Cryptosporidium*. Source: the global multi-pollutant model (model description is provided in the "Methods" section, and in Supplementary Tables 1–6, model inputs are in Supplementary Figs. 1–14). Model uncertainties are discussed in the "Methods" section.

treatment rates. This results in the following scenarios: low urbanization and low wastewater treatment rates (Low$_{urb}$–Low$_{wwt}$, based on SSP3), moderate urbanization and moderate wastewater treatment rates (Mod$_{urb}$–Mod$_{wwt}$, based on SSP2), high urbanization and low wastewater treatment rates (High$_{urb}$–Low$_{wwt}$, based on SSP4), high urbanization and moderate wastewater treatment rates (High$_{urb}$–Mod$_{wwt}$, based on SSP5), and high urbanization and high wastewater treatment rates (High$_{urb}$–High$_{wwt}$, based on SSP1) (Fig. 2). The five scenarios consider interactions between global change (socio-economic pathways), urbanization, sanitation and wastewater treatment.

Low, moderate and high urbanization reflect different levels of increases in urban population, and, indirectly, people with sewer connections between 2010 and future years (see the "Methods" section). As a net effect, the number of people practicing open defecation (direct inputs of human waste to rivers) may decrease. Increasing sewer connections assume higher capacities of treatment plants to manage increasing volumes of the wastewater. Low, moderate and high rates of wastewater treatment are defined based on a shift towards a next treatment type: e.g., from primary (technologies with <10% removal rates[10,18,20], low) to secondary (50% removal rates[10,18,20,37], moderate) or to tertiary (>75% removal rates[10,38–44], high, see the "Methods" section). The differences between the Low$_{urb}$–Low$_{wwt}$, and High$_{urb}$–Low$_{wwt}$ scenarios indicate the impact of urbanization in terms of increasing numbers of people with sewer connections with low ambitions to improve the wastewater treatment under different socio-economic developments. The Mod$_{urb}$–Mod$_{wwt}$ scenario could be considered business as usual. The differences between the High$_{urb}$–Low$_{wwt}$, High$_{urb}$–Mod$_{wwt}$ and High$_{urb}$–High$_{wwt}$ scenarios indicate the impact of improving the wastewater treatment in highly urbanized areas. Details are given in the "Methods" section on qualitative and quantitative descriptions of the five urbanization scenarios.

RESULTS

River pollution today

River pollution in Europe, South-East Asia and North America is already severe today. For these regions, we calculate high inputs of N (>50 kg km^{-2} year^{-1}), P (>30 kg km^{-2} year^{-1}), triclosan (>10 g km^{-2} year^{-1}), microplastics (>5 kg km^{-2} year^{-1}) and *Cryptosporidium* (>100 × 10^{17} oocysts km^{-2} year^{-1}) to many rivers in 2010 (Fig. 3). These regions experience severe water pollution

problems[9,16,21,25,45], contributing to negative impacts[21] such as eutrophication[45] and waterborne diseases (South-East Asian countries). For African sub-basins, pollution levels are not as high as in those regions (Fig. 3). However, some impacts of polluted water on children's health are already indicated[21]. Globally, 9.5 Tg of N, 1.6 Tg of P, 0.45 Tg of microplastics, 0.72 kton of triclosan and 1.6 × 10^{17} oocysts of *Cryptosporidium* entered rivers in 2010 (Fig. 4, Supplementary Table 7). More than half of these inputs are to rivers in South-East Asia. Most of the pollutants in rivers are from sewer systems (see details in Supplementary Figs. from 1 to 29). Exceptions are some sub-basins in Africa and South-East Asia where open defecation contributes to over 20% of N, P and *Cryptosporidium* to their rivers. Existing assessments[9,10,13,20,23] reveal similar global estimates, but with diverse spatial scales. Our consistent spatial and temporal scales increase the robustness of our comparisons between multiple pollutants worldwide (e.g., Fig. 4).

High pollution levels result from the net effect of population densities, sewer connection rates (Supplementary Figs. 1, 2 and 3), production of pollutants in human waste (Supplementary Figs. 4, 5, 6, 7 and 8 for individual pollutants) and wastewater treatment efficiencies (Supplementary Figs. 9, 10, 11, 12 and 13 for individual pollutants) in countries (Supplementary Figs. 14 and 15). For South-East Asia, high pollution levels are driven by high population densities (Supplementary Figs. 3 and 16). This region accommodates approximately half of the global population (3 billion people, Supplementary Fig. 1) on 12% of the global surface area (Fig. 4). For comparison, sub-basins of Europe (excluding Russia) and North America accommodate around 10% of the global population (0.8 billion people, Supplementary Fig. 1) on 20% of the global surface area (Fig. 4). Approximately 20% of the total population in 2010 was connected to sewer systems (Supplementary Fig. 1) with relatively low wastewater treatment efficiencies (removal levels <50% for most pollutants, Supplementary Figs. 9–13). For Europe and North America, the high pollution levels per km^2 of sub-basins are driven by high connection rates to sewer systems especially in urban areas. Here, over two-thirds of the population live in urban areas and are largely connected to sewer systems with removal efficiencies above 50% for the studied pollutants (Supplementary Figs. 9–13). Supplementary Fig. 17 shows the results of the sensitivity analysis indicating the importance of wastewater treatment and human development in river pollution (see the "Discussion" section).
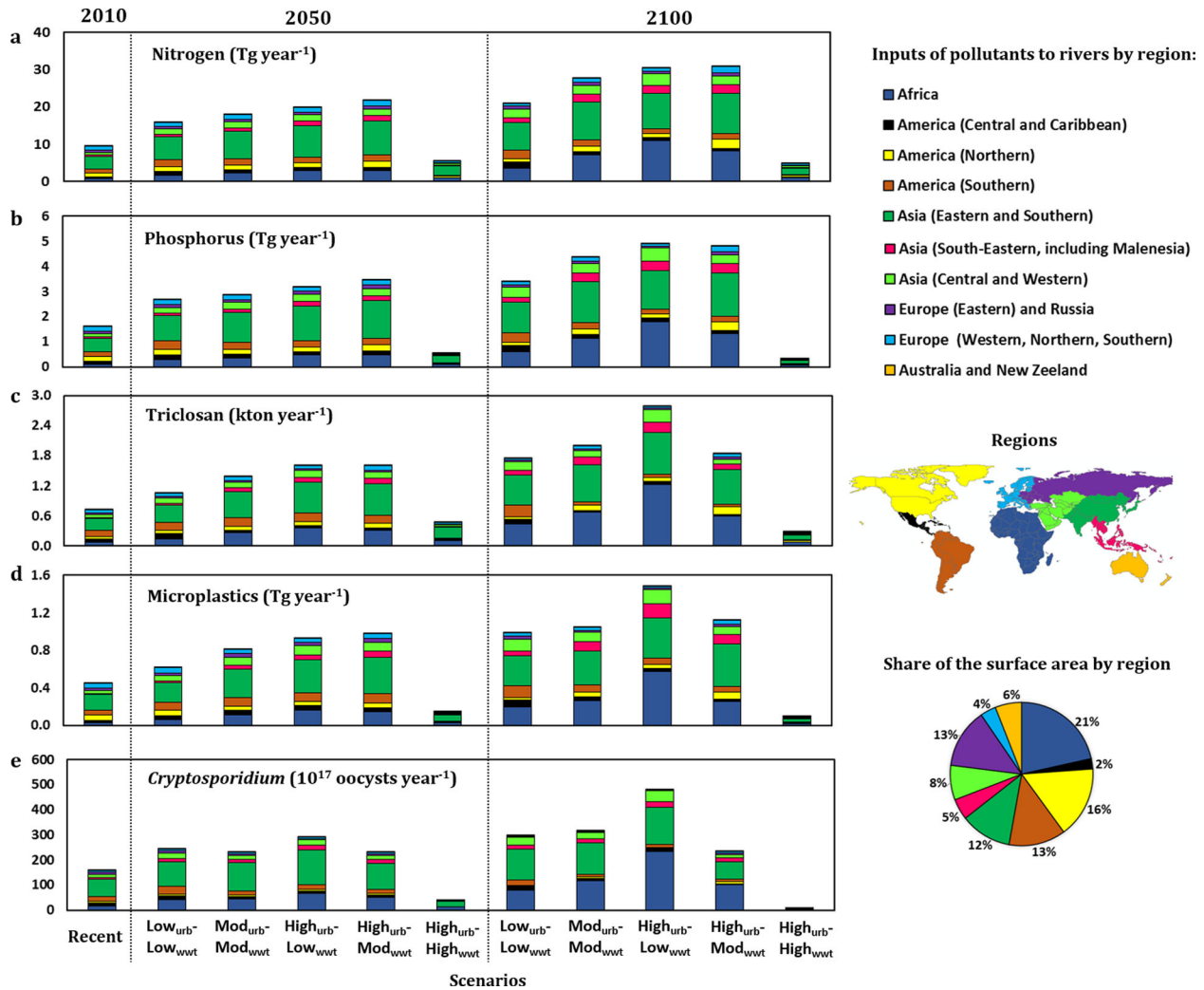
Fig. 4   Future trends in inputs of multiple pollutants to rivers by region in 2010, 2050 and 2100 according to the five scenarios. a–e Future trends for individual pollutants. Pies show the shares of the surface areas by region as % of the global surface area. Spatially explicit results are shown in Fig. 3 for 2010 and Fig. 5 for the future. The description of the scenarios is in Fig. 2, in the "Methods" section and Supplementary Tables 1–6. Source: the global multi-pollutant model (model description is provided in the "Methods" section, and in Supplementary Tables 1–6, model inputs are in Supplementary Figs. 1–14). Model uncertainties are discussed in the "Methods" section.

Future river pollution globally

In the future, ~80% of the global population is projected to live in sub-basins with multi-pollutant problems (Figs. 5 and 6). These sub-basins cover over half of the global surface area (Fig. 6) for which inputs of more than one pollutant will increase at least 30% (Fig. 5) between 2010 and 2050 or 2100. This is for all scenarios, except for High_urb–High_wwt. In the scenario assuming low urbanization and low wastewater treatment (Low_urb–Low_wwt), global inputs of most pollutants will less than double between 2010 and 2050 (Fig. 4). In this scenario, the population growth is high, and almost doubles between 2010 and 2100 (Supplementary Fig. 3). Approximately one-third of the total population globally will be connected to sewer systems. This number is much lower than in the other scenarios in 2100 (Supplementary Fig. 3). As a net effect of the low sewer connection (Supplementary Fig. 3) and low wastewater treatment (Supplementary Figs. 9–13), future inputs of pollutants to rivers from sewage are lower in the Low_urb–Low_wwt scenario than in the others (Fig. 3). However, as a trade-off, more nutrients and *Cryptosporidium* are projected to enter rivers from open defecation, mainly in developing countries (see Supplementary Figs. 14 and 15) compared to the other scenarios.

The future inputs of most pollutants to rivers are projected to be higher in the scenarios with moderate (Mod_urb–Mod_wwt) and high urbanization (High_urb–Low_wwt, High_urb–Mod_wwt, Fig. 4). The population grows not as fast as in the Low_urb–Low_wwt scenario, but the rate of urbanization is much higher, especially in the High_urb–Low_wwt and High_urb–Mod_wwt scenarios (Supplementary Tables 4–6). As a result, over two-thirds of the global population is projected to be connected to sewer systems in 2100 (Supplementary Fig. 3). Wastewater treatment efficiency is slightly improved (Mod_urb–Mod_wwt, High_urb–Mod_wwt) depending on the economic development (Supplementary Figs. 9–13). As a net effect, the High_urb–Low_wwt and High_urb–Mod_wwt scenarios project, generally, higher inputs of most pollutants to rivers than the Low_urb–Low_wwt and Mod_urb–Mod_wwt scenarios (Fig. 4).

Pollutants differ in their future trends. For example, High_urb–Low_wwt projects the highest inputs of *Cryptosporidium*, microplastics and triclosan globally in 2100 compared to the other pollutants and scenarios (Fig. 4). For N and P, High_urb-Low_wwt and High_urb-Mod_wwt project somewhat similar amounts globally (Fig. 4). All these differences between pollutants and scenarios are a net effect of three important factors: socio-economic development (e.g., population, GDP), urbanization rates
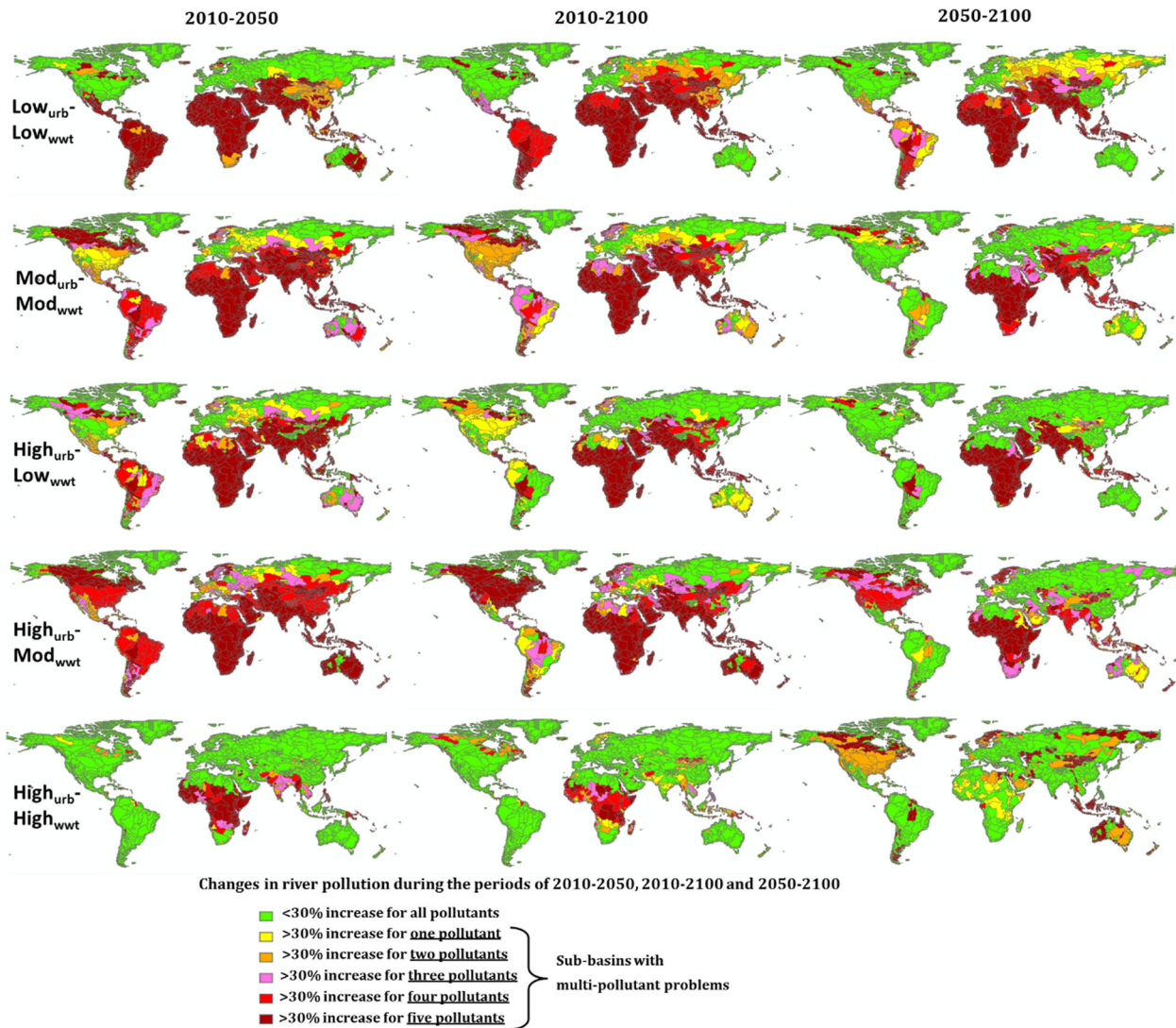
Fig. 5   **River pollution by multiple pollutants in 2050 and 2100 compared to 2010 in 10,226 sub-basins.** Maps show changes in inputs of pollutants to rivers during the periods of 2010–2050, 2010–2100 and 2050–2100 according to the five scenarios. We classify sub-basins based on the number of pollutants for which the increases are higher or lower than 30% (Note: 30% is arbitrary; see Supplementary Figs. 18 and 20 for results based on 10 and 50% thresholds). The pollutants include *Cryptosporidium*, microplastic, triclosan, nitrogen and phosphorus. More information is available in Supplementary Figs. 18–29. The description of the five scenarios is in Fig. 2, in the "Methods" section and Supplementary Tables 1–6. Results for 2010 are in Fig. 3. Source: the global multi-pollutant model (model description is provided in the "Methods" section, and in Supplementary Tables 1–6, model inputs are in Supplementary Figs. 1–14). Model uncertainties are discussed in the "Methods" section.

(population connected to sewer systems) and treatment efficiencies. For example, higher GDP results generally in higher N and P excretion rates per capita because of changes towards protein-rich diets[31,46] (Supplementary Figs. 4–5). Developed countries (Human Developing Index, HDI > 0.785) have generally lower infection rates, leading to less per capita excretion of *Cryptosporidium*[23] (Supplementary Fig. 8), but may lead to higher production of microplastics from car tyres[31] (Supplementary Fig. 7) as a result of industrialization. All these interactions are considered together with different trends in the population growth (Supplementary Fig. 3), urbanization rates (Supplementary Figs. 1 and 2) and treatment levels (Supplementary Figs. 9–13) among scenarios and regions.

Future river pollution in Africa

Future river pollution is projected to be 11–18 times higher than in 2010 in the scenario with high urbanization and low wastewater

improvements (High_urb–Low_wwt). This range is for increasing inputs of the five pollutants by at least 30% during the period of 2010–2100 (Fig. 5). Africa may become a major contributor to river pollution in the world (Fig. 4). For example, by 2100, up to half of the global inputs of multiple pollutants are projected in Africa in High_urb–Low_wwt (Fig. 4). For comparison: in 2010 the contribution of African rivers to the global river pollution was <5% (Fig. 4). All scenarios project increasing river pollution in the future for Africa (Figs. 5 and 6). This is largely associated with the projected population growth and assumed wastewater treatment. The African population is projected to more than double in many sub-basins during 2010–2100 in all scenarios (Supplementary Fig. 3). Many people will live in urban areas (High_urb–Low_wwt and High_urb–Mod_wwt, Supplementary Figs. 1–3). More people will inevitably generate more waste, and this may not be treated effectively enough (e.g., High_urb–Low_wwt). This all explains the large future increases in river pollution in Africa (Fig. 5). In the low urbanization scenario (Low_urb–Low_wwt), less people will live in
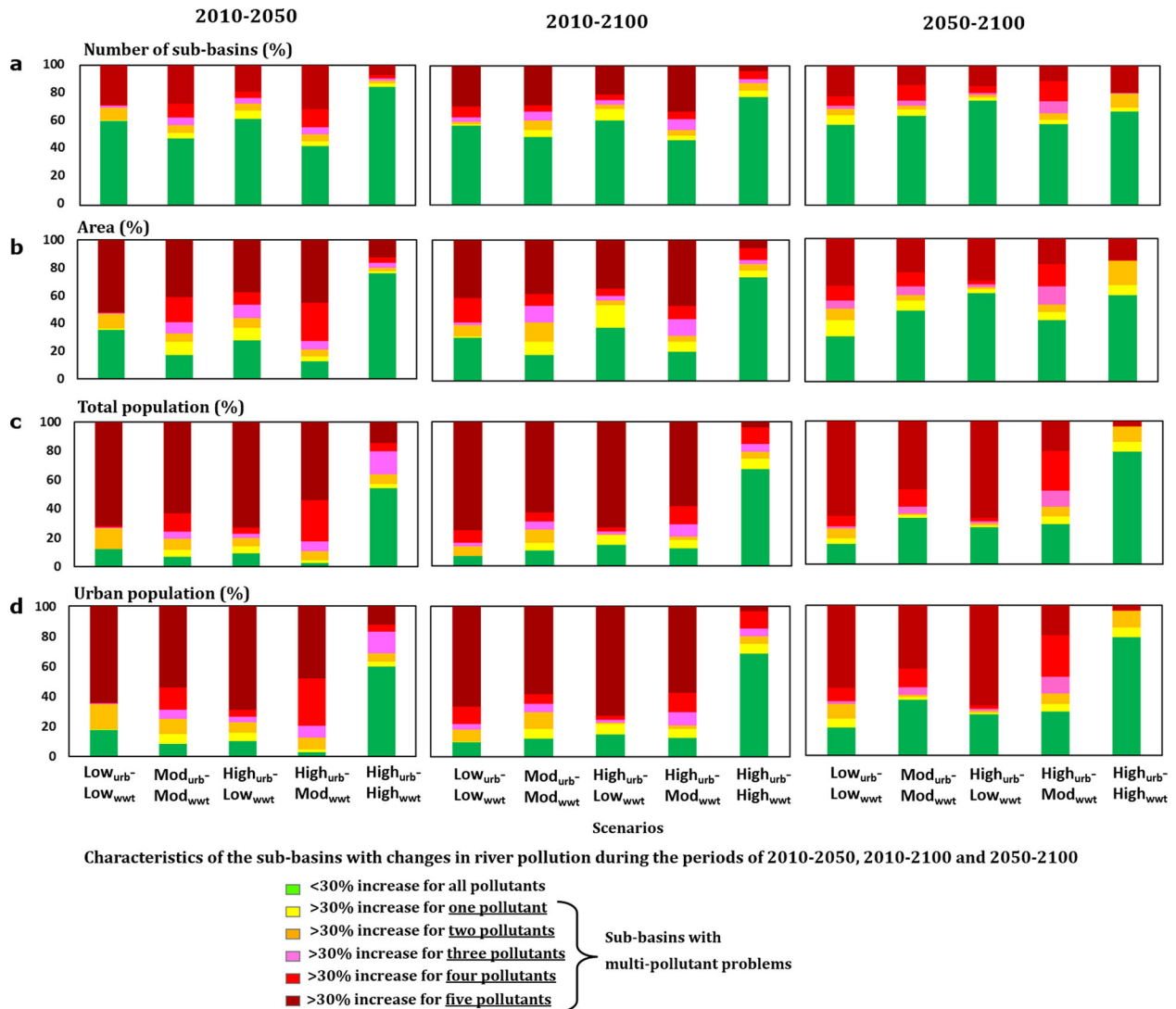
Fig. 6   Characteristics of the sub-basins with multi-pollutant problems in the future. Sub-basins are classified based on the number of pollutants for which the increases are higher or lower than 30% during the periods of 2010–2050, 2010–2100 and 2050–2100 according to the five scenarios. Graphs show the number of sub-basins (**a**), sub-basin areas (**b**), total population (**c**) and urban population (**d**) for the sub-basins with the increases of higher or lower than 30% (Note: 30% is arbitrary; see Supplementary Figs. 19 and 21 for results based on 10% and 50% thresholds). More information is available in Supplementary Figs. 18–29. See Fig. 5 for the changes in inputs of pollutants during the periods of 2010–2050, 2010–2100 and 2050–2100. The description of the scenarios is in Fig. 2, in the "Methods" section and Supplementary Tables 1–6. Results for 2010 are in Fig. 3. Source: the global multi-pollutant model (model description is provided in the "Methods" section, and in Supplementary Tables 1–6, model inputs are in Supplementary Figs. 1–14). Model uncertainties are discussed in the "Methods" section.

urban areas, and a lower percentage of people will be connected to sewer systems. Thus, open defecation may continue in Low_{urb}–Low_{wwt} especially by 2050. This is an important source of nutrients and *Cryptosporidium* to African rivers in this scenario. Supplementary Figs. 18, 19, 20 and 21 show results for increasing inputs of the five pollutants by at least 10% and 50% during the period of 2010–2100. Supplementary Figs. 22, 23, 24, 25 and 26 show future trends in river pollution by individual pollutants. Supplementary Figs. 27, 28 and 29 show scenarios and sub-basins where open defecation is an important source of P, N and *Cryptosporidium* in rivers.

Future river pollution in Asia

Future river pollution is projected to be 2–3 times higher than in 2010 in the scenario with high urbanization and low wastewater improvements ($High_{urb}$–Low_{wwt}). This range is for at least 30% increases in inputs of the five pollutants for the period 2010–2100

(Fig. 5). Exceptions are rivers in sub-basins of China (Fig. 5). These rivers are projected to be cleaner in 2100 than in 2050, but inputs of the pollutants may still be higher in 2100 than in 2010 in the urbanized scenarios with the low ($High_{urb}$–Low_{wwt} and Low_{urb}–Low_{wwt}) and moderate (Mod_{urb}–Mod_{wwt} and $High_{urb}$–Mod_{wwt}) wastewater treatment improvements (Fig. 5). The Chinese population is projected to decrease in the future in all scenarios (Supplementary Fig. 3). However, with the rapid urbanization (Supplementary Figs. 1–2), the wastewater treatment (Supplementary Figs. 9–13) may not keep up with the pollution loads. This explains higher river pollution levels. This is different for some other Asian countries such as India and Pakistan. By 2050, the total population of India and Pakistan will have increased (Supplementary Fig. 3). By 2100, the total population will have decreased or increased depending on the socio-economic development in the scenarios (Supplementary Fig. 3, Supplementary Tables 4–6 for the scenario description). However, the wastewater treatment is poorer or absent compared to the

Chinese sub-basins (Supplementary Figs. 9–13), resulting in more pollutants in rivers (Fig. 5, Supplementary Figs. 18–21).

Future river pollution in Europe and North America

Many rivers in Europe and North America may be cleaner in the future. European rivers (Western, Northern and Southern) may get cleaner in the future because of high removal efficiencies to treat wastewater (Supplementary Figs. 9–13). However, in the $High_{urb}$–Mod_{wwt} scenario, high wastewater treatment efficiencies (>50% for all pollutants) may not be enough to reduce future pollution to the level below 2010. For American rivers, future trends differ largely between South and North in the scenarios with the low (Low_{urb}–Low_{wwt}) and high ($High_{urb}$–Low_{wwt}) urbanization trends. In the Low_{urb}–Low_{wwt} scenario, lower increases (<30%) in inputs of pollutants are projected for many Northern rivers whereas higher increases (>30%) for most Southern rivers (Fig. 5, Supplementary Figs. 18–21). This difference can be explained by the higher population growth (Supplementary Figs. 1–3) and less efficient wastewater treatment (Supplementary Figs. 9–13) in South America compared to North America. In the $High_{urb}$–Low_{wwt} scenario, higher increases in river pollution are projected for South America by 2050, but lower by 2100. This is associated with the decreased population (Supplementary Fig. 3) and with the increased efficiencies of wastewater treatment between 2050 and 2100 (Supplementary Figs. 9–13). Rivers in Australia may be more polluted in the future (Fig. 5). Exceptions are the Low_{urb}–Low_{wwt} and $High_{urb}$–Low_{wwt} scenarios with less pollution in 2100 than in 2050. This is largely associated with the decreasing population during 2050–2100 (Supplementary Figs. 1–13, 18–21).

Reducing future river pollution

Advanced wastewater treatment can reduce future river pollution in many world regions, but not in Africa ($High_{urb}$–$High_{wwt}$). In $High_{urb}$–$High_{wwt}$, all developed countries (HDI > 0.785) will shift completely towards tertiary treatment with enough capacities and high efficiencies to remove pollutants from the wastewater (>75% for all pollutants, Supplementary Figs. 1–14). Examples of such technologies are annomox[47] for N, calcium precipitation for P[48], disinfection by Ultraviolet radiation for *Cryptosporidium*[42], reverse osmosis for nutrients[41] and microplastics[49]. Developing countries (HDI < 0.785) will also shift towards tertiary technologies, but in combination with secondary technologies[10,46] (Supplementary Figs. 1–14). Open defecation will stop by 2100. Thus, $High_{urb}$–$High_{wwt}$ shows the technical potential of advanced technologies with enough treatment capacities to reduce future pollution from highly urbanized areas.

It will be difficult to reduce future river pollution in Africa to the level of 2010, even with advanced technologies ($High_{urb}$–$High_{wwt}$, Fig. 5). Inputs of most pollutants to many African rivers are projected to increase by at least 30% during 2010–2100 in $High_{urb}$–$High_{wwt}$ (Fig. 5). The main reason is an increase in the total population, which is much higher (>doubling) than in other world regions (Supplementary Fig. 3). As a result, implementing advanced technologies in 2100 may help to reduce inputs of most pollutants to the level of 2050, but not to the level of 2010. For many other world's rivers, advanced technologies with enough treatment capacities are projected to lower future inputs of pollutants in $High_{urb}$–$High_{wwt}$ (Fig. 5, Supplementary Fig. 20). This may have a positive impact on the overall pollution status depending also on the contribution of diffuse sources from agriculture. However, for some rivers in Asia (e.g. India, Pakistan), inputs of most pollutants from point sources will still increase by 2050, but may be lower by 2100 in $High_{urb}$–$High_{wwt}$ (Fig. 5). Some rivers in North America, Middle Asia and Australia are projected to have higher inputs of pollutants in 2100 than in 2050, but lower than in 2010 (Fig. 5, Supplementary Fig. 20). These trends are the

net effect of the population growth, urbanization and wastewater treatment in $High_{urb}$–$High_{wwt}$ (Figs. 2, 5 and 6).

DISCUSSION

Scenario analyses are widely used to explore possible futures[1,34,36,50–52]. Our five scenarios are a combination of possible trends in urbanization, socio-economic development (existing SSPs[1,36,53]) and our assumptions on sanitation, wastewater treatment capacities and removal efficiencies of pollutants. Our assumptions may, however, seem ambitious (Supplementary Tables 5 and 6). For example, we assume the full implementation of advanced technologies with enough treatment capacities in $High_{urb}$–$High_{wwt}$ for all developed countries. We did this to show the effects of sustainable practices in urban areas on increasing the availability of clean water for people and nature. This assumption, however, might be ambitious to achieve. In our scenarios, we reflect a relation between urbanization (e.g., more urban people) and sewer connections (see $High_{urb}$–Low_{wwt}, $High_{urb}$–Med_{wwt}) with sustainable urbanization practices (see $High_{urb}$–$High_{wwt}$). This relation may, however, not emerge everywhere in the world. On the other hand, we explore possible futures; we do not state how likely or desirable these futures are. Our scenarios aim to identify impacts of future urbanization (e.g., differences between Low_{urb}–Low_{wwt} and $High_{urb}$–Low_{wwt}) and the technical potentials of proven wastewater treatment technologies to reduce future river pollution from point sources (e.g., differences between $High_{urb}$–Low_{wwt} and $High_{urb}$–$High_{wwt}$). Our insights may contribute to the formulation of sustainable urbanization practices where wastewater treatment is effective enough to reduce pollutants in the urban waste (e.g., SDG11) and thus to increase the availability of clean water in the future (e.g., SDG6).

Our global multi-pollutant model quantifies, simultaneously, five pollutants in rivers with consistent datasets in space and time. However, uncertainties exist. The model is developed based on existing, evaluated models for pollutants[11,18,20,23,29,32] (e.g., comparisons with observed concentrations and sensitivity analyses). We further evaluate our combined model using five approaches[54] (see the "Methods" section). First, we compare our model outputs with existing studies (see the "Methods" section, Supplementary Table 7), showing a good agreement for the five pollutants. Second, we compare the spatial pattern of pollution problems with existing models[8–12,16,55,56], indicating the river pollution in densely populated and highly urbanized areas (Figs. 3–5, Supplementary Tables 7 and 8). However, existing studies did not focus on a simultaneous reduction of the five pollutants from urbanized activities in the 21st century, which is a multi-pollutant perspective of our study. Third, we performed a sensitivity analysis for pollution hotspots. We define multi-pollutant hotspots as places with >30% increases in two or more pollutants between 2010 and future years (Fig. 5). This is an elegant way to combine the five pollutants. We realize that the 30% threshold is arbitrary. The results should, therefore, be interpreted as warning signals of future river pollution. In the sensitivity analysis, we changed the 30% threshold to 10% (Supplementary Figs. 18–19) and 50% (Supplementary Figs. 20–21). The results confirm the robustness of our main messages about future multi-pollutant hotspots. Fourth, we performed a sensitivity analysis for all important model inputs underlying the calculations (Supplementary Tables 9, 10, 11 and 12, Supplementary Fig. 17). In total, 25 model inputs are changed with ±10%, resulting in 50 model runs for 10,226 sub-basins and five pollutants. The results show that the model is not very sensitive to changes in most model inputs. For most sub-basins, the model outputs are relatively sensitive to changes in <5 model inputs. These inputs are related to HDI, wastewater treatment types and removal efficiencies. The 10% changes in these inputs, resulted in

up to 5% change in model output for sub-basins covering over two-thirds of the global surface area (see details in the "Methods" section for all sub-basins). Fifth, we compare model inputs with independent datasets (Supplementary Table 8, Supplementary Figs. 15 and 16). All this gives trust in the model performance (see the "Methods" section).

Our results are future oriented. We focus on trends in future hotspots of multi-pollutant problems in the world. We believe that not all model uncertainties affect our main messages about trends. We also realize that our results are relatively sensitive to the assumptions on future HDI and wastewater treatment (see Approach 4 in the "Methods" section and sensitivity analysis). For HDI, we assumed an increase of 0, 10 and 20% between 2010 and 2050 and further increase by 2100 depending on scenario (Supplementary Tables 5–6). For wastewater treatment rates, we assumed a shift towards a next treatment type between 2010 and future years (e.g., 0–50% shift depending on scenario). To increase trust in our assumptions for future trends, we compared our model inputs with other independent studies. We did this for our five scenarios (Supplementary Table 8, Supplementary Fig. 15). For example, future trends in our HDI between 2010 and future years are strongly in line with an independent study[57] (R^2 above 0.88, see Supplementary Fig. 15). Crespo Cuaresma and Lutz[57] took into account differences in human development and their socio-economic wealth in projecting future HDI. Our wastewater treatment types in 2050 are also well compared with an independent study[10] (Supplementary Table 8).

Another potential source of uncertainties relates to the local variation in pollution levels. For example, sewage overflows may happen under heavy rain events, causing local peaks in water pollution. Such events are time dependent and may also contribute to global pollution levels[58]. We do not account for such local events in our model. We, however, believe that such omissions of events do not affect our messages for the multi-pollutants worldwide. This is because we explore future trends in the multi-pollutant hotspots worldwide that are influenced by global change, urbanization and wastewater treatment. Local analyses should, however, account for the impact of local events on local water quality (e.g., cities).

Our study aims to analyze the impact of the socio-economic drivers (e.g., GDP) and urbanization on future inputs of pollutants to rivers from point sources worldwide. However, we do not consider the transport of pollutants to rivers from agricultural fields, nor the impact of climate change on future river pollution. Next steps could be to further develop our global multi-pollutant model by calculating inputs of pollutants from agricultural fields and associated river export of pollutants. This will allow to explicitly combine the impact of both climate change and of socio-economic developments.

A multi-pollutant approach supports the search for effective solutions. A multi-pollutant approach might be more effective in reducing river pollution than a single-pollutant approach (Fig. 1). For example, reducing one pollutant may reduce (synergies) or increase (trade-offs) another pollutant. Our study serves as an illustrative example for the five pollutants. For example, increasing sewer connections may increase inputs of the five pollutants to rivers, but decrease inputs of N, P and *Cryptosporidium* from open defecation (Low$_{urb}$–Low$_{wwt}$; trade-off). Higher economic developments may lead to less excreted *Cryptosporidium* per capita because of lower infection risks in developed countries[11,23] (Supplementary Fig. 8), but may generate more N and P in human excreta (Supplementary Figs. 4–5) as a result of protein-rich food consumption[10,46] (trade-off). Synergies also exist. For example, increasing sewer connections with advanced technologies and sufficient wastewater treatment capacities is projected to decrease the inputs of all five pollutants to many rivers in the future (High$_{urb}$–High$_{wwt}$). This is also associated with synergies in treatment technologies to remove multiple pollutants. Some

technologies are developed to target specific pollutants (e.g., N[47], P[48], *Cryptosporidium*[42]). This implies that implementing technologies for one pollutant may not strongly influence another pollutant. However, technologies exist to treat more than one pollutant (e.g.,[10,38–40,42,59]). For example, secondary treatment with removal efficiencies of around 40–50% (assumed in Mod$_{urb}$–Mod$_{wwt}$ and High$_{urb}$–Mod$_{wwt}$) converts organic N into inorganic and gas, removing N from the waste[10]. They can also facilitate the biodegradation of triclosan[59]. Microplastics can host microorganisms (e.g., *Cryptosporidium*) and serve as vectors for chemicals[15,49,60]. As a result, biofilms and flocs can form in, for example, activated sludge ponds and then settle down[49]. Triclosan can sorb to large particles and also settle down with other pollutants[38,39,59]. Advanced technologies (assumed in High$_{urb}$–High$_{wwt}$) such as efficient ultrafiltration methods can reduce *Cryptosporidium*[42] and microplastics[49], and reverse osmosis can recover nutrients[41] and reduce microplastics[49]. Nature-based solutions such as stabilization ponds and constructed wetlands are largely effective to reduce *Cryptosporidium*[42] and nutrients[61]. Accounting for synergies and trade-offs is essential to identify effective solutions for multiple pollutants. This can support the achievement of SDG11 for sustainable cities and SDG6 for clean water.

Our results can support policy assessment of water pollution in urban areas, and form the basis for actionable and region-specific solutions. We identify hotspots of urban-related river pollution and show possible effects of future urbanization on river quality under global change. This could help to prioritize short-term actions to avoid river pollution in the 21st century. Improving wastewater treatment is important to avoid multi-pollutant problems in an urbanized world (Fig. 5, differences between High$_{urb}$–High$_{wwt}$ and High$_{urb}$–Low$_{wwt}$). Our sensitivity analysis indicates where improved wastewater treatment could have a larger impact (Supplementary Fig. 17). Our model indicates that water pollution is related to human development (expressed as human development index). This is important to realize when reducing *Cryptosporidium* and microplastics. Some countries in the world already introduced policies such as a ban of detergents and triclosan in products. Combing such policies with improved wastewater treatment may contribute to synergetic solutions for achieving SDGs and reducing river pollution from urban waste. For Africa, improving wastewater treatment may not be enough. Controlling the African population growth to reduce waste production in the future may be needed in urban and water policy assessments.

Our study quantifies future trends in inputs of five pollutants to rivers for five scenarios. We argue that a multi-pollutant perspective is needed in quantitative analyses of future trends in global change, urbanization, sanitation and wastewater treatment. We analyzed multiple pollutants simultaneously in a consistent way. We did this for 10,226 sub-basins for 2010, 2050 and 2100. Our insights are in how future trends differ between pollutants, sub-basins and how hotspots of multi-pollutant problems change in the 21st century. Our study provides an example of multi-pollutant problems from urban point sources. We show that future inputs of pollutants are projected to increase with increasing urbanization. We also show that it is technically possible to avoid these increases with advanced proven technologies to treat wastewater, except in Africa. In Africa, clean water availability is projected to remain a challenge because of the fast increasing population. This will consequently challenge the achievement of SDGs 6 and 11 in Africa. Our model may serve as an example for multi-pollutant modelling of diffuse sources such as agricultural runoff and other pollutants, such as pesticides[62], antibiotics[24] and antimicrobial resistance. Another opportunity is to analyze the economic (e.g., costs), societal, institutional and political feasibilities of future pollution reduction options. This is important to identify region-specific solutions. Our long-term

projections can help to increase the awareness of society and decision makers about pollution hotspots in the 21st century. This can facilitate short-term actions in different regions to avoid pollution in the future and contribute to achieve SDGs 6 and 11.

METHODS

Model description and inputs

We used a model of Strokal et al.[31] that takes the sub-basin scale modelling approach of Strokal et al.[32] for nutrients and integrates modelling approaches for other pollutants[18,20,23]. We developed it further for future analyses of point-source inputs of pollutants to rivers (Supplementary Table 1). Our model quantifies inputs of five pollutants to 10,226 rivers: nitrogen (N), phosphorus (P), microplastics, triclosan and *Cryptosporidium* for 2010, 2050 and 2100. The model of Strokal et al.[31] was developed for 2010 taking the sub-basin modelling approach of Strokal, et al.[32] for N[29,32], P[29,32] and integrating the existing modelling approaches for microplastics[18], triclsan[20] and *Cryptosporidium*[23]. We developed the model for the years 2050 and 2100 based on the urbanization storylines of the SSPs and our assumptions. Our multi-pollutant model quantifies simultaneously annual inputs of the five pollutants to rivers at the sub-basin scale using the consistent spatial and temporal dataset for model inputs for 2010, 2050 and 2100. The model quantifies inputs of the five pollutants from sewer systems and open defecation. These are the point sources of the pollutants in rivers. Sewer systems discharge five pollutants to rivers. Open defecation is a point source of N, P and *Cryptosporidium* in our model. Model evaluation is presented below after the scenario descriptions.

Inputs of the pollutants to rivers from open defecation are quantified as a function of the population that is open defecating and the excretion or consumption rates of pollutants per person per year (Supplementary Tables 1 and 2). Inputs of pollutants from sewer systems are quantified as a function of the population that is connected to sewer systems, the excretion or consumption rates of pollutants per person per year and removal efficiencies of pollutants during treatment. We quantified inputs of the pollutants at 0.5° grid and then aggregate the results to 10,226 river sub-basins (Supplementary Table 1). Model inputs for 2010 are directly from Strokal, et al.[31]. Model inputs for 2050 and 2100 are based on the SSPs with different trends in urbanization and wastewater treatment (see scenario descriptions below).

Below, we explain how model inputs were derived (Supplementary Tables 1–6). Population for 2010, 2050 and 2100 are aggregated to 0.5° grid from the global, 0.125 degree cell database of Jones and O'Neill[53]. The number of people with sewer connections and open defecation are quantified at 0.5° grid using the population map of 0.5° grid and the fraction of people with sewer connections or open defecation. For 2010, the fraction of urban and rural people with sewer systems and open defecation are available by country from the Joint Monitoring Program (see details in Strokal et al.[31] and Hofstra and Vermeulen[11]). We assigned the national values to grids of 0.5° grid. Then, we multiplied the number of people per grid (aggregated from Jones and O'Neill[53]) with the fraction of people connected to sewer systems or open defecating (based on Hofstra and Vermeulen[11]). For 2050 and 2100, we made assumptions for the fractions of people connected to sewer systems and with open defecation. These assumptions were based on storylines of SSPs for economy, population and urbanization (Fig. 2, Supplementary Tables 4–6). Our assumptions differ among urban and rural people, and among developing and developed countries (see scenario descriptions below).

Excretion or consumption rates of pollutants were largely derived based on existing, evaluated approaches and sources. Excretion rates of N and P in human waste per person are quantified as a function of GDP (gross domestic product) at purchasing power parity, following the approach of Van Drecht et al.[46], but adjusted to the unit of 2005 (see details in Strokal et al.[31], Supplementary Tables 1–6). For 2010, 2050 and 2100, GDP at 0.5° grid was derived from the global SSP database with the projections from the International Institute for Applied Systems Analysis (IIASA,[63]). P in detergents was from Van Drecht et al.[46] for the world regions (Supplementary Tables 1–6).

Excretion rates of *Cryptosporidium* were quantified based on the infection rate in developed (5%) and developing (10%) countries and the excretion rate per ill person (10^9 oocysts) according to Hofstra et al.[23]. For 2010, developed and developing countries were defined based on the Human Development Index (HDI), following the approach of Hofstra et al.[23]: HDI > 0.785 (developed) and HDI < 0.785 (developing). For 2050

and 2100, we made assumptions for HDI for countries depending on SSP storylines for the economy, population growth and urbanization (see scenario descriptions below and Supplementary Tables 4–6).

Consumption rates of microplastics per person per year were derived directly from Siegfried et al.[18], but with some modifications (details are in Strokal et al.[31]). Microplastics in sewer systems result from car tyres, PCPs (personal care products), household dusts and laundry. For PCPs, dust and laundry, consumption rates are 0.071, 0.08 and 0.12 kg of microplastics per person per year according to Siegfried, et al.[18]. We assumed that these values do not change over time. For tyres, this is different. Strokal et al.[31] assumed that developed countries will contribute more microplastics to sewage from car tyres as a side-effect of economic and infrastructural developments. Thus, we assigned 0.18 kg of microplastics from tyres per person for developed countries (HDI > 0.785) and 0.018 kg of microplastics from tyres per person for developing countries (HDI < 0.785) according to Strokal et al.[31]. We assumed changes in HDI by country in the future based on the SSPs storylines (see scenario descriptions below and Supplementary Tables 1–6).

Consumption rates of triclosan per person in the world were directly taken van Wijnen et al.[20] (0.5 kg per person per year for 2010). We assumed that the consumption rate will not change largely in the future and thus will remain as in 2010.

Removal efficiencies of pollutants during treatment were derived based on the existing studies. For N, P and *Cryptosporidium*, removal efficiencies were quantified by country using the national distribution of wastewater treatment types (primary, secondary, tertiary, no treatment) and their treatment efficiencies for pollutants, following the approaches of[11,23,46] (see Supplementary Tables 1–6, Supplementary Figs. 1–14). The quantified national removal efficiencies were then assigned to corresponding grids of 0.5°. For 2010, national distributions of wastewater treatment types were derived from Hofstra and Vermeulen[11] with a few corrections for countries with missing data (details are in Strokal et al.[31]). For 2050 and 2100, we assumed changes (low, moderate, high) in the distribution of the treatment types depending on the storylines of SSPs (see scenario descriptions below). These changes imply a shift towards a next treatment type: e.g., from primary to secondary to tertiary (Supplementary Tables 1–6). Removal efficiencies of pollutants for different treatment types were taken directly from literature (see Supplementary Table 3) and do not vary among years.

For triclosan and microplastics, removal efficiencies were quantified based on the approaches of van Wijnen et al.[20] and Siegfried et al.[18] (details are in Strokal et al.[31]). We used the known removal rate of phosphorus to assume the removal of triclosan and microplastics. For our assumptions, we used data about the removal of triclosan and microplastics from literature[39,59,64–66]. Based on these data, we related average phosphorus removal in a watershed to triclosan removal. We formulated three classes of triclosan removal (0, 60 or 90%) and related these to known phosphorus removal in each sub-basin (details are in van Wijnen et al.[20]). A similar approach was carried out for microplastics. We formulated four microplastics removal classes based on literature and related those to the known average phosphorus removal in each sub-basin[18,30]. These classes represent an average microplastics removal in each sub-basin. Microplastic removal depends on the size and density of the microplastics. Therefore, the removal at each individual WWTP will be dependent on these and other characteristics. In our study, on a global scale, we chose to assume average removal for each sub-basin.

Scenario description

Storylines of the five scenarios are summarized in Fig. 2, Supplementary Tables 1–6 and Supplementary Figs. 1–14. Our five scenarios are with low urbanization and low wastewater treatment rates (Low$_{urb}$–Low$_{wwt}$), moderate urbanization and moderate wastewater treatment rates (Mod$_{urb}$–Mod$_{wwt}$), high urbanization and low wastewater treatment rates (High$_{urb}$–Low$_{wwt}$), high urbanization and moderate wastewater treatment rates (High$_{urb}$–Mod$_{wwt}$), and high urbanization and high wastewater treatment rates (High$_{urb}$–High$_{wwt}$) (Fig. 2). These scenarios follow future trends in the socio-economic development based on the existing SSPs[1,63], combined with our assumptions for population with sewer connections, open defecation and for wastewater treatment capacities and technologies (Supplementary Tables 4–6). Below, we describe each scenario. Quantitative interpretations of the scenario assumptions are presented in Supplementary Tables 4–6 for 2050 and 2100, and inputs are given in Supplementary Figs. 1–14.

The Low_urb-Low_wwt scenario is based on SSP3 projections for the socio-economic development (Fig. 2, Supplementary Tables 4–6). The scenario assumes a fragmented world with difficulties to control population growth. In this world, It is projected a low economic development with low urbanization rates and high population growth. For example, a global population of approximately 12 billion people is projected for 2100, of which 58% will be urban (Supplementary Figs. 1–3). Low economic developments will not allow to develop technologies largely. For 2050, HDI is assumed to stay as in 2010 and increase by 10% between 2050 and 2100 on a county level (Supplementary Tables 4–6). The society will not focus on reducing or avoiding future river pollution. As a result, the fraction of the population with sewer connections (around one-third of the global population) and the treatment efficiencies of wastewater (e.g., 14–18% globally depending on pollutant) will remain in 2050 as in 2010 (Supplementary Figs. 3, 9–13). The same holds for the wastewater treatment capacities. However, by 2100 more people may be connected to sewer systems (above one-third of the global population). This will result in higher capacities of the wastewater treatment plants with slightly improved treatment technologies (e.g., 21–24% of removal efficiencies globally depending on pollutant). However, future wastewater treatment efficiencies vary largely among world countries: e.g., 0–96% in 2100 depending on region and pollutant. In general, higher wastewater treatment efficiencies are projected for Europe, North America and Australia (Supplementary Figs. 9–13),

The Mod_urb-Mod_wwt scenario is based on SSP2 projections of the middle of the road for the socio-economic development (Fig. 2, Supplementary Tables 4–6). The scenario assumes a moderate economic development, moderate urbanization rates and moderate population growth compared to the other scenarios. For example, 9 billion people are projected globally for 2100 and 80% will be urban (Supplementary Figs. 1–3). From 2010, HDI is assumed to increase by 10% by 2050 and further increase by 10% by 2100 on a county level (Supplementary Tables 4–6). Technological development follows the business as usual trends. As a result, more people will be connected to sewer systems than today (45% in 2050 and 68% in 2100 globally, Supplementary Fig. 3). A number of wastewater treatment plants will be constructed to maintain the increasing volume of the wastewater from connected population to sewer systems. The amount of waste that is collected will be treated with slightly improved wastewater treatment. For example, on average, 33–42% of removal efficiencies globally are projected for 2100. This range is for the five pollutants. The removal efficiencies vary largely among regions (0–97% depending on region and pollutant, Supplementary Figs. 9–13). The number of people connected to sewer systems will be larger for urban (over two-thirds) than for rural (less than one-third) population. Some people may still experience open defecation in 2050. By 2100, all people who opened defecated in 2050 will become connected to sewer systems.

The High_urb-Low_wwt scenario is based on SSP4 projections for the socio-economic development (Fig. 2, Supplementary Tables 4–6). The scenario assumes a large gap between urban and rural developments. The economic development is projected to be moderate compared to the other scenarios. HDI is projected to increase as in the Mod_urb–Mod_wwt scenario (Supplementary Tables 1–3, Supplementary Fig. 14). The population is projected to increase in the future, but not largely: e.g., around 30% between 2010 and 2100 globally. By 2100, the global population is projected to reach 9.3 billion people (Supplementary Fig. 3a). However, the urban population will develop faster than the rural. Urbanization will be high: e.g., 76% and 90% of the global population will be urban in 2050 and 2100, respectively. As a result, the connection rate of the population to sewer systems will increase in the future for urban areas. For example, 80% of urban and 11% of rural population globally is projected to be connected to sewer systems in 2100 (Supplementary Figs. 1–3). Wastewater treatment capacities will be enough to maintain the waste from sewer systems and treatment will be improved as in the Mod_urb-Mod_wwt scenario. For rural areas, the fraction of people connected to sewer systems in 2050 may remain the same as in the Low_urb-Low_wwt scenario and will be improved by 2100 (Supplementary Tables 4–6). By 2050, some rural people may still open defecate. By 2100, all rural people who opened defecated in 2050 will become connected to sewer systems with better treatment.

The High_urb–Mod_wwt scenario is based on SSP5 projections for the socio-economic development (Supplementary Tables 4–6, Fig. 2). The scenario assumes a high economic development with high urbanization and low population growth (Fig. 2, Supplementary Table 4). For example, the total population globally is projected to increase by less than 10% between 2010 and 2100, reaching 7.4 billion people in 2100 (Supplementary Fig. 3a).

However, more than 90% of the global population will be urban in 2100. From 2010, HDI is assumed to increase by 20% by 2050 and further increase by 20% by 2100. The technological development is relatively high compared to the Mod_urb-Mod_wwt scenario. This will lead to a higher population with sewer connections. More than half of the global population will be connected to sewer systems in 2050. For 2100, this number is over two-thirds of the global population (Supplementary Figs. 1–3). The capacities of the wastewater treatment plants will be enough to manage the amount of waste from sewer systems. However, people will invest less in improving wastewater treatment. People will focus more on the economy rather than on reducing river pollution. As a result, wastewater treatment may follow the business as usual trends. For example, on average, 34–44% of the wastewater treatment efficiencies are projected globally for 2100. However, these efficiencies vary largely among regions (0–97% depending on area and pollutant, Supplementary Figs. 9–13). Furthermore, some people may still open defecate in nearby water systems in the future. By 2100, all people who opened defecated in 2050 will become connected to sewer systems.

The High_urb–High_wwt scenario is based on SSP1 projections for the socio-economic development (Fig. 2, Supplementary Tables 4–6). The society will develop fast with high urbanization rates as comparable to the High_urb–Mod_wwt scenario. The global population is projected to reach 6.9 billion people in 2100 (Supplementary Fig. 3a). The share of urban people globally is projected to be 77% in 2050 and 92% in 2100 (Supplementary Figs. 1–3). The share of the total connected people to sewer systems is projected to be 55% in 2050 and 82% in 2100. HDI is projected to increase in the same rate as in the High_urb–Mod_wwt scenario. However, in this world, a strong focus is on reducing or avoiding river pollution by using the best available advanced technologies in all areas. Technological development is high because of the high economic development. People will invest in improving technologies to treat wastewater with multiple pollutants. There will be opportunities to develop technologies for multiple pollutants and combine them with nature-based solutions. As a result, the wastewater treatment is assumed to be improved largely with high removal efficiencies (60–98% depending on year, area and pollutant, Supplementary Figs. 9–13).

Model evaluation

We evaluated the uncertainties in our model using four approaches following a building trust circle method[54]. This method has been applied in several water quality studies[32,67,68]. First, we compare model outputs with existing studies. Second, we compare the spatial pattern of the pollution problems with existing models for individual pollutants. Third, we perform a sensitivity analysis for pollution hotspots. Fourth, we perform a comprehensive sensitivity analysis for all important model inputs underlying the calculations. Fifth, we compare model inputs with independent datasets. Model validation against observed concentrations is, unfortunately, challenging. This is because our model does not quantify concentrations. Some of the existing global models calculate concentrations and were evaluated against observations (Supplementary Tables 7–8). Thus, we used those models to compare their results with ours for individual pollutants. Below, we elaborate on these five approaches. Details are in Supplementary Tables 7–12 and Supplementary Figs. 15, 17.

Approach 1: evaluating model outputs by comparing them with other models and studies for individual pollutants. This comparison is presented in Supplementary Table 7. The results show that our model outputs for global inputs of nitrogen, phosphorus, microplastics, triclosan and *Cryptosporidium* are generally in line with other models and studies. For example, our model quantified 9.5 Tg of nitrogen to rivers from point sources in 2010. Other models quantified 6.4–10.4 Tg of nitrogen to rivers from points sources during 2000–2010[10,46,69] (Supplementary Table 7). For phosphorus, we quantified 1.6 Tg in 2010 whereas the other models quantified 1.0–1.5 Tg for the period of 2000–2010[10,46,69]. For 2050, we quantified 5.4–21.0 Tg of nitrogen and 0.6–3.5 Tg of phosphorus in 2050 (ranges for the five scenarios). van Puijenbroek et al.[10] quantified 13.5–17.9 Tg of nitrogen and 1.6–2.4 Tg of phosphorus in 2050 under the five SSPs. For *Cryptosporidium*, our model quantified 1.6×10^9 oocysts in 2010 which is 1.1–1.4×10^9 oocysts in another model in 2000–2010[11,23] (Supplementary Table 7). For 2050, our model quantified 0.4–2.9×10^9 oocysts (range for the five scenarios). For the Low_urb-Low_wwt scenario, this value is 2.44×10^9 oocysts, which is comparable with 2.28×10^9 oocysts from the other model[11,23]. To our knowledge, van Wijnen, et al.[20] is the only study quantifying triclosan export by rivers. Our estimates for Danube, Zhujiang and Ganges are comparable with estimates of van Wijnen et al.[20]

(Supplementary Table 7). For microplastics, our model quantified 0.45 Tg entering rivers globally in 2010. Best[9] indicated loads of 0.41–4.00 Tg of plastics in 32 world's rivers. This is higher than our estimate because Best[9] accounts for macro- and microplastics whereas we only consider microplastics. Avio et al.[13] indicated 0.27 Tg of plastics to oceans in some regions in the world. This is lower than our estimate because we quantify inputs of plastics to rivers and not to the oceans. The other reasons for the differences between our model and other studies are in data inputs and the spatial level of detail. We focus on sub-basin analyses with the consistent model inputs for multiple pollutants (Supplementary Table 7, Supplementary Figs. 1–13).

Approach 2: evaluating model outputs by comparing the spatial variability in pollution hotspots with other studies. We reviewed the literature on pollution hotspots in the world for individual pollutants[8–12,16,55,56,70]. Our pollution hotspots for multiple pollutants are in line with the existing studies for individual pollutants. For example, most pollution often happens in densely populated and highly urbanized areas[8–12,16,55,56]. For example, Best[9] indicated over 80% of large transboundary rivers in the world with multiple pollutants. For many large cities in polluted regions, the demand for water already exceeds its availability. For example, water scarcity (ratio between the water demand and availability) has been already reported for cities in countries such as China (e.g., Shanghai, Beijing), India (e.g., Delhi, Kolkata, Bangalore, Hyderabad), Mexico, North America (e.g., Los Angeles)[70]. In the future, river pollution will further decrease the availability of clean water in many urban regions[4,7,8,71]. We show that it is technically possible to increase the availability of clean water with implementing advanced technologies (High$_{urb}$_High$_{wwt}$, Figs. 3–6). However, future analyses for multi-pollutant hotspots are lacking in the existing literature. A few global models performed future analysis for individual pollutants[10,11,18,20] where urbanization was taken into account by 2050. Their results indicate pollution hotspots where human activities are most intensive, which is in line with our study. However, studies exploring trends in multi-pollutant hotspots by 2100 do not exist. We explore trends in pollution hotspots for multi-pollutant problems covering the entire 21st century under the five scenarios with different socio-economic developments and levels of wastewater treatment.

Approach 3: evaluating model outputs for pollution hotspots by sensitivity analysis. In Fig. 5, we showed multi-pollutant hotspots. These hotspots were defined as at least a 30% increase in inputs of more than one pollutant to rivers during 2010–2050, 2010–2100 and 2050–2100. This definition is modest and easier to understand and interpret. We checked if the pollution hotspots remain the same by changing a 30% increase to 10% (Supplementary Figs. 18–19) and 50% (Supplementary Fig. 20–21). Results of this sensitivity analysis indicate that our main messages stay the same: Africa will become a hotspot region with multiple pollutants in rivers in the 21st century and advanced technologies may help to reduce pollution in many rivers of the world.

Approach 4: evaluating model inputs by a sensitivity analysis. We performed a comprehensive sensitivity analysis for all important model inputs underlying the calculations. In total, there are 25 model input parameters included in this analysis. Every model input was changed by +10% and −10%. As a result, we did 50 runs of the model for the year 2010. We analyzed the results of the 50 runs for 10,226 sub-basins and five pollutants: Cryptosporidium, nitrogen, phosphorus, triclosan and microplastics. Details can be found in Supplementary Tables 9–12 and Supplementary Fig. 17.

In general, increasing the model inputs (13 out of 25) that are responsible for excretion or consumption rates of pollutants in urban waste lead to more pollutants in rivers (Supplementary Tables 10–12). The opposite is observed when these model inputs are decreased. An exception is HDI for Cryptosporidium and microplastics. Model inputs that are responsible for wastewater treatments (6 out of 25) have the following effect on the model outputs: increases in these inputs lead to less pollutants in rivers and vice versa. Model inputs (6 out of 25) that are responsible for the number of people (urban and rural) connected to sewage systems have the following effect on the model outputs: increases in these inputs lead to more pollutants in rivers and vice versa (Supplementary Tables 10–12).

We find that model outputs are most sensitive to changes in 2–5 out of the 25 model inputs. The sensitivities vary among sub-basins and pollutants. These model inputs are HDI (sensitive for Cryptosporidium and microplastics), the fractions of secondary (sensitive for triclosan and microplastics) and tertiary (sensitive for all five pollutants) treatment, and the removal efficiencies of secondary (sensitive for triclosan and microplastics) and tertiary (sensitive for all five pollutants) treatment. We analyze model outputs for 10,226 sub-basins that are sensitive to changes

in those 2–5 model inputs. Supplementary Tables 11–12 show the percentages of the sub-basin areas where model outputs for the five pollutants change by: <5%, 5–10%, 10–50% and >50%. Supplementary Fig. 17 shows the location of the sub-basins for which model outputs are sensitive to one or more model inputs.

The model results for sub-basins covering over two-thirds of the global surface area changed by less than 5% (Supplementary Tables 11–12). For ≤13% of the global surface area the model outputs changed between 5–10%. This is for all pollutants. For ≤8% of the global area, the changes are between 10–50% in the model outputs. Exceptions are Cryptosporidium and microplastics, which are relatively sensitive for HDI. In one-third of the sub-basin area the model output for Cryptosporidium changed 10–50% as a result of changes in HDI. For microplastic, the changes may be even higher. However, the number of basins with changes above 50% is small. These results show that HDI is an important model input for Cryptosporidium and microplastics (see Supplementary Tables 1, 9–12).

Approach 5: evaluating model inputs by comparing them with independent datasets. We provide this comparison in Supplementary Table 8, Supplementary Figs. 15 and 16. Comparison results build trust in our model inputs. We compared the following important model inputs for 2010 and 2050 scenarios: total population, population with sewer connections, distribution of treatment types, removal efficiencies of pollutants, nutrients in human excretion (Supplementary Table 8). We compared these inputs with van Puijenbroek et al.[10] who recently published global analyses of nutrient inputs to rivers from point sources. We also compared our population from Jones and O'Neill[53] with another global dataset from Kc and Lutz[34] (Supplementary Fig. 16). Our model inputs are well compared with the mentioned studies. Furthermore, we compared our HDI index for 2010 and 2050 with the HDI index from Crespo Cuaresma and Lutz[57] (Supplementary Fig. 15). HDI is an important input in our model to quantify the excretion of Cryptosporidium. HDI influences the treatment developments and consumption of microplastics associated with the use of car tyres. Our values for HDI under the five scenarios are well compared with the values of Crespo Cuaresma and Lutz[57] ($R^2 > 0.88$ for the five scenarios).

Results of these five approaches give us trust in using our multi-pollutant model to explore future trends in inputs of multiple pollutants to rivers from urbanization activities. All data are available in Strokal et al.[72] and Strokal et al.[73].

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

DATA AVAILABILITY

All the datasets generated and analysed during this study are publicly available in the Data Archiving and Networked Services (DANS Easy) repository: https://doi.org/10.17026/dans-zyx-jce3[73]. The data will be available for download from 01-04-2021. The data supporting the findings of this study are described in the following metadata record: https://doi.org/10.6084/m9.figshare.13333796[72].

CODE AVAILABILITY

All equations to the model are provided in the supplementary information files of this study and in the Data Archiving and Networked Services (DANS Easy) repository: https://doi.org/10.17026/dans-zyx-jce3. The data will be available for download from 01-04-2021.

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AUTHOR CONTRIBUTIONS

M.S. led this manuscript. M.S. was responsible for designing the manuscript, developing a multi-pollutant model, and analyzing and writing the manuscript. C.K. substantially assisted in designing the manuscript, developing the model and analyzing the results. Z.B., W.F., N.H., A.A.K., L.V., M.T.H.V., J.E.S. and J.W., contributed largely in developing the global multi-pollutant model that was used in the manuscript for future analyses of the impact of urbanization on river pollution. They and other authors provided information to the manuscript and advised on the analyses. All authors assisted the interpretations of the Shared Socio-economic Pathways. These pathways are used in the manuscript for multiple pollutants. All authors read and commented on the text. All authors approved the final version and were involved in the accountability for all aspects of the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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