Article

Domestic wastewater is an overlooked source and quantity in global river dissolved carbon

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Riverine dissolved carbon (DC) plays a crucial role in global carbon cycle. Yet, the contribution of wastewater to global riverine DC remains unquantified. Here, we quantify the impact of treated and untreated domestic wastewater on dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) loadings at nation and river basin scales. We show that, globally, domestic wastewater discharges ~21.4 Tg DC annually—6.42 Tg DIC and 1.17 Tg DOC from treated, and 9.64 Tg DIC and 4.21 Tg DOC from untreated, collectively accounting for $3.13 \pm 0.46\%$ of the global riverine DC export. Contributions are highest in densely populated regions with high treatment capacity. Effluent DC levels are influenced by treatment technology, temperature, precipitation, economic growth and urban development. This underscores a need to incorporate the wastewater derived carbon into global carbon budget assessment, as well as to monitor and reduce carbon in wastewater effluents.

Accurate estimation of the land-to-ocean carbon transport is critical[1,2], as it influences evaluation of carbon sinks and sources, which is vital for understanding and predicting climate dynamics[3]. Riverine DIC and DOC present a major pathway for terrestrial-to-aquatic carbon transportation and transformation. However, the current global estimation of land-sea DIC and DOC exports carries a large uncertainty, with estimates ranging from 381 to 520 Tg C yr^{-1} for DIC and from 129 to 300 Tg C yr^{-1} for DOC[3–5]. Reducing the uncertainty has been an intense effort in global river carbon research during the past decade.

Several factors may have contributed to the large uncertainty in land-sea DC estimation. In addition to the limited field measurements and different scaling-up approaches, anthropogenic activities exacerbate uncertainties in current global riverine carbon flux estimates, particularly in rapidly urbanizing watersheds[6]. A study by Noacco et al.[7] reported a century-long rising trend of DOC in the River Thames, and the researchers found that the trend could be reasonably predicted for the period before the 1940s using a general model considering climate and soil factors. However, the standard deviation of the modeling increases largely and cannot be explained after the 1940s. They

concluded that the increase in DOC was primarily due to the population increase in the drainage basin. Several recent studies have reported a close relation of DOC and DIC levels in rivers with urbanized areas, when compared with other land use/land cover types[8–10]. Collectively, these studies help establish the knowledge of urban impact on river carbon, but none of them have pinpointed an exact cause. Globally, rivers are among the most threatened ecosystems, facing multiple anthropogenic stressors[11], yet accurately assessing the extent of anthropogenic perturbations to riverine carbon fluxes remains challenging. Understanding the precise magnitude and direction of these anthropogenic influences on riverine carbon exchange processes is essential for improving global carbon budget assessments and identifying other potential terrestrial carbon sources.

Riverine DIC is commonly considered to be generated from rock weathering and organic respiration, while DOC originates from the erosion of organic matter in soils or from aquatic plants[12,13]. This conventional understanding is now being challenged, since treated wastewaters are used as an essential source of ecological recharge (namely reclaimed water) for rivers[14,15], and increasing studies have found that

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treated domestic wastewater could be a carbon source to rivers[16–18]. Globally, annual total wastewater volume is estimated to be about $3594 \times 10^8 \, m^3$, with 41.4% treated in wastewater treatment plants (WWTPs) and discharged, and 47.2% released untreated directly into the environment[19]. Notably, 1.2 million km of the global river network receive effluents from upstream WWTPs, and treated wastewater constitutes over 10% of river flow in more than 72,000 km of rivers, mostly in areas of high population densities[20]. While WWTP effluents enhance local river water quality, it also contributes substantial amounts of DC. Despite its significance, the contribution of effluent-derived DC relative to the total DC flux from river basins remains poorly quantified. This gap underscores the need for a more detailed assessment, as the role of effluent-derived carbon is frequently over-looked in global carbon budgets, particularly within the context of the land-to-ocean aquatic continuum[19].

Here, we assess domestic wastewater-derived DC discharges at both the river basin scale in China and the national level globally. We hypothesize that domestic wastewater is a globally significant source to riverine DC, and that its contribution is shaped by environmental conditions and anthropogenic factors, such as population density and wastewater management. To test this hypothesis, we evaluate domestic wastewater DC discharge at the river basin scale in China (Fig. 1a) and at the country level in the world. The overarching goal of our assessment is to answer the question of how much dissolved carbon global WWTPs discharge and to what extend the effluent-derived DC contributes to the global riverine DC loading. We created a dataset of wastewater from seven major basins in China to analyze factors that affect treated wastewater DC level and flux. We utilized an existing dataset of global wastewater discharge to estimate the contribution of wastewater to the total riverine DC in the world.

Results and discussion
Meta-analysis of effluent DC concentration
DIC level in effluents waters ranged from 31.34–67.08 mg C L^{-1} (5th percentile to 95th percentile) across China major river basins (Supplementary Data 1), with a median of 44.26 mg C L^{-1}. DOC level varied from 3.10 to 17.08 mg C L^{-1} (5th percentile to 95th percentile) (Supplementary Data 2), with a median of 7.40 mg C L^{-1}. Apparently, the DIC concentration in effluents was six times higher than DOC concentration (Fig. 1b). The relative standard deviation (RSD) for effluents DIC and DOC were 23% ($n = 73$) and 60% ($n = 255$), respectively, indicating greater variability in effluents DOC compared to DIC. Figure 1c further demonstrates significant variation in DOC concentrations across major river basins in China, ranked as follows: HAIRB (median 10.10 mg C L^{-1}) > YRB (median 8.76 mg C L^{-1}) > LRB (median 8.70 mg C L^{-1}) > HLRB (median 7.48 mg C L^{-1}) > HUAIRB (median 7.29 mg C L^{-1}) > YZRB (median 6.69 mg C L^{-1}) > PRB (median 6.01 mg C L^{-1}). This trend shows that the northern Chinese basins exhibit relatively high DOC concentrations. However, due to the limited availability of DIC data, basin-specific analyses were not performed. When compared with other countries, the median DC concentration from China's major basins fall within the ranges with only minor (Supplementary Fig. 1a, Supplementary Data 3) difference (DOC < 2% and DIC < 8%). This suggests that the DC concentrations in Chinese WWTP effluents are generally comparable to those in other regions of the world.

Globally, WWTP effluents DIC concentration range from 16.68 to 69.80 mg C L^{-1}, with a median of 43.80 mg C L^{-1} (5th to 95th percentile, $n = 138$), and the DOC range from 3.55 to 17.08 mg C L^{-1}, with a median of 7.50 mg C L^{-1} ($n = 459$; Supplementary Fig. 1b). The RSD values are 38% and 54%, respectively. Similarly, Hu et al.[21] also reported a median DOC concentration of 7.50 mg C L^{-1} ($n = 117$) based on a statistical analysis of treated wastewater, indicating relatively limited variability in median DOC levels. A recent study revealed that the global river median concentrations of DIC and DOC

are 10.4 mg C L^{-1} and 4.10 mg C L^{-1}, respectively[22]. Therefore, the global DIC and DOC concentrations in WWTP effluents are ~4.2 and 1.8 times higher, respectively, than those observed in natural river waters. For those China's major river basins (Supplementary Data 4), effluent DIC and DOC concentrations are, on average, 2.3 and 2.4 times higher than the corresponding riverine values, respectively. Our findings lend further support to the conclusions of prior studies, such as Worrall et al.[23] reported that the median DOC concentration in final effluents (9.4 mg C L^{-1}) was 1.9 times greater than that in surface waters (4.8 mg C L^{-1}) during 2000–2016 from UK. Flint et al.[24] cited a median WWTP effluent DIC concentration of 48 mg C L^{-1} from United States. Additionally, the global median effluent DIC concentration shown karst-dominated rivers characteristic (e.g., 44.3 mg C L^{-1} in the Schwabach River, Germany)[25], while the median DOC is slightly lower than that of swamp-dominated rivers (e.g., 8.5 mg C L^{-1} in the Atchafalaya River, USA)[26].
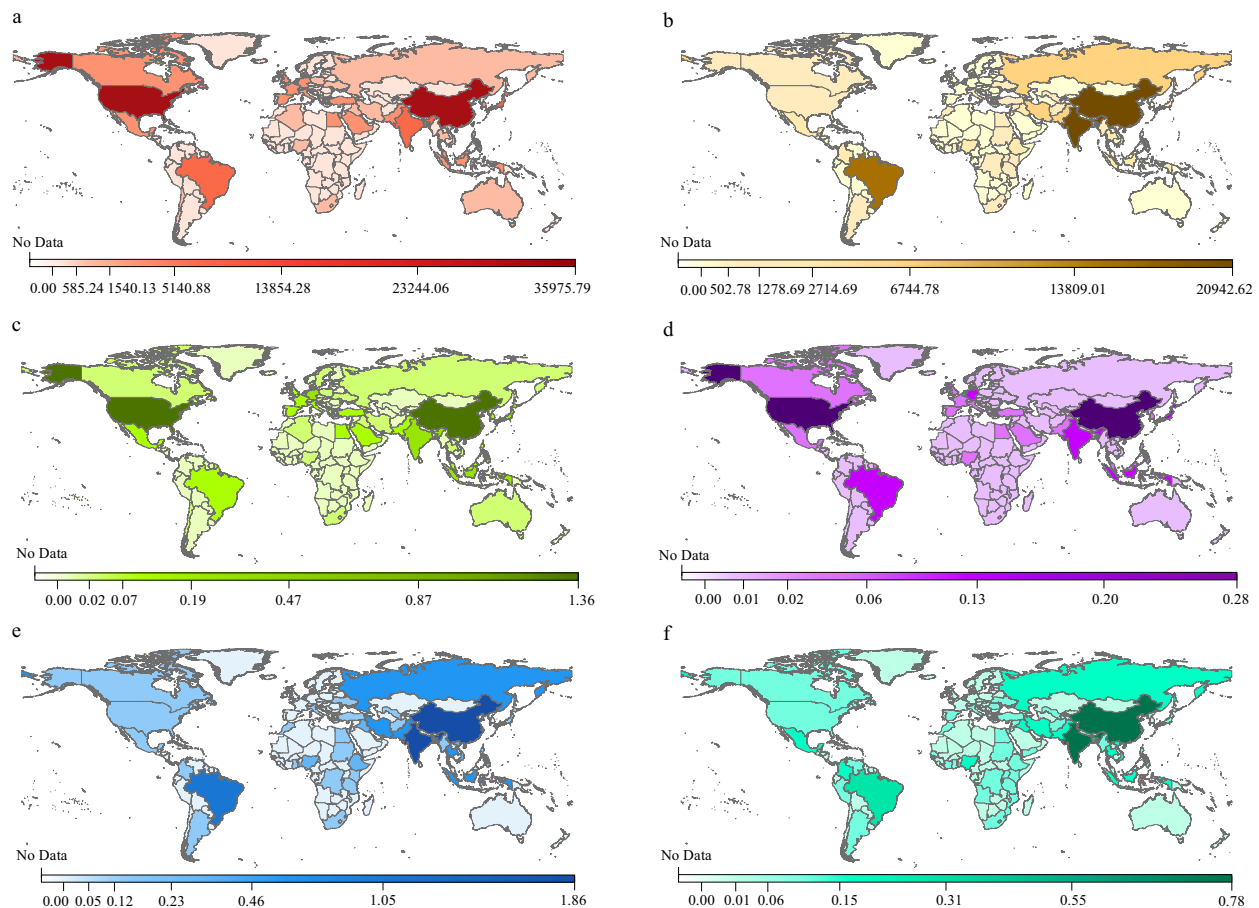
Wastewater discharge and DC flux
Globally, ~267.55 billion m^3 domestic wastewater generated each year, of which 154.99 billion m^3 (57.9%) be safely treated, and 112.56 billion m^3 (42.1%) without be safely treated. Significant regional disparities exist in the volume of treated and untreated domestic wastewaters, reflected by geographical and economic influences (Fig. 2). The annual global DIC and DOC fluxes from wastewater reach 21.44 Tg C, of which treatment plant effluents are ~6.42 Tg C and 1.17 Tg C, respectively (Supplementary Data 5). In comparison, untreated sewage discharges are substantially higher, with DIC of 9.64 Tg C yr^{-1} and DOC of 4.21 Tg C yr^{-1}. The global distribution of these fluxes mirrors the patterns associated with both treated and untreated wastewater sources. Safely treated domestic wastewater discharges are primarily concentrated in a few countries, including Brazil, China, Egypt, Germany, India, Indonesia, Japan, Mexico, the United Kingdom, and the United States, which together account for 68% of the global total. In contrast, untreated wastewater discharges are mainly concentrated in Bangladesh, Brazil, China, India, Indonesia, Iran, Nigeria, Pakistan, Russia, and Thailand, collectively contributing 61% of the global total. These regions share common characteristics—large populations and varying levels of economic development. While high population densities generate substantial volumes of domestic wastewater, the extent of wastewater treatment infrastructure is largely determined by each country's economic capacity.

In China, the average urban domestic wastewater treatment rate has reached 98.6%, with a total treatment capacity of 57.60 billion m^3 across the major river basins. This accounts for 91.9% of the country's total municipal wastewater treatment volume (Fig. 1a). Among the seven river basins, the YZRB has the most WWTPs, i.e., 1025 or 35.4% of the country's total number of urban treatment plants. These WWTPs have an annual treatment capacity of 23.32 billion m^3, accounting for 37.2% of the national total urban treatment capacity. The PRB follows with 454 WWTPs and an annual treatment capacity of 11.45 billion m^3, accounting for 15.7% and 18.3% of the national totals, respectively. As a result, these two river basins have more than half of the country's WWTPs and treatment capacity. The other fiver river basins are in the following order based on the percentage of their WWTPs in the national total: the HAIRB, HUAIRB, YRB, LRB, and HLRB. Annually, the WWTPs in China's seven major basins discharge 2.97 Tg C of DC (Fig. 3), of which DIC accounted for 85.9% (2.55 Tg C yr^{-1}), while only 14.1% is DOC (0.42 Tg C yr^{-1}). DC fluxes in each basin aligned with effluents volumes, with the order of total DC from effluents as follows: YZRB > PRB > HAIRB > HUAIRB > YRB > LRB > HLRB. The YZRB and PRB together had the highest percentage in the seven basin's total DIC (60.4%) and DOC (52.4%) from WWTPs, closely relating to drainage area and the population distribution in China. Additionally, the proportion of effluent DIC and DOC in the total effluent DC flux varied among river basins. Southern basins, such as the Yangtze and Pearl
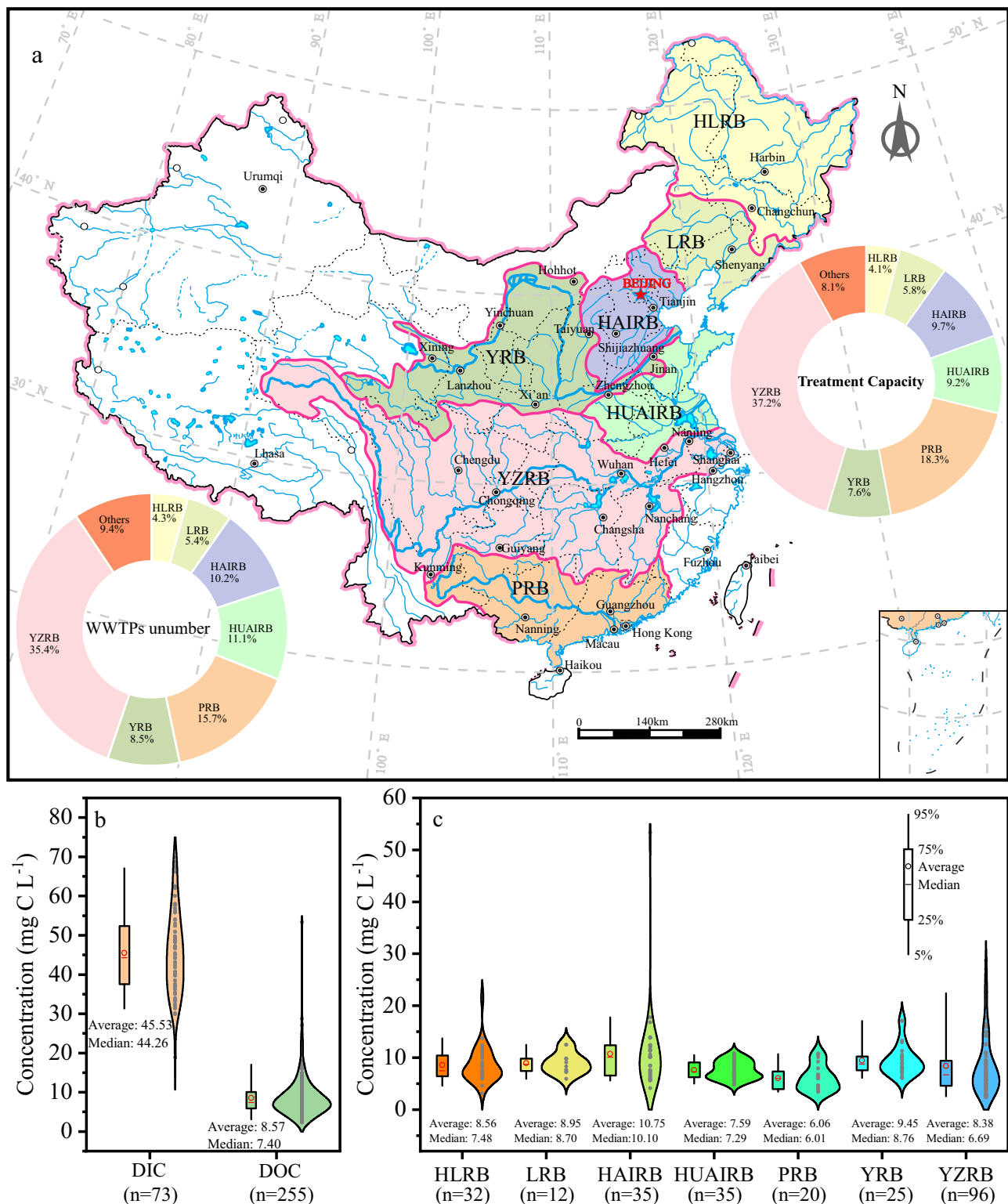
Fig. 1 | The number of municipal wastewater treatment plants (WWTPs), their treatment capacities, as well as effluent dissolved carbon (DC) concentrations in China's seven major river basins. a River basins from the Northeast to Southwest: HLRB Heilongjiang River Basin, LRB Liaohe River Basin, HAIRB Haihe River Basin, HUAIRB Huaihe River Basin, YZRB Yangtze River Basin, YRB Yellow River Basin, PRB Pearl River Basin, Others indicate regions besides the seven basins). The pie chart presents the distribution of urban WWTPs' treatment capacity and facility numbers across major river basins, with percentages representing their respective contributions to the national total. **b** Statistical distribution for DIC and DOC concentrations in WWTP effluents across the seven major river basins. **c** Variation in DOC concentrations specifically in WWTP effluents across the seven major river basins. Box plots indicate average (red circle) and median (red line), 25th, 75th percentiles (box), and 5th and 95th percentile (whiskers). Source data are provided in Supplementary Data 1 and Data 2. The boundaries of China's major river basins were adapted from the China Water Resources Bulletin (2022).

Fig. 2 | Domestic wastewater discharges and their dissolved carbon (DC) fluxes at the country level in the world. a, b Treated and untreated domestic wastewater discharge ($\times 10^6$ m^3 yr^{-1}). **c, d** DIC and DOC exports from treated domestic wastewater (Tg C yr^{-1}). **e, f** DIC and DOC exports from untreated domestic wastewater (Tg C yr^{-1}). Source data are provided as a Source data file. Source map of political administrative boundaries adapted with permission from geoBoundaries Global Database[66].

Rivers, exhibited a higher proportion of DIC and a lower proportion of DOC, whereas northern basins showed the opposite pattern.

Effluents are crucial contributors of DC to rivers

In the context of global land-to-sea DC transport, wastewater contributes ~3.13 ± 0.46% (range: 2.61–3.48%, depending on the global estimates referenced in the introduction) of global riverine DC exports to the oceans. Of this, treated and untreated wastewater account for 1.37 ± 0.17% (range: 1.24–1.57%) and 2.06 ± 0.26% (range: 1.85–2.35%) of total riverine DIC exports, respectively, and 0.60 ± 0.28% (range: 0.39–0.91%) and 2.14 ± 0.99% (range: 1.40–3.26%) of total riverine DOC exports. Although domestic wastewater discharges account for a relatively small proportion of global riverine DC exports, significant spatial variability exists across countries and regions, and untreated domestic wastewater contribution contributes more than treated. In particular, domestic wastewater-derived DC contributions are disproportionately concentrated in several countries—especially in South and East Asia—where they represent a substantial share of local riverine carbon outputs (Fig. 4). These two regions collectively have 55% of the global population, with both treated and untreated domestic wastewater contributing 10.2%, 9.7%, respectively, to regional riverine DC, and with the higher DOC contribution from untreated domestic wastewater. Another key factor contributing to the high proportion of DC from untreated wastewater in these regions is the relatively low rates of safely treated domestic wastewater—only 62.6% in East Asia and 24% in South Asia—compared to the higher average treatment rates of 86.5% in Europe and North America[19,27]. At the same time, the

contributions of DIC and DOC from untreated wastewater were also notably higher in other lower-middle-income regions (Africa, South America, and Central Asia). In contrast, the contributions of DIC and DOC from treated wastewater were, on average, 3.5 and 1.4 times greater than those from untreated wastewater in both Europe and North America, respectively. This disparity indicates that domestic wastewater contributes disproportionately to riverine DC in these regions, and the influence from treated and untreated domestic wastewater cannot be ignored. Prior studies, based on worldwide meta-analyses, have shown that rivers in Asia and Europe exhibit higher DOC and DIC concentrations compared to other regions. These elevated concentrations have been attributed to the effects of increased urbanization in these areas[22]. Our findings further support this association, demonstrating that urbanization significantly contributes to rising DC concentrations in rivers by generating large volumes of domestic wastewater. Therefore, in high-income regions, although wastewater is treated, effluent still contributes a substantial portion of riverine DC flux due to the volume of discharge. In low- and middle-income countries, untreated wastewater not only poses greater ecological risks but also significantly alters the riverine carbon composition. These findings underscore the need for region-specific strategies in carbon accounting and wastewater management and suggest that improvements in wastewater treatment infrastructure in developing countries could play a dual role in both public health protection and carbon mitigation.

Although treated wastewater discharges contribute a comparably low proportion to the global total DC exports, its regional impact is
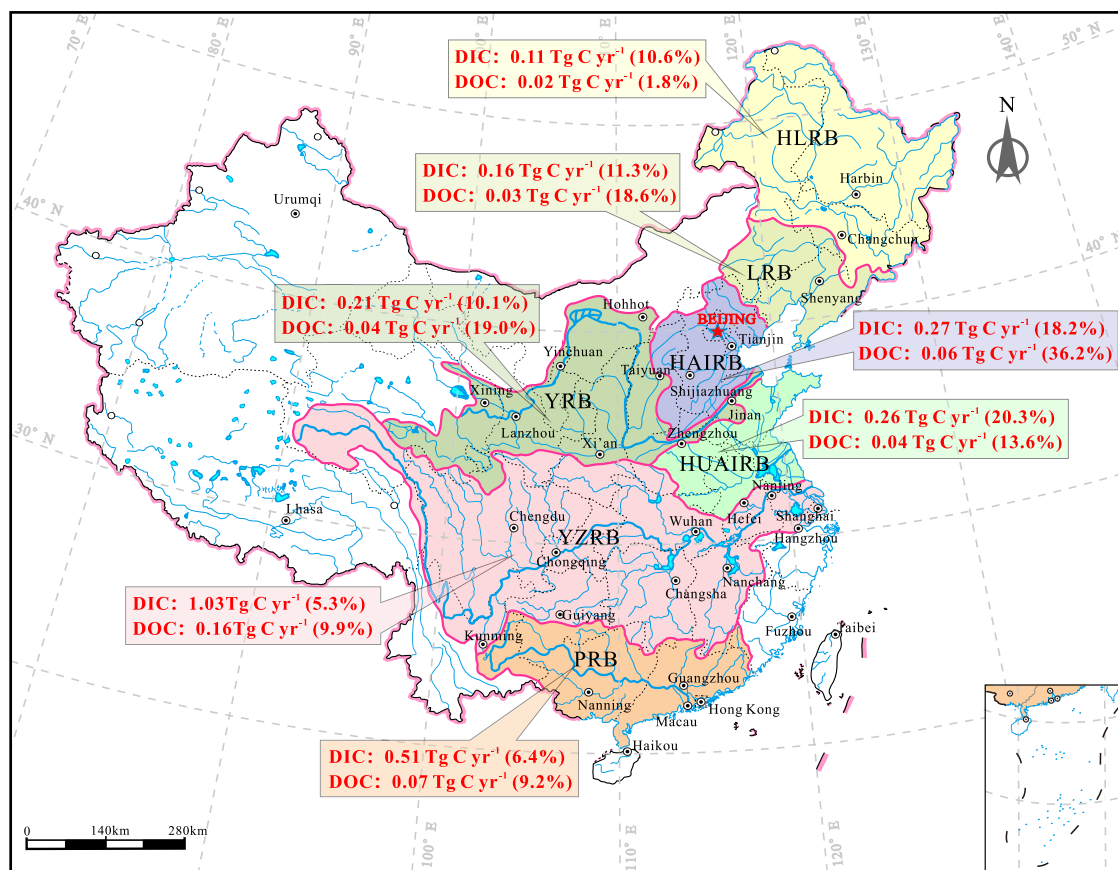
Fig. 3 | Treated domestic wastewater-derived dissolved carbon (DC) fluxes in China's seven major river basins. The percentages in parentheses indicate the proportion of urban WWTPs effluent DIC/DOC fluxes relative to the total regional river DIC/DOC exports. The boundaries of China's major river basins are adapted from the China Water Resources Bulletin (2022).

significant in countries with high population densities. For example, Liu et al.[3] estimated that the East Asian rivers are estimated to transport 12 Tg of DOC and 37 Tg DIC to the oceans, therefore, in China' seven major river basins, urban effluents contribute 6.9% of total DIC and 3.5% of total DOC exports for the total East Asian rivers, while total urban effluents accounts for average 7.3% of total DIC and 9.9% of total DOC exports in the seven major basins (Supplementary Data 4), underscoring the importance of urban effluent-derived DC in river basin carbon accounting. The effluent DOC contribution varies significantly across China's major river basins (Fig. 3) following the order: HAIRB (36.2%) > YRB (19.0%) > LRB (18.6%) > HUAIRB (13.6%) > YZRB (9.9%) > PRB (9.2%) > HLRB (1.8%). The effluent DIC contribution shows a different order: HUAIRB (20.3%) > HAIRB (18.2%) > LRB (11.3%) > HLRB (10.6%) > YRB (10.1%) > PRB (6.4%) > YZRB (5.3%). This trend shows that rivers in the northern China exhibit a higher contribution of effluent-derived carbon to the local riverine DC export. These findings align with those reported by three recent studies using stable carbon isotope methods. For instance, DOC from sewage increased from 2% in headwater areas to 19% in the downstream YRB[28]. Additionally, 8%, 22%, 23%, and 83% of DOC in four river types in the HARIRB were attributed to sewage[29]. In the densely populated Pearl River Estuary, Ye et al.[30] reported ~27–33% of DOC originated from domestic wastewater sources, highlighting the significant contribution of domestic wastewater effluents to DOC levels in highly urbanized regions. A recent study hypothesized that treated municipal wastewater has been the key contributor to riverine inputs of DOC to the ocean in mainland China over the past 60 years[31], and the results of this study support this assertion by providing the contribution of municipal wastewater to DOC at the watershed scale.

Key factors influencing DC level and mass fluxes

The complete mineralization of organic compounds produces substantial amounts of CO_2 during wastewater treatment. A portion of this CO_2 is released into the atmosphere through aeration, while the remainder dissolves into the treated effluent, contributing to the elevated DIC concentrations commonly observed in WWTP effluents[32]. These processes are key drivers in the formation of characteristic DIC species. During nitrogen removal—specifically through nitrification—the pH is tightly controlled within a narrow range (7.0–8.5) to maintain optimal nitrogen removal efficiency[33]. As pH variations in wastewater treatment are largely governed by the equilibria of carbonic acid[34], DIC concentrations in biochemically treated domestic wastewater typically exhibit limited variability. Nevertheless, some variation in DIC concentrations is observed across different land regions (Supplementary Fig. 1c), suggesting potential influences from the composition of organic carbon in the influent and the efficiency of the biochemical treatment processes.

Several factors could have contributed to the difference in effluent organic carbon levels. WWTPs equipped with denitrification (partial or full) or membrane bioreactor systems generally achieve lower DOC concentrations[35]. Moreover, 60% to 85% of the DOC in effluents from urban WWTPs originates from C_3 plants, reflecting the source characteristics of influent organic matter[16,36,37]. Therefore, the variation in DC levels could reflect local dietary habits. The total area used for cultivating soybeans and wheat in Northeast and North China makes up 68% and 47% of the whole country, respectively, while 66% of the rice-planting area in Central and South China[38,39]. It is therefore evident that significant variations in food preferences are observed between the northern and southern regions due to their distinct geographical
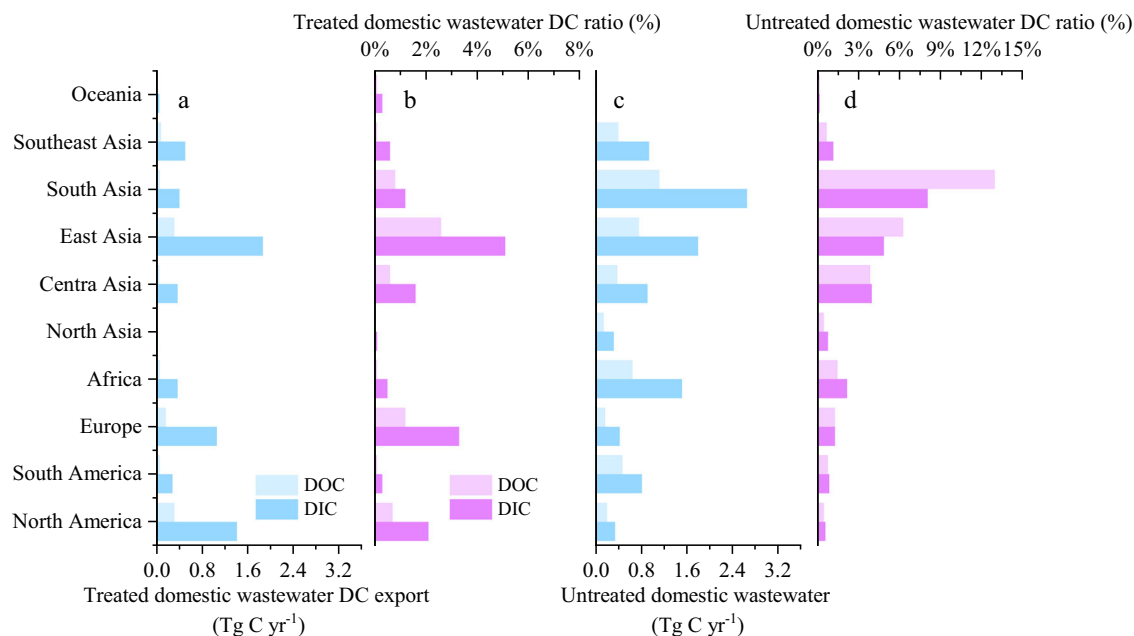
Fig. 4 | Flux and proportion of domestic wastewater-derived dissolved carbon (DC) at the land region scale. a, b Treated wastewater DC flux and its contribution to total riverine DC export in each land region. **c, d** Untreated wastewater DC flux and its contribution to total riverine DC export in each land region.

environments[40]. Generally, northern Chinese consume more wheat and soybean products, whereas southern Chinese consume more rice, meat, as well as vegetables[41]. Wheat and soybeans contain higher levels of carbon-bearing nutrients compared to rice and vegetables[42,43], and plant proteins are often less digestible[44]. Although river basins in the northern China exhibit relatively high concentrations of DOC in their effluents, it remains uncertain whether this is related to local dietary habits. A study by Sakdullah and Tsuchiya[45] showed that domestic waste-derived organic matter in a Japanese estuary was linked with the diet of tilapia. However, we found no study that has linked DOC derived from sewage directly with food habits in China and other regions. Studies are needed to elucidate possible relations between effluent DOC and diet. DOC levels in effluents may also be influenced by environmental factors. A negative relationship was observed between DOC concentration and air temperature (Supplementary Fig. 2a). Generally, most microorganisms involved in biological wastewater treatment are temperature-dependent, with optimal activity occurring between 20 °C and 35 °C[46]. Temperatures in the northern China are far below the range, ranging normally from 2 °C to 16 °C in monthly averages[47]. These lower temperatures likely suppress microbial metabolism and reduce the efficiency of contaminant removal processes, potentially contributing to the higher DOC concentrations observed in effluents. Interestingly, a significant negative relationship was observed between effluent DOC concentration and rainfall (Supplementary Fig. 2b). We attribute this to the dilution effect of rainfall, which is generally more abundant in southern China compared to northern regions. In addition, most WWTP facilities are typically open systems, allowing rainwater to enter either directly or through the influent network, thereby reducing the concentration of organic carbon in the treated effluent.

The key factors that control WWTPs' effluent DC flux and its proportion to river DC export variation are also complicated. A significant positive correlation was observed between WWTPs effluent DC flux and factors such as precipitation, drainage area, annual basin runoff, population, and economic levels across China's seven major river basins (Fig. 5a). The proportion of WWTP effluent-derived DC showed a positive correlation with population density (Fig. 5b), suggesting that both hydrological conditions and population distribution

play critical roles in governing DC mass transport at the river basin scale. Moreover, DIC and DOC flux proportions from WWTP effluents show a positive correlation ($r = 0.697$ for DIC; $r = 0.952$, $p < 0.01$ for DOC) with the effluent discharge proportion of basin runoff, indicating that higher effluent discharge within a basin leads to greater DC contributions from these sources. Two recent studies reported that riverine CO_2 levels rose with increasing urban land area[10,48]. Consistent with these findings, our further analysis reveals that urban population, effluent discharge, and DC export all show significant positive correlations with the extent of built-up area (Supplementary Fig. 3). These results suggest that human activities—reflected by regional economic development, urban population size, and the expansion of built-up areas—can further amplify the transport of wastewater-derived carbon to river systems. Although the proportion of WWTP effluent-derived DC showed a negative correlation with drainage area. It is also implying that in upstream areas of a large river basin, the proportional contribution of effluents tends to be. For instance, in the Nanming River, Southwest China, which constitutes only 0.06% of the total YRB area, effluents contribute 21–66% of the river's DIC[17]. It is, however, not clear how much effluents-derived DC can contribute to riverine CO_2 emission at the river basin scale. Further studies are necessary to discern the loss of effluents-derived carbon to the atmosphere at the river basin scale.

The relatively high effluent DC contribution in the North China basins is likely attributed to their location within a semi-humid to semi-arid continental monsoon climate zone, coupled with higher population densities, particularly in the HAIRB and HUAIRB. This region faces water scarcity, expanding the reuse of WWTP effluents has proven to be an effective strategy to alleviating the water crisis; for example, in Beijing (located in HAIRB), 84.2% (1.11 billion m³) of the ecological water supply is derived from WWTP effluents. For instance, in the downstream section of the Chaobai River at the city's Shunyi District, Beijing, effluent supply reaches 0.4 million m³ yr⁻¹, comprising 40% of the annual runoff and 95% of winter streamflow[14]. Recent studies have shown a 20% increase in riverine DOC exports in China (from 3.76 to 4.53 Tg C yr⁻¹) over the short period from 2001 to 2015, with significant increases in DOC concentrations observed in the YRB and HUAIRB[47]. While this analysis attributes the rise to anthropogenic activities, it
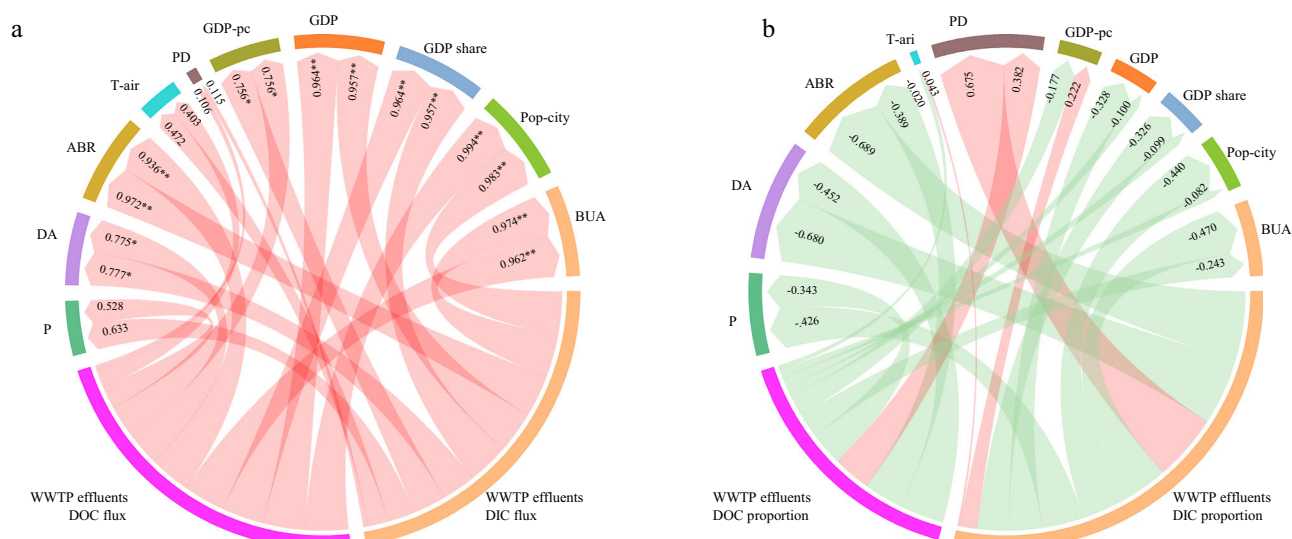
Fig. 5 | Correlations of effluent dissolved carbon (DC) flux with social economic factors. a Relationships between effluent DC flux and key influencing factors. **b** Relationships between the proportion of effluent DC in basin river DC exports and key influencing factors. The red arrows indicate positive correlations, while the green arrows indicate negative correlations. The values at the arrow tips represent the corresponding Pearson correlation coefficients ($*p < 0.05$, $**p < 0.01$). P Precipitation, DA Drainage area, ABR Annual basin runoff, T-air Air temperature, PD Population density, GDP-pc GDP per capita, GDP Total GDP, GDP share GDP in percentage of country, Pop-city City population, BUA Built-up area.

does not specify the exact activities responsible. Based on our analysis and the observed annual increase in treated wastewater discharge (Fig. 2), we propose that this trend is closely linked to effluents discharge increased within these basins. Additionally, the significant declines in annual runoff have been observed in the LRB, HAIRB, and YRB, primarily driven by land surface changes such as urbanization and surface water withdrawals[49]. Under the pressures of climate change, the growing dependence on treated wastewater to sustain river base flows demands close examination, especially regarding its effects on the carbon cycle within these semi-humid, semi-arid continental monsoon climate basins.

Implication for global wastewater DC discharge to rivers
Overall, effluents are characterized by high DC concentration, thus potentially affecting carbon transport and transformation in the receiving water bodies. High DIC inputs from effluents can significantly enhance CO_2 outgassing fluxes in receiving water bodies[50,51]. Such CO_2 spikes have been seen primarily near effluents discharge points, with pCO_2 and CO_2 diffusion rates decreasing downstream[52,53], resulting in spatial discontinuities in riverine greenhouse gas profiles. Notably, CO_2 emissions from in arid and semi-arid climates urban rivers, are markedly elevated[54]. The discharge of treated domestic wastewater into the river will also discharge a number of low aromaticity, small molecular weight protein-like substances into the river[21], not only to facilitate the use of microorganisms and photodegradation[55,56], implying a role that effluent-derived DOC can play in elevating CO_2 envision of receiving waters, but also its impact on a series of environmental factors such as turbidity, dissolved oxygen, and may further increase the rate of anaerobic methanogens methanogenic rate, and thus greatly increase the river's potential for carbon emissions[18,57]. Therefore, the influence of wastewater on carbon cycling processes and flux dynamics within watersheds warrants careful consideration and should not be overlooked.

Our study highlights the significant contribution of dissolved carbon from domestic wastewater treatment plants to river systems, an impact that is expected to grow as urbanization advances and more wastewater treatment plants will be constructed globally. For instance, in China's seven major river basins, the number of urban wastewater

treatment plants rose from 513 in 2003 to 2,623 in 2022, accounting for 83.8% of all municipal wastewater treatment plants (Supplementary Fig. 4). During the same period, total WWTP effluents in China increased from 326.1×10^8 m³ to 587.12×10^8 m³, with most growth occurring after 2008. The proportion of treated urban wastewater to total basin runoff rose from 0.38–5.38% in 2002 to 2.2–21.1% in 2022. Among the basins, the HAIRB had the highest wastewater treatment ratio at 21.1%, followed by the HUAIRB at 7.8%, the LRB at 7.5%, the YRB at 7.2%, the PRB at 2.6%, the YZRB at 2.5%, and the HLRB at 2.2%. In Europe and North America, where domestic wastewater treatment rates are high, the contribution of treated wastewater DIC to basin riverine DIC output surpasses that of untreated wastewater (Fig. 4a). Thus, while the expansion of wastewater treatment infrastructure has effectively reduced the DC contribution from untreated sewage, treated wastewater continues to serve as a source of ecological recharge, maintaining a substantial DC input to rivers. This underscores the ongoing significance of treated wastewater in global riverine carbon dynamics.

On the other hand, as the global population grows, the expansion of wastewater treatment infrastructure may face significant challenges in developing countries due to financial and resource constraints. Taking the world's most populous country, India, as an example, India's current municipal wastewater generation is 26.4 billion m³, but only 28% of that volume is safely treated[27]. The population of India is expected to exceed 1.5 billion by 2050. At this time, more than 50% of the total population (0.75 billion) will be in urban centers, and the number as well as size of settlements will multiply[58], raising the challenge of municipal wastewater treatment. Globally, urbanization is expected to reach 68.4% by 2050, with ~6.68 billion people living in cities, as estimated by the UN World Cities Report 2022 (https://unhabitat.org/wcr/). Notably, 52% of this urban population will be in Asia. Asian rivers, accounting for only 29% of global river-surface area, contribute disproportionately to global freshwater discharge (35%), and total organic carbon (50%) and dissolved inorganic carbon (39%) exports to the oceans[59]. The rapid urbanization in Asia would imply that riverine DIC and DOC dynamics will be significantly influenced as the rivers flow through more metropolitan areas, receiving more WWTP effluents and transporting and transforming more carbon to the ocean and the atmosphere.

While this study provides an estimate of domestic wastewater-derived DC to global rivers, some limitations remain. These include the lack of long-term and high-resolution effluent data, especially in the low-income regions. The exclusion of industrial wastewater can lead to an underestimation of total anthropogenic carbon input. More studies are needed to discern the spatiotemporal variability of wastewater-derived carbon at the regional scale. Possible dietary impacts on legacy DC should be investigated, since our data reveals a difference in effluent-derived DC between North and South China. Currently, unlike with nitrogen, phosphorus, and other water quality parameters, most countries have no monitoring on effluent carbon. We postulate that such monitoring system be implemented to help develop best management practices at the watershed scale for reducing anthropogenic carbon into riverine systems. As urbanization and population growth continue, the number of wastewater treatment plants is expected to increase. The findings from our study demonstrates the need to include WWTP carbon sources into the global carbon budget as well as the importance to monitor and reduce effluent carbon.

Methods

Study area
The seven major river basins of China cover a surface area of 5.05 million km^2, which account for 52.5% China's total land area (Fig.1a). These river basins include the Heilongjiang River Basin (HLRB), Liaohe River Basin (LRB), Haihe River Basin (HAIRB), Huaihe River Basin (HUAIRB), Yangtze River Basin (YZRB), Yellow River Basin (YRB), and Pearl River Basin (PRB). The large area stretches from 20° to 53° in latitude and 90–135° in longitude, crossing several climatic zones from semi-arid to warm subtropical and variable terrains from low-lying coastal plains to high-elevation Tibet Plateau, representing natural conditions of many regions in the world. In the past two decades, these regions have experienced rapidest population and economic growth in the world. The average urbanization rate has been reached 63.9%. These river basins are home to more than 1.16 billion people, accounting for 82.7% China's total population, or one seventh of the world's population. The seven river basins contribute 82.6% of in China's total GDP[60].

Data collection
Data on the domestic wastewater. Global data on treated and untreated domestic wastewater discharges up to 2022 were obtained from the official report jointly published by UN-Habitat and WHO[27]. This report provides estimates of total domestic wastewater generation for 232 countries, areas, and territories, covering over 99% of the global population. Therefore, the global and regional estimates presented in the report are considered representative of worldwide domestic wastewater flows. In the report, "safely treated" domestic wastewater refers to effluent that is either discharged in compliance with relevant standards or treated to a level equivalent to secondary (or higher) treatment processes. Based on this definition, we calculated the volume of treated effluents using the safely treated wastewater data. There are 92 countries and territories lacking data on treated wastewater; however, the total wastewater volume from these regions accounts for only 7.2% of the global total. Following the reporting methodology, the regional average proportion of household wastewater safely treated in 2022 was used to estimate values for these countries and territories without specific data. The volume of untreated domestic wastewater was estimated by subtracting the safely treated quantity from the total domestic wastewater generated. Source data are provided as a Source data file.

For the seven major river basins in China, data on municipal wastewater generated and safely treated were derived from the China Urban-Rural Construction Statistical Yearbook (2003–2022). The yearbooks offer comprehensive data on the number, discharge volumes, and treatment capacities of wastewater, categorized by city locations. Using the basin boundaries outlined in the China Water Resources Bulletin 2022, we identified and grouped cities within each watershed. This categorization allowed us to summarize the number of urban wastewater treatment plants, the volumes of wastewater discharged and treated, as well as the urban population and built-up area for each watershed. Source data are provided as a Source data file. However, the yearbook only reports the number and discharge volumes of wastewater treatment plants at the county and township levels by province, without specific data for individual counties and townships. As a result, this data could not be included in the analysis. Consequently, the treated wastewater discharge considered in this study represents only urban wastewater treatment plant outputs. The Yearbook also indicates that China's urban wastewater collection and treatment rate is nearly 100%. As a result, untreated municipal wastewater in China's seven major watersheds was not included in the analysis. Although some of the treated wastewater is reused, the overall reuse rate of wastewater in China is less than 10%, and ecological recharge of downstream rivers is one of the main ways of reuse[61]. Seventy-five percent of China's total wastewater is treated from urban wastewater treatment plants, while 25% of treated wastewater from county and township is not included in the statistics, so the results of the statistics can reflect the overall characteristics of China's treated wastewater discharged.

Data on effluent DC concentration
We used the largest database of WWTP effluent DC measurements. DC concentration data were collected from published literature both in English and Chinese. We searched for peer-reviewed articles by using the ISI-Web of Science, Google Scholar, and China National Knowledge Infrastructure (CNKI). The related keywords applied for literature searching included: WWTPs, municipal wastewater treatment plant, sewage, wastewater effluents, reclaimed water, DOM, effluent organic matter, EfOM, dEfOM, dissolved organic C, DOC, dissolved inorganic C, DIC, as well as country name. To reflect the DC concentrations in treated domestic wastewater, the data were obtained from constructed and operational wastewater treatment plants with predominantly domestic influent, as reported in the literature and dissertations. Pilot-scale studies, synthetic wastewater, and industrial wastewater were excluded. A total of 80 research papers from China were identified, yielding 328 data points, including 73 for DIC and 255 for DOC. Detailed information on effluent DC concentrations and locations is provided in Supplementary Data 1–2. In addition, 92 research papers from other countries were reviewed, contributing 65 DIC and 204 DOC data points, along with representative DC concentrations from typical rivers, as presented in Supplementary Data 3. Since some literature sources did not report measured DIC concentrations, we calculated DIC by converting the concentrations of individual carbonate species provided or by using pH and alkalinity values with the hydrogeochemical software Visual MINTEQ 4.0. These calculated values are labeled accordingly in Supplementary Data 1–3.

Data on the major basin characteristics in China
We obtained data on drainage area, annual runoff, and precipitation from the China Water Statistical Yearbook (2022), while the urban population and built-up area were derived from the China Urban-Rural Construction Statistical Yearbook (2003–2022). Information on population density, total GDP, national GDP share, GDP per capita, and annual air temperature was sourced from published literature. Additionally, the mean concentrations of DIC and DOC in global major rivers were collected from published studies. All data sources and corresponding references are provided in Supplementary Data 4.

Calculation of domestic wastewater DC flux and its ratio in basin DC export

Annual DOC and DIC exports from treated and untreated domestic wastewater discharges were calculated using the formula:

$$F_{DOC/DIC} = Q \times C \times 10^{-12} \quad (1)$$

Where $F_{DOC/DIC}$ represents the annual treated and untreated domestic wastewater DOC or DIC flux (Tg C yr^{-1}, 1 Tg = 10^{12} g), Q is the effluent and untreated domestic wastewater discharge volume (m^3 yr^{-1}, 1 m^3 = 10^3 L), C is the median effluent DOC or DIC concentration (mg C L^{-1}, 1 mg = 10^{-3} g), the factor 10^{-12} accounts for unit conversion to Tg C yr^{-1}. Globally, we analyzed all available DC data collected in this study. In addition, we calculated the median DC concentrations for each major continent, including America (North and South), Europe, Asia (North, Central, East, South, and Southeast), Oceania, and Africa, to quantify domestic wastewater DC fluxes at the national and continental levels. Due to the limited data for Africa, we used the global median DC concentration derived from all data in this study to estimate the DC fluxes for the continent. Similarly, because no DIC concentration data were available for Oceania, the global median DIC value was used as a substitute. The calculation results are presented in the Source Data file.

We analyzed the DIC concentrations in Chinese effluents and used the median basin-scale DOC concentrations to estimate the DC fluxes from the seven major river basins in China. For untreated wastewater, municipal WWTPs typically reduce influent DIC concentrations by ~54.4% and DOC concentrations by 84.2%[62]. Based on the median effluent DC concentrations derived in this study, untreated wastewater DIC and DOC concentrations were estimated to be twice and five times the median values, respectively.

$$P_{DC/DOC/DIC} = \sum F_i / F_{global/land\ region/basin} \quad (2)$$

Where $P_{DC/DOC/DIC}$ denotes the proportion of treated or untreated domestic wastewater-derived DC (DOC or DIC) flux relative to riverine carbon fluxes at the basin or land-region scale. F_i represents the domestic wastewater DC (DOC or DIC) flux at the country or basin level, and $F_{global/land\ region/basin}$ is the total riverine DC (DOC or DIC) export at the global, land regional scale, or major basin in China. In this study, DC (DOC or DIC) output fluxes for China's seven major river basins were calculated based on total annual runoff and the mean riverine DC concentrations for each basin. The global riverine DC export were cited from three key studies: The global river DC export were cited from Li et al.[4] (total DC 650 Tg C yr^{-1}, DIC 410 Tg C yr^{-1}, 240 Tg C yr^{-1}), van Hoek et al.[5] (total DC 616 Tg C yr^{-1}, DIC 487 Tg C yr^{-1}, 129 Tg C yr^{-1}), Liu et al.[3] (total DC 820 Tg C yr^{-1}, DIC 520 Tg C yr^{-1}, 300 Tg C yr^{-1}). The final domestic wastewater contribution to global riverine DC fluxes is relative to the average of these studies. Land-region-scale riverine DC export data were obtained from Liu et al.[3] with land area divisions (North America, South America, Europe, Africa, North Asia, Central Asia, East Asia, South Asia, Southeast Asia, and Oceania) following the RECCAP2 (Regional Carbon Cycle Assessment and Processes, Phase 2) continental boundary definitions used in their study. The results of these calculations are presented in Supplementary Data 4–5.

Statistical analyses

The average and median concentrations of DC were calculated using the full dataset, and additional analyses were conducted at the river basin, country, and continental scales. A range of environmental and anthropogenic factors can influence the effluent DC flux and its proportion at the river basin scale. To explore the relationships of wastewater DC flux and its contribution to riverine DC, statistical analysis and testing were performed using SPSS 27.0 (IBM SPSS Inc.). DIC and DOC variations with the key climatic factors were also analyzed. Pearson's correlation coefficient was applied to evaluate the connections between variables and factors.

Major sources of uncertainty

Chemical characteristics of WWTP effluents have been studied for several decades, yet tracing and quantifying the downstream impact of WWTP effluents on carbon is rather limited. Here, we quantified the contribution of effluents as well as untreated wastewater to riverine carbon at the drainage basin and global scales. For such a large undertaking, some limitations exist.

First, river hydrology is marked by seasonal fluctuations, with high rainfall and river flow in the wet season and low rainfall and flow in the dry season. Consequently, the proportion of DC from effluents is likely higher during the dry season than in the wet season. A recent study found that China has a total of 104,698 km of river segments downstream of WWTPs. Under normal flow conditions, 20.2% of these segments receive more than 10% treated wastewater. However, during low-flow conditions, this proportion increases sharply up to 37.1%[20], showing that WWTP effluents constitute a larger share of river discharge when natural flows are low. Further research is needed to clarify how changes in the hydrological cycle affect the contribution of effluents DC to the overall DC output of the basin.

Second, according to the China Urban-Rural Construction Statistical Yearbook (https://www.mohurd.gov.cn/), China's county-level treated domestic wastewater discharge in 2022 reached 11.14 billion m^3, with a treatment rate of 96.9%. While ~64.2 billion m^3 of domestic wastewater is generated annually in rural areas of China[63], the treatment rate remains low at around 31%[64]. In this study, data from rural areas are excluded from this study due to the lack of information at this administrative level in the official yearbooks. As indicated by the median DC concentrations of the major river basins in China, the domestic wastewater that has undergone treatment at the county level, along with both treated and untreated domestic wastewater in rural areas, is estimated to generate ~1.07 Tg C yr^{-1} of DC (0.97 Tg C yr^{-1} as DIC and 0.10 Tg C yr^{-1} as DOC). This suggests that the contribution of domestic wastewater-derived DC to major Chinese river basins is likely underestimated. Furthermore, the global wastewater discharge data from UN-Habitat and WHO report[27] likely underestimates current domestic wastewater discharge levels. For instance, while the report estimated annual domestic wastewater production for China at 49.67 billion m^3, actual figures show that China's urban domestic wastewater production alone now reached 63.89 billion m^3 annually based on the China Urban-Rural Construction Statistical Yearbook (2022). Therefore, in fact, the actual effluent DC from global river basins could be much higher.

Third, this study excluded industrial wastewater. Jones et al.[19] estimated a global volume of 359.4 billion m^3 yr^{-1} combined from domestic and industrial wastewaters. According to data from UN-Habitat and WHO report[27], domestic wastewater accounted for 267.6 billion m^3 yr^{-1}. Therefore, the global industrial wastewater production is estimated to be ~91.8 billion m^3 yr^{-1}. However, quantifying the DC flux from industrial wastewater is challenging due to the complexity of industrial sectors, which produce highly variable wastewater characteristics. Notably, industrial effluents tend to have higher DOC concentrations. For example, Su et al.[65] reported that the DOC concentration in secondary effluent from an industrial park wastewater treatment plant reached 34 ± 5 mg L^{-1}. Therefore, the actual total effluent-derived DC flux from global rivers and China's major basins may be substantially underestimated.

Finally, it is also not clear how much the effluents DC is carried to the coastal waters and metabolized by aquatic organisms/or transformed into the atmosphere via CO_2. Therefore, more studies are needed to determine variation in DC concentration from various wastewater treatment facilities across different regions, as well as

develop a comprehensive understanding of effluent carbon dynamics at watershed and river basin scales.

Data availability

All data are generated and used in this study are available in the Supplementary Data 1–5. Source data are provided with this paper.

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X.C. and Y.X. conceptualized, designed the research, and acquired the funding. X.C., Y.L., S.C., and G.L. collected the data and conducted the data analysis. X.C. and Y.X. were responsible for writing the manuscript and interpreting the data.

Competing interests
The authors declare no competing interests.

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