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Carbon cycling in the Asian Oceania region in a changing world

Hydroclimatic Drivers of Dissolved Organic Carbon in Asia's Major Rivers

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Abstract Dissolved organic carbon (DOC) plays a vital role in the global carbon cycle, with river discharge as a major transport mechanism from land to ocean. As the second-largest freshwater contributor to oceans, Asia experiences significant hydroclimatic variations, yet, observations are patchy across watersheds and climate zones. Here, we compiled 1,593 DOC observations from 40 studies spanning most Asian climate zones to map large-scale patterns, and tested hydroclimatic controls for a set of representative watersheds (Yangtze, Yellow, Mekong, Ganges-Brahmaputra, and Rajang) where sufficient time series records exist. Our findings show DOC concentrations peaking near the equator (tropical rainforest) and again above ~40°N (humid continental dry winter), with tributaries exhibiting higher and more variable levels than mainstems. Hydroclimatic responses were basin-dependent: DOC-precipitation correlation was not significant, yet DOC significantly differed across precipitation groups with highest means at low precipitation, indicating nonlinearity and likely thresholds; temperature effects diverged by basin; and soil moisture was a consistent positive driver, especially in Mekong and Yangtze. Overall, this study highlights that DOC behavior in Asia cannot be captured by uniform assumptions across basins and climate zones. As most existing observations are limited to short-term data sets, the impacts of hydroclimatic change on carbon transport remain uncertain and require long-term data sets. Future research should take an interdisciplinary approach by integrating hydrology, geomorphology, and climate indicators by fusing remote sensing based observations and advanced analytics, to address differences in DOC behavior and climate challenges.

Plain Language Summary River discharge is the principal carrier of dissolved organic carbon (DOC) to the oceans. Asia's vast landmass, with its diverse water and climate variations, impacts land-to-ocean DOC transport through the river systems. We gathered and analyzed 1,593 measurements from 40 studies across watersheds from most of Asia's climate zones, to see how hydroclimatic factors (such as rainfall, temperature, and soil moisture) affect the DOC levels. Our study found that DOC tends to peak in two areas: near the equator (very warm and wet) and in higher latitudes in the northern part of Asia (>40°N). We observed a non-linear relationship between DOC and precipitation. Temperature shows a positive effect on DOC in Mekong, but a negative influence in case of Yangtze. However, soil moisture shows a consistent and positive influence on DOC, particularly in the Mekong and Yangtze basins. Future research needs to integrate longer-term data with geomorphology and climate extremes using technology such as satellite remote sensing and machine learning to better predict DOC movement based on discharge and soil moisture.

Key Points:

- High DOC concentrations occurred in both equatorial and 40°–60°N related to tropical rainforest and humid continental dry winter climates
- Both precipitation and temperature have non-linear relationship with DOC that varied across basins
- Soil moisture is a consistent positive driver on DOC, especially in the Mekong and Yangtze basins

Supporting Information:

Supporting Information may be found in the online version of this article.

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1. Introduction

Carbon (C), a fundamental element that regulates planetary and its ecosystem functioning, is strongly shaped by the global hydrological cycle (Schefuß et al., 2016). Organic carbon (OC) compounds in the water are varied and classified into three main forms, which are volatile organic carbon (VOC), particulate organic carbon (POC), and dissolved organic carbon (DOC) (Mopper & Qian, 2000). DOC is the most prevalent form of organic carbon in water, with the approximate proportion of living organisms, POC and DOC at 1:13:250, respectively (Romankevich & Vetrov, 2013). DOC is primarily derived from sewage input, autochthonous sources, terrestrial plants, and soil erosion (Seitzinger et al., 2005; Z. Wen et al., 2020), which are then transferred and transformed along the hydrological flow path through runoff and baseflow (Pacific et al., 2010; van Verseveld et al., 2008).

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Many studies have characterized C fluxes across the three common interfaces: land–atmosphere, land–water–air coupling, and land–sea interactions (Y. Gao et al., 2022). A recent study has revealed that the terrestrial C transport to the ocean is in the range of 1.02 ± 0.22 Pg C/yr (M. Liu et al., 2024), 43% higher than the previous estimate of ∼0.78 Pg C/yr (Battin et al., 2023; Tian et al., 2023) and nearly double its initial calculated value of ∼0.4 Pg C/yr (Meybeck, 1982; W. H. Schlesinger & Melack, 1981). Of this exported C, 47% is organic carbon (OC) and 53% is inorganic carbon (IC) (Tian et al., 2023. The ocean mineralizes more than 90% of terrestrial C exports into CO_2 that is emitted back to the atmosphere. Only 3% of the total C transported to the ocean is buried in sediments and incorporated into the long-term carbon cycle (Romankevich & Vetrov, 2013).

The behavior of OC in transit from land and the marine environment varies within the ocean. C from terrestrial sources is often more refractory, which can cause a portion of it to persist in the ocean as part of the long-lived DOC pool (Lee et al., 2020). Most terrestrial DOC, however, is transformed or removed in estuaries and coastal zones through microbial degradation and photodegradation, converting it into dissolved inorganic carbon (DIC) and CO_2. This process drives local CO_2 release and acidification in nearshore waters, leading to a minor fraction being exported to open ocean (Y. Gao et al., 2024; Ward et al., 2017; J. Yao et al., 2024). Thus, monitoring riverine DOC is essential to assess its role in regional C cycling and land-to-ocean C transport.

Terrestrial DOC mobilization is influenced by catchment scale factors including, land use types, geomorphological conditions, hydroclimatic conditions, and microbial activity (Clair et al., 2002; Gaspar et al., 2020; Gentine et al., 2019; Huntington et al., 2016; Pagano et al., 2014; Wilson & Xenopoulos, 2009). The fate of inland DOC begins from leaf scale biochemical processes linked to photosynthesis and C release during respiration (Field et al., 1998). The remaining biomass including leaves litter and plants eventually die, contributing to C deposition on topsoil with the help of microbes during the decomposition process (H. Wen et al., 2020). Upon export to the rivers, this DOC source is classified as an allochthonous source, along with sewage, animal waste, and urban runoff (Figure 1). On the other hand, autochthonous DOC is produced within aquatic ecosystem, largely by microphytes and phytoplankton through photosynthetic activity, as well as by microbial metabolism of organic matter (Kritzberg et al., 2004). Nutrients carried by runoff can enhance autochthonous DOC production via in situ gross primary production (Stanley et al., 2012).

River discharge is the major transport mechanism for nutrient delivery from land to the oceans (Meybeck, 1982). Low latitudinal zones (0–30°N and 0–30°S) are found to be the area with the most abundant land-to-ocean DOC export (Dai et al., 2012; M. Li et al., 2017). In earlier research, Asian rivers accounted for 40%–50% of TOC exports to global ocean, with POC and DOC contributing ∼34% and ∼44% of the global riverine fluxes, respectively (Park et al., 2018). Asian regions deliver the second largest load, with 18.8% and 21.7% of the global inland DOC and POC export to the ocean, excluding Indonesia—a significant carbon source from Asian regions (Seitzinger et al., 2005). While there is a growing amount of in situ OC data for freshwater, it is often concentrated in specific geographical regions. Globally, most long-term DOC monitoring projects are based in high-latitude countries, supported by global and national agencies, such as ArcticGRO, USGS-NWIS, and boreal areas such as Northern Sweden (S. Liu et al., 2022; Oni et al., 2013; Stackpoole et al., 2017; Wei et al., 2021). In contrast, many areas in Asia are underrepresented due to gaps in the availability and consistency of aquatic OC data. More specifically, monsoonal river systems that carry large TOC loads during the wet season are vulnerable to climate change. These regions are also impacted by anthropogenic perturbation, which potentially elevate pollution levels and alter catchment hydrological properties (Park et al., 2018). Combined, these factors pose a great challenge for researchers investigating the aquatic C cycling in Asian rivers.

Field samples of DOC data are more densely concentrated in Chinese watersheds while remaining unevenly distributed across other regions of Asia (Figure 2). The duration of sampling in these studies varies, reflecting differences in data availability, ranging from monthly to seasonal observations, with most studies consistently spanning up to three consecutive years (Q. Ma et al., 2022; Shah et al., 2018; G. Shi et al., 2016). This limited duration in some regions highlights challenges in accurately representing the DOC trends and changes.

The Tibetan-Himalayan plateau, also known as the World's Water Tower, is the largest source of freshwater outside the poles that supplies a large portion of the world's population. This region has been severely impacted by climate change and is showing a declining trend in its total water storage (Miller et al., 2012). The increasing temperature escalates ice melt and freshwater discharge into the ocean (Feng et al., 2021; Rawlins et al., 2019) and will eventually increase sediment flux during high flow months (Andermann et al., 2012). Moreover, ground ice

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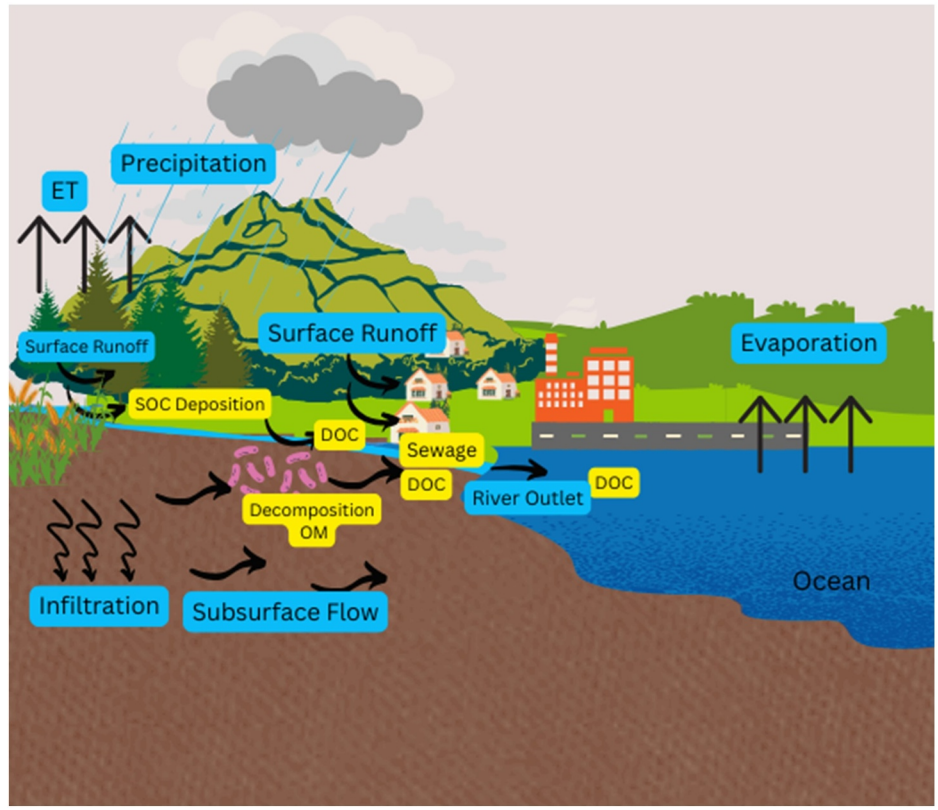


Figure 1. Hydrological DOC transport framework: key pathways of DOC movement from land to ocean (adapted from Ward et al. (2017); Wen et al. (2020)). Blue Box: hydrological parameter; Yellow Box: organic carbon (OC) source. Rainfall runoff carries the stored OC and nutrients from land to water bodies (McCabe et al., 2021). The OC content of the runoff may increase as water passes through forests and vegetation (Germer et al., 2007). Dilution generally occurs following the flushing process during high flow events, which leaves less DOC content in the water (H. Wen et al., 2020). The infiltrated water helps transfer the C from the topsoil into groundwater, leaving more POC in the soil voids and more DOC in the groundwater, eventually flowing into the ocean.

in Tibetan Plateau contains aged DOC at ~9 times higher concentration than those in the streams that flow out of the region (Y. Yang et al., 2022). The glacial melt and permafrost thaw from the Tibetan Plateau can lead to subsequent rise in sediment flux and increase the transport of DOC (T. Gao et al., 2019; Shah et al., 2018; X. You et al., 2022). This continuous impact of the changing climate is thus likely to increase the release of DOC from the ice sheets of this vast region and deliver a considerable amount of C to the ocean.

Recent studies have shown that the actual amount of terrestrial C reaching the ocean is significantly higher than previously estimated, emphasizing the need for a better understanding of this process (Kwon et al., 2021). The ocean plays a crucial role as a global carbon sink, but excessive C inputs from land can lead to negative environmental impacts such as increased acidification (Lønborg et al., 2020). The uneven distribution of in situ C data in freshwater systems, particularly in Asian river basin regions, poses a challenge that needs to be addressed in order to gain a comprehensive understanding of the coupled carbon-water cycle. Furthermore, the diverse impacts of climate change experienced across the Asian continent may exert influence on the C transports from land to ocean in these specific regions.

In this study, we assemble a large data set spanning most of Asia's climatic regions, to improve our understanding of riverine DOC patterns in under-represented regions that were previously excluded from comprehensive reviews of Asian rivers as a whole. We integrate harmonized groupings and consistent statistics to test DOC relationships to hydroclimatic characteristics including precipitation, temperature, and soil moisture for. We selected **40** peer-reviewed papers related to DOC research in Asia to investigate: (a) the current distribution and

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concentration of riverine DOC across Asia's varied watersheds; (b) the sources of riverine DOC in these watersheds; and (c) the impact of hydroclimatic changes on identified riverine DOC values.

2. Materials and Methods

2.1. DOC Data Sources

We performed a literature search involving DOC research in Asia using ScienceDirect, Scopus, and Google Scholar. Search keywords included "riverine dissolved organic carbon", "land-to-ocean DOC transport", combination of "dissolved organic carbon", and related phrases such as *Ganges, Brahmaputra, Indus, Yangtze (Changjiang), Yellow (Huang He), Pearl (Zhu Jiang), Hei He, Mekong (Lancang), Borneo, Kalimantan, Himalaya, Tibetan Plateau,* and *Asia*. We applied the following criteria for the peer-reviewed papers selection: (a) DOC samples were collected from riverine systems and ice sheets in Asia and excluded soil solution samples; (b) the collected DOC data should have more than one data point in either temporal and/or spatial distribution; and (c) the research was conducted in the major Asian watersheds. A total of 40 articles were selected for the study (see Dataset S1).

2.2. DOC Data Pre-Processing

A comprehensive DOC data set was compiled by extracting information from published studies, including author, title, year of publication, sampling station, latitude, longitude, total number of samples, DOC concentration, sampling interval, sampling date, potential DOC sources, and sample type. Based on the reported sampling dates, each record was classified by season. For data quality control, a station-by-station evaluation was conducted to identify and eliminate duplicate records, along with unit conversions standardized to mg C/L. We then examined the concentration distribution and frequencies (histogram) to flag outliers with exceptionally high values (Figure S1 in Supporting Information S1). Samples with DOC concentrations >10 mg/L, a case-by-case assessment was performed to verify the sources and context. Stations located in peatland, tropical forest, or regions with high humic content were retained (Gandois et al., 2020; Sun et al., 2017; Zhao & Song, 2018) while those situated near wastewater discharge points were excluded to avoid bias. When the total number of samples was not clearly stated in the source paper, the samples were assumed to represent duplicate measurements.

2.3. DOC Data Distribution

After pre-processing, a total of 1,593 data points were selected. As the majority of DOC concentrations fall below 3.8 mg C/L, the distribution was right-skewed with a long tail toward high values (Figure S1 in Supporting Information S1). The upper 10% of data set exceed 9.4 mg C/L while the top 5% go beyond 23 mg C/L. Spatially (Table S1 in Supporting Information S1), ∼16% of studies were conducted within 0–20° latitude (tropical regions), ∼74% within 20–40° (subtropical to temperate zones), and ∼9.5% within 40–60° (temperate to cold regions). Longitudinally, most samples (≈60%) were from 100 to 120°E in East and Southeast Asia, with fewer from 80 to 100°E (16%), 60–80°E (10%), and 120–140°E (14%), indicating a concentration of research in eastern Asia. The longest continuous sampling period spanned 48 months at monthly to weekly intervals in the upper Heihe River on the Tibetan Plateau (Y. Zhang et al., 2019), whereas the typical DOC record in Asia covered about 6 months, often representing seasonal variations. To evaluate the spatial variability of dissolved organic carbon (DOC) under different climatic conditions, the Köppen–Geiger climate classification was utilized to categorize each sampling location according to its dominant climate type (Beck et al., 2018).

2.4. Study Area for Hydroclimatic Drivers Analysis

We selected six watersheds in Asia for hydrological analysis: Yangtze, Yellow, Mekong, Brahmaputra, Ganges, and Rajang (Figure 2). These watersheds were selected due to their large area coverage and availability of long-term data, representing different geographical settings: tropical monsoonal basins (Mekong, Ganges-Brahmaputra), temperate basins (Yangtze, Yellow), and tropical rainforests (Rajang). In addition to the large Himalayan basins, which encompass significant land areas and populations, we included a smaller watershed (Rajang) in Borneo Island to provide a comparative view of the DOC concentration in a tropical forested area undergoing rapid urbanization. A total of 9 stations were selected for our meta-analysis (Figure 2, Table S2 in Supporting Information S1).

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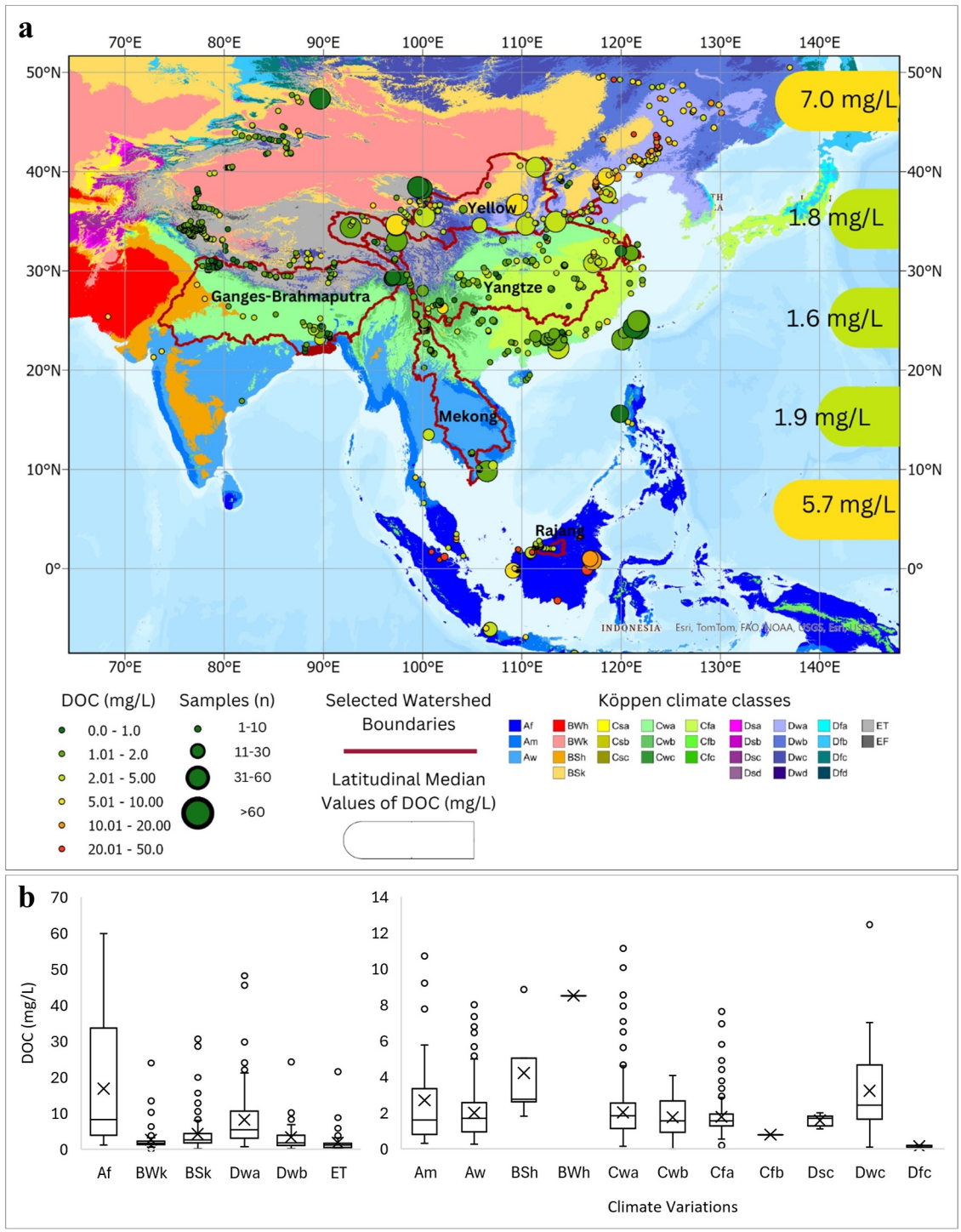


Figure 2. Selected watersheds, dissolved organic carbon (DOC) sample distribution, and concentration in Asia. (a) DOC concentration variations from 0 to 50 mg/L (color coded circle). The number of the samples range from 1 to >60 (Circle size); the five selected watersheds boundaries (area marked with red line). Color variations across the land area represent Köppen-Geiger climate classification; Color coded bars on the left side represent the median values of DOC concentrations within latitude 0°–10°, 10°–20°, 20°–30°, 30°–40°, and 40°–60°. (b) Box and whisker plot chart of DOC distribution across the Köppen-Geiger climate classification. *x* marks represent average values, horizontal line within the box represent median, and small circles represent the data outliers. The high concentrations of DOC are mostly found in tropical rainforest climate (Af) which is related to high primary production activities in tropical rainforest (Müller-Dum et al., 2019; Rosset et al., 2022; Sanwlani et al., 2022; Warren et al., 2017); and arid, steppe, and cold (BSk), which is mostly found in the mountainous areas in Yellow headwaters; Dwa and Dwb (humid continental with dry winter) climates are associated with high humic content (Q. Ma et al., 2022).

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For our temporal analysis, we selected four sampling locations from the Yangtze and Yellow watersheds, ensuring that they had at least a year of consecutive monthly data. To support our temporal analysis, we chose one station each from the Brahmaputra and Ganges watersheds, which provided a year-long time series DOC data set. In order to capture sufficient spatial variation, we collected data from multiple stations in the Rajang and Mekong watershed, all of which were collected within a short-term period.

2.5. Hydroclimatic Data Acquisition

For the purpose of hydroclimatic analysis of DOC, we selected six representative catchments across different climatic regions in Asia where sufficient data were available: the Yellow, Yangtze, Ganges-Brahmaputra (GBM), Mekong, and Rajang River Basins. We obtained daily precipitation data from NASA's Global Precipitation Measurement (GPM) mission through the Integrated Multi-satellitE Retrievals for GPM (IMERG) data sets for all sampling locations that capture more variability up to the low-range precipitation data sets (G. Tang et al., 2016). To match the daily DOC data points, we calculated the average daily precipitation for each month. However, for the Datong station in China during the period of 1998–1999, we had to use data from the tropical rainfall measuring mission (TRMM) as GPM-IMERG data were not available at that time. We used on NASA's Gravity Recovery and Climate Experiment (GRACE) mission products to obtain soil moisture data for all selected regions.

We relied on multiple sources due to inconsistent availability of satellite temperature data (Table S2 in Supporting Information S1). For Nogorbari, Rajbari, Xiuliujing, Lijin, and Huayuanku stations, we collected temperature data from the Atmospheric Infrared Sounder (AIRS) on NASA's Aqua satellite. For Datong and Longchuanjiang, where AIRS data was not available, we utilized the Modern-Era Retrospective analysis for Research and Applications-2 (MERRA-2) temperature model. Additionally, for Rajang and Mekong, we used the high-resolution Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS) temperature model due to the smaller regions of these locations.

2.6. Statistical Analysis

We performed correlation analysis between each group of hydroclimatic components: precipitation (P), temperature (T), and soil moisture (SM); coupled with DOC data collected from literature using the Spearman's correlation method. One way ANOVA was applied to test whether DOC concentrations showed significant differences across hydroclimatic groups for C-P, C-T, and C-SM for each selected river basin. Temperature and precipitation were grouped per basin into terciles using the 33rd and 66th percentile cut points (low, medium, high). Meanwhile, soil moisture was grouped into quartiles (0%–25%, 25%–50%, 50%–75%, 75%–100%).3 Current DOC Trends in Asia.

3. Current DOC Trends in Asia

3.1. Latitudinal and Longitudinal Distribution of DOC

Our collected data indicates that in mid-low latitude regions (10°–20°), the median concentration of riverine DOC is at 1.8 mg C/L. Moving to slightly higher latitudes (20°–30°), the median concentration slightly decreases to 1.6 mg C/L. In the latitude range of 30°–40°, the median riverine DOC concentration is 1.9 mg C/L. However, it is in the latitude range of 40°–60° where an increase in DOC concentration is observed, with a median of 5.7 mg C/L (Figure 2).

Most high DOC concentrations were found near the equatorial region and in areas above 40° latitude, with mean values of 15.2 and 8.2 mg C/L, respectively. For comparison, the mean riverine DOC concentration in the US and the Arctic region are 6.42 and 9.11 mg C/L, respectively (Kaiser et al., 2017; Q. Yang et al., 2017). The equatorial region in our data set, characterized by a tropical climate, also exceeds the global tropical riverine DOC average of 10.4 mg C/L (F. Liu & Wang, 2022). The elevated DOC levels in our equatorial samples can be largely attributed to peat-rich soils in Kalimantan (Borneo) Island (Gandois et al., 2020; Müller-Dum et al., 2019).

Longitudinally, across the bands 60–80°, 80–100°, 100–120°, and 120–140°, the median DOC concentrations were 1.2, 1.7, 2.4, and 2.4 mg C/L, respectively. The mean concentrations also showed an increasing trend with longitude, at 1.3, 2.4, 5.7, and 5.5 mg C/L for each corresponding band. Chaplot and Mutema (2021) previously reported a positive correlation between DOC concentration and both latitude and longitude ($r = 0.27$, $p < 0.05$). In

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contrast, our results show a negative correlation with latitude ($r = -0.32$, $p < 0.05$) and a positive correlation with longitude ($r = 0.34$, $p < 0.05$) (Figure S2 in Supporting Information S1). This apparent difference is largely influenced by the high DOC concentrations within the 0–10° latitude band, which skew the correlation results. When this group is excluded, the correlation with latitude becomes positive ($r = 0.40$) (Chaplot & Mutema, 2021).

3.2. Distribution of DOC Based on Asia's Climate Classification

Asia is a large continent and comprises different climatic zones (Hijioka et al., 2014). Central Asia experiences arid to semi-arid conditions due to high mountain systems (Haag et al., 2019). East Asia encompasses varied climatic regions, including humid, arid to semi-arid, and high land from the Himalayan terrains. The northern part of Asia is dominated by tundra regions that experience extremely cold winters and hot summers (Jacobyl et al., 1999). The climate of South Asia is varied from cold temperatures due to the complex terrain of the Himalayan Mountain range, temperate climatic regions in the north, and tropical climate in the central south (Ullah et al., 2020). Located around the equatorial area, South–East Asia experiences a tropical climate, which is very humid and hot most of the year. The climate of West Asia can be defined as warm to hot temperatures with high evaporation rates, and low unpredictable rainfall (Ortas & Lal, 2013).

We overlayed the DOC data points into the Köppen-Geiger climate classification map (Figure 2) to analyze the concentration variation across different climate zones (Beck et al., 2018). Our results indicate that throughout Asia, the tropical rainforest climate zone (Af) has the highest riverine DOC concentrations in Asia with a mean of 16.8 mg C/L (Figure 2). This could be associated with elevated gross primary production (GPP) and biomass in the rainforest and the higher soil bacterial activity in warmer temperatures (Malhi, 2012). This is higher than the mean DOC concentration in the Congo River Basin (12.7 mg C/L)and the Amazon river basin (4.47 mg C/L), which are considered the same climate zones (Drake et al., 2021; N'Kaya et al., 2020). The longer residence times in bigger basins can play a big role in C degradation before it reaches the water bodies (Du et al., 2021). The presence of peatlands on the Borneo Island in Indonesia is a major contributor to the high DOC concentration in this region which has the mean of 18 mg C/L (Müller-Dum et al., 2019; Rosset et al., 2022; Sanwlani et al., 2022; Warren et al., 2017). The colder regions such as the Tibetan Plateau, which is considered a polar-tundra climate show DOC in the range of 0.1–21.5 mg C/L. However, the mean concentration in the Tibetan Plateau (1.82 mg C/L) is lower than DOC concentration from upstream regions of the Arctic with tundra forest that has an average concentration of 3.6 mg C/L (Shogren et al., 2021).

High DOC levels were also found in the arid, steppe, and cold (BSk) regions in northern China, commonly associated with mountainous and semi-arid areas in the Yellow River Basin, where soil leaching and limited dilution can lead to DOC enrichment. Humid continental climates (Dwa, Dwb) regions showed high DOC concentration due to inputs from humic-rich soils (Q. Ma et al., 2022). Meanwhile, the lowest concentration was observed at the headwaters of the Ganges river, originating from glacier meltwaters (Begum et al., 2021).

3.3. Tributary-Mainstem Distribution of DOC in Selected Watersheds

We compiled our collected data sets for the selected watersheds (Table S2 in Supporting Information S1) and analyzed the distribution of DOC concentration in these regions (Figure 3). The results reveal distinct patterns in DOC concentrations across all basins. As discharge is typically larger in the mainstem, DOC concentrations are expected to decrease due to dilution. The Yangtze and Mekong showed lower median concentrations in the mainstem compared with tributaries, where sewage input and lower discharge may lead to elevated concentrations at the branches. Furthermore, cropping and other agricultural activities may increase both allochthonous and autochthonous DOC levels in the tributaries. While the Yellow River had relatively similar distribution between mainstem and tributaries, the spiking DOC concentrations at the GBM mainstem are likely related to wastewater disposal and sewage input from big cities along the river (Begum et al., 2021).

The Rajang watershed shows a relatively high median DOC concentration in the mainstem at 3.4 mg C/L due to peat-sourced OC. On the other hand, the Yellow River Basin poses the highest median concentration among all tributaries at 2.7 mg C/L. The dry conditions in the Yellow River Basin might contribute to more concentrated DOC values due to lower water discharge. These differences imply that DOC sources and controls may vary significantly between watersheds, potentially driven by climatic, hydrological, and land-use factors unique to each region. Further investigation into these drivers could elucidate the mechanisms underlying DOC variability across diverse hydrological contexts.

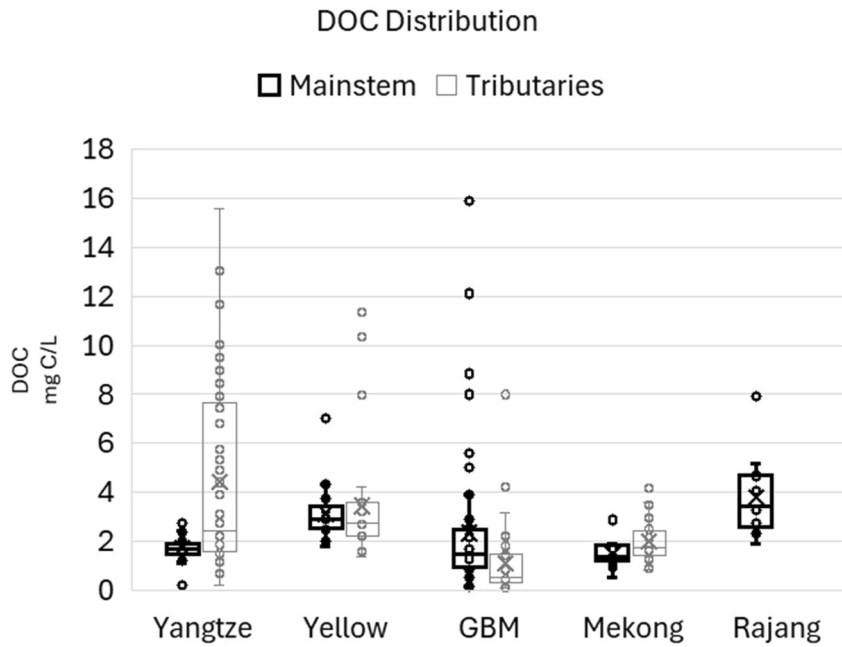


Figure 3. DOC Concentration Across Selected Watershed (Data period: 2003–2018).

3.4. The Sources of DOC in Selected Watersheds

The sources of organic carbon (OC) in water bodies can be characterized as allochthonous landscape-derived C and autochthonous biologically produced aquatic C (Goñi et al., 2003). Allochthonous C may be transported through an erosion process of soil organic carbon (SOC) by runoff, and through soil lateral flow during low flow season (William H Schlesinger, 1977). Extreme weather events such as typhoons may also elevate allochthonous DOC input to the riverine system (T.-Y. Lee et al., 2017).

The atmospheric deposition from biomass burning and other anthropogenic activities has been found to be one of the main contributors to the DOC in the Tibetan glaciers and the Chinese Altai Mountains (Y. Zhang et al., 2018, 2019). The headwaters of the Ganges and Brahmaputra rivers (also in Tibetan glaciers) contain higher amounts of bioavailable-rich DOC (Hemingway et al., 2019). Whereas, the highly populated and more urbanized watersheds in the downstream regions of these rivers exhibit high amount of anthropogenic DOC components.

The East China Sea and the Bohai Sea receive outflows that are dominated by sewage-originated DOC due to industrial and agricultural activities (J. Kim et al., 2020; Z. Wen et al., 2020; X. Zhang et al., 2021). The expansion of cropland and population growth in Chinese river basins caused a surge in DOC flux during 1953–2016 (D. Liu et al., 2020). Agricultural activity can result in allochthonous input to the stream by increasing soil erosion (Chen et al., 2021), and also boost autochthonous and microbial-like DOC by discharging extra nutrients to water bodies and promoting aquatic primary producer growth (Graeber et al., 2015).

In tropical Asian rainforests such as those in Borneo, the significantly higher DOC concentration is linked to the greater forest biomass and extensive peatlands (Huang et al., 2017; Rosset et al., 2022; Warren et al., 2017). Phenol oxidase, the enzyme that controls C storage in peat, shows greater productivity in warmer temperatures resulting in higher DOC release in tropical peatlands compared with those in boreal regions (Freeman et al., 2001; Rosset et al., 2022). Further, the smaller mountainous watersheds in Borneo and other tropical islands in the region have relatively shorter riverine travel paths, which limit the amount of time for DOC decomposition before it reaches the ocean. Taken together, multiple factors lead to elevated DOC content in rivers of tropical Asian rainforests.

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4. Hydroclimatic Influence on DOC Concentration

4.1. Hydroclimatic Condition in Asia

The seasons in Asia are mainly driven by the Indian Summer Monsoon (ISM), which carries moisture from the Indian Ocean, and the East Asian Summer Monsoon (EASM) from the Indian and Pacific Oceans and Western North Pacific Summer Monsoon (WNPSM) (T. Li & Wang, 2005; B. Wang, 2002). The EASM covers the eastern region of the continent while ISM and WNPSM expand from Indochina to the southeastern part of the Tibetan Plateau (B. Wang, 2002). Generally, the Indian monsoon peaks in June–July while the monsoon rain peaks in August in the east (B. Wang et al., 2003). The Tibetan Plateau also plays an important role in regulating the monsoon and hydrological cycle over the mainland Asia continent (Goswami et al., 2022; Son et al., 2020).

Precipitation varies widely across Asia. The highest rainfall occurs in the Southeast Asia region with mean precipitation of 400–630 mm/month during the rainy season. Typically, teleconnections such as La Nina causes higher precipitation in the Southeast Asia tropical climate (Singh & Qin, 2020; Z. Zhang et al., 2004). At the same time, atmospheric moisture originating from the Indian Ocean can cause a heavy rainy season over South Asia with the average precipitation rate at 92.3–327 mm/month during the monsoon season (Patel et al., 2021). Both in South and Southeast Asia, extreme rainfall >1,500 mm/month is common during heavy rainy days (C. Yao et al., 2008). Unlike ISM-influenced regions, the Tibetan Plateau area has a polar tundra climate and receives rainfall at an average of 68.2 mm/month in high precipitation seasons that peak in autumn (Y. Tang et al., 2022). Conversely, the EASM causes a moderate precipitation rate across East Asia regions with the average rainfall at ∼179 mm/month between May and July (Son & Seo, 2022).

4.2. DOC Response to Hydroclimatic Variations in Asia

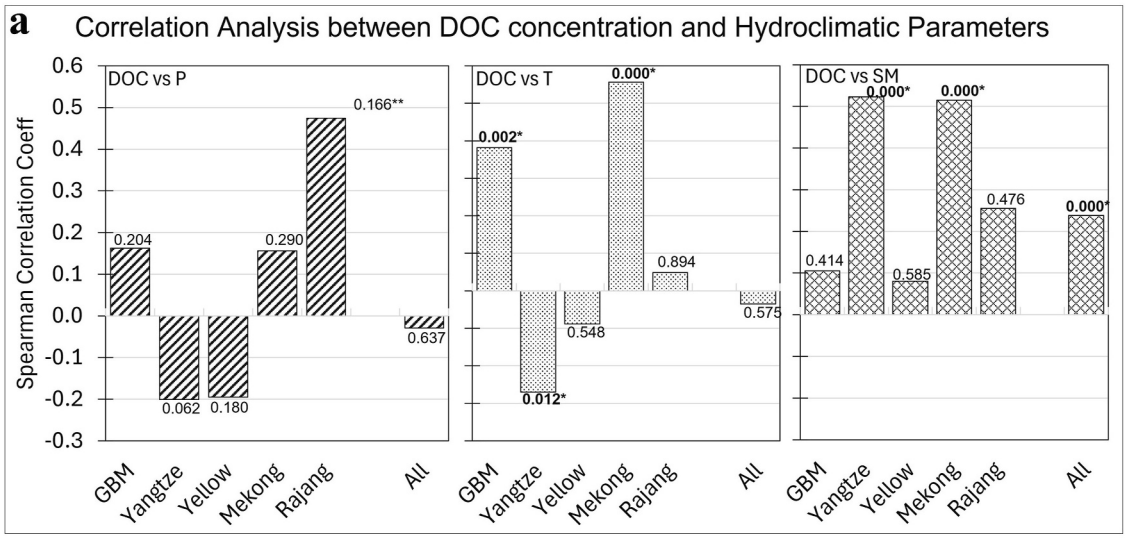
We investigated the spatial and temporal distribution of DOC across six selected watersheds to analyze the pattern of DOC transport in different hydroclimatic conditions (Figures S1 and S2 in Supporting Information S1). Further, to investigate the impact of hydroclimatic factors on DOC concentration in Asia, we plotted the data from selected watersheds between DOC and these variables and conducted one-way ANOVA analysis (Figure 4).

4.2.1. Precipitation

The influence of precipitation on DOC concentration can vary, leading to either positive or negative feedbacks, depending on the specific mechanisms at play (van Verseveld et al., 2008). Precipitation can act as a dilution mechanism, reducing DOC concentrations through increased water volumes (Germer et al., 2007). However, precipitation can also act as a flushing mechanism, mobilizing and transporting nutrients from the surrounding environment into water bodies (Drake et al., 2021; Hemingway et al., 2019). Based on the compiled data from the selected watersheds, there is a weak negative and non-significant correlation between precipitation and DOC concentration when considering all regions together ($\rho = -0.03$, p-value = 0.64) (Figure 4a, Table S3 in Supporting Information S1). This finding suggests that, in the context of the combined data set encompassing various regions in Asia, higher precipitation rates tend to be associated with lower levels of DOC. However, the low p-value highlights that the relationship may not be linear.

Within each river basin, the relationship between precipitation and DOC concentration was also not statistically significant, but appeared variable in strength and direction. Three out of five selected basins showed positive correlation (GBM, Mekong, and Rajang) and the other two showed negative values (Yangtze and Yellow). While these correlations were not significant and we cannot draw strong conclusions, this variability in correlation signs underscores the importance of watershed characteristics and local conditions between precipitation and DOC dynamics (Gao et al., 2021; Seitzinger et al., 2005; Wei et al., 2021).

The Yellow and Yangtze River basins exhibited an initial spike generally found during early monsoon season (Figure S3 in Supporting Information S1), followed by a gradual decrease as the season progresses (G. Shi et al., 2016). The increasing temperature and rainfall in both river basins lead to DOC dilution early in the wet season, resulting in a negative relationship between precipitation and DOC (G. Shi et al., 2016). In tropical monsoon regions such as the lower GBM and Mekong, DOC concentrations increased during the monsoon season while the dry season is associated with lower DOC content (T. Liu et al., 2021; Niloy et al., 2021).



b ANOVA Analysis

Basin	F-Statistic		
	P	T	SM
GBM	0.80	0.05	1.80
Yangtze	1.12	**7.23***	**10.84***
Yellow	2.69	0.03	0.79
Mekong	1.56	**6.33***	**3.57***
Rajang**			
All basins	**4.34***	1.07	2.04

*(Bold) Significant P-value < 0.05
** Limited Dataset

Figure 4. Statistical Analyses between DOC Concentration and Hydro-Climatic Parameters: (a) Spearman correlation analyses (DOC vs. precipitation (P); DOC versus temperature (T); DOC versus soil moisture (SM); numbers on the bars represent *p*-values); (b) ANOVA Analysis Results.

In the case of the Rajang River, which features numerous peatlands, an increase in precipitation tends to elevate the DOC derived from the forest floor (N'Kaya et al., 2020; Schefuß et al., 2016; Zeri et al., 2014). However, precipitation is uniform throughout the year and did not appear to be influencing DOC concentrations in these watersheds. Despite the weak overall correlation between DOC and precipitation across all river basins combined, the ANOVA results revealed a significant difference in DOC concentrations among precipitation categories ($F = 4.34$, $p < 0.05$) compared with soil moisture and temperature (Figure 4). The highest mean DOC occurred under low-precipitation conditions while the lowest mean was observed in the medium-precipitation group (Table S4 in Supporting Information S1). These results indicate that DOC and precipitation likely exhibit a nonlinear relationship, with a possible precipitation threshold where DOC dynamics change the direction.

We grouped the data in each basin by season (Monsoon: JJAS, Post-Monsoon: ONDJ, and Pre-Monsoon: FMAM) to examine how hydroclimatic variables influence DOC under different seasonal conditions. The results indicated that the onset of the monsoon season triggers an increase in DOC concentration across all basins except for the GBM river basin (Table S5 in Supporting Information S1). This suggests that elevated rainfall during the monsoon likely enhances the flushing potential through runoff (B. Kim et al., 2000). In contrast, the post- and pre-monsoon seasons tend to show negative correlations with DOC concentration, with the pre-monsoon period showing the strongest values. These results indicate that DOC in these seasons may primarily originates from autochthonous sources (Haque et al., 2022; Hood et al., 2006). An increase in water volume during these times has

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a dilution effect, reducing the concentration. This aligns with ANOVA results, which revealed the highest concentration under medium-to-low precipitation conditions when all basins are combined (Figure 4b).

4.2.2. Temperature

Temperature plays a significant role in the dynamics of DOC in water systems. Generally, higher temperatures can increase DOC concentrations due to elevated autochthonous GPP and bacterial activity (Jacobyl et al., 1999; Malhi, 2012; H. Wen et al., 2020). Within region analyses showed mixed support for this general relationship. The DOC versus T correlation analysis in GBM, Mekong and Rajang showed positive correlations (Figure 4a, Table S3 in Supporting Information S1). However, in temperate regions such as Yangtze and Yellow, the rise in temperature can also lead to a decrease in DOC content through snow and ice melt, resulting in chemical dilution (Du et al., 2021). Higher temperatures could lead to drier soil conditions, which lower the production of OC (Bertolet et al., 2018). In general, there is a positive correlation between temperature and DOC concentration across the study area. Statistically, our analysis revealed a significant relationship (p-value < 0.05) in the GBM, Yangtze, and Mekong, while the rest remains insignificant. For all river basins combined, temperature showed a weak negative and non-significant correlation with DOC, similar to precipitation.

Under seasonal conditions, temperature generally shows positive correlation during monsoon and post-monsoon seasons. However, in the Mekong region, temperature showed a significant positive correlation during pre-monsoon season (Table S5 in Supporting Information S1). Based on the ANOVA results, DOC concentrations did not differ significantly across temperature groups when all basins were combined ($F = 1.07$, $p = 0.343$). Significant differences were found only in the Mekong and Yangtze river basins ($F = 6.33$, $p < 0.05$ and $F = 7.23$, $p < 0.05$, respectively). In the Mekong River Basin, DOC concentrations increased progressively with temperature, suggesting a positive association between warming and OC mobilization. In contrast, in the Yangtze basin, DOC concentrations increased from the low- to medium-temperature groups, but declined in the highest-temperature group (Table S4 in Supporting Information S1).

The impact of higher temperatures on DOC in water ecosystems can lead to both increased DOC flux and decreased DOC content. These findings emphasize the complex interplay between temperature and DOC in water systems. Examining the relationship between temperature and DOC stand alone may be insufficient to fully understand the dynamics. Other factors, such as the catchment's morphology and hydrological response, also play significant roles in this complex relationship.

The source of DOC plays a significant role in determining the relationship between temperature and DOC dynamics. Depending on whether the dominant source is allochthonous or autochthonous, the response to temperature changes can vary. Allochthonous sources may experience increased mobilization and transport with rising temperatures, leading to an overall increase in DOC flux (Pagano et al., 2014). In contrast, autochthonous sources may respond directly to temperature increases by enhancing biological processes that generate DOC, resulting in higher concentrations in the water (Lu et al., 2012; Niloy et al., 2021). Understanding the specific source of DOC is thus crucial for comprehending how temperature influences its dynamics in aquatic systems. Further analysis and long-term data sets are necessary to fully understand this relationship.

4.2.3. Soil Moisture

The presence of high soil moisture content has been recognized as a factor that can enhance the production of DOC (Christ & David, 1996). Recent research suggests that soil moisture plays a significant role in shaping the molecular characteristics of the DOC pool, which can have implications for its bioavailability, transport, and ecological effects in aquatic environments (Bertolet et al., 2018).

Based on our comprehensive analysis of compiled data, a statistically significant influence was observed between soil moisture and DOC concentration in all basins, as indicated by a positive correlation ($\rho = 0.24$, p-value = 0.00). Notably, a distinct positive relationship between soil moisture and DOC concentration emerged in the Yangtze and Mekong regions (both have $\rho = 0.5$, p-value = 0.00) (Figure 4a, Table S3 in Supporting Information S1). The ANOVA results showed that soil moisture had a significant effect on DOC concentrations in the Mekong and Yangtze River Basins ($F = 3.57$, $p < 0.05$, and $F = 10.84$, $p < 0.05$, respectively; Figure 4b). DOC concentrations increased progressively with higher soil moisture groups, consistent with our seasonal

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analysis, which showed a positive correlation between DOC and soil moisture across all seasons in these basins (Table S5 in Supporting Information S1).

Soil moisture is known to play a critical role in DOC production, but its role should be understood in concert with other climatic variables such as temperature, precipitation, and evapotranspiration, as well as geomorphological factors such as topography and land cover. Additionally, lateral flow could become a factor between DOC and soil moisture (Bernard-Jannin et al., 2018). While DOC is generated in moist soils, its transfer to water bodies often requires a push from lateral flow processes. This suggests that there may be additional factors or mechanisms influencing the transport and movement of DOC beyond the direct influence of soil moisture (Gaspar et al., 2020; van Verseveld et al., 2008; H. Wen et al., 2020).

5. Impact of Climate Change

The hydrological cycle is evolving in response to changing climate conditions, leading to uncertainties of extreme weather events, which are key aspects that underscore the influence of hydroclimatic change on DOC dynamics (Easterling et al., 2012; Gentine et al., 2019). Higher rainfall may elevate C transport through increased runoff (Schefuß et al., 2016), the interaction between water and atmosphere during rain may also increase the gas transfer and chemical dilution (Turk et al., 2010), and extreme storm events may promote rapid C delivery from land to the ocean (Goldsmith et al., 2008). Long term climate and hydrological changes have already shifted the DOC Concentration—Discharge (C-Q) relationship into steeper trend (Huntington et al., 2016). Extreme warming could lead to increased tree mortality and shifted forest composition which impacts on the abundance and chemical characteristics of DOC in watershed runoff (Huntington et al., 2016; Pagano et al., 2014; Tiwari et al., 2018). Furthermore, the ongoing global temperature increase is actively accelerating the melting of glaciers, which in turn can result in the release of previously trapped C into the atmosphere and water streams.

In Asia, climate change has caused local and regional alterations in seasons across the region, which is expected to see wetter and more intense monsoons (Gawali et al., 2019; Seth et al., 2019). For instance, as temperatures increase over the Tibetan plateau, there is an increase in precipitation over the South China Sea region since 1998 due to the influence of monsoon wind (Liang et al., 2020). However, there is high spatiotemporal variability of climate change impacts on Asian river basins due to the continent's large area (Shrestha et al., 2021). Approximately 50% of major Asian rivers exhibit increasing discharge rates while the other 50% experience decreasing discharge rates (X. Shi et al., 2019).

During a span of 60 years (1953–2016), the input of DOC from mainland China has exhibited an increase, primarily attributed to global warming and anthropogenic factors. However, localized factors such as vegetation dynamics and water discharge alterations can lead to specific regional changes such as downward DOC pattern in the Yellow River Basin (D. Liu et al., 2020). The annual runoff is projected to decrease by 9.5% by 2046 in Yangtze while it is 16.9% in the Yellow River Basin due to climate change (Liu & Xu, 2017). Thus, if the concentration of DOC in the basins remains the same, the flux of DOC from these basins is expected to decrease. However, as these regions experience an intensification of heavy precipitation on rainy days and extreme weather conditions (You et al., 2022) there is a likelihood of increased DOC concentration during such events (Goldsmith et al., 2008).

In South Asia, overall precipitation shows a decreasing trend across both the Ganges and Brahmaputra River Basins (Nguyen et al., 2018) while heavy precipitation events are increasing during the monsoon season (Hasan et al., 2018; Imran et al., 2023). Projections indicate that river discharge is expected to decrease in the Brahmaputra and Ganges River Basins during the pre-monsoon period, but monthly river discharge will increase during the monsoon season (Curtis et al., 2018; Islam et al., 2018). This increasing discharge is accompanied by a notable rise in sediment transport by up to 40% which will likely become the main driver of excessive nutrient export to the ocean including DOC (Fischer et al., 2017).

In general, Southeast Asia is anticipated to see an increase in precipitation between 10% and 20%. Indonesia, in particular, is expected to experience an even higher increase of up to 30% during the monsoon season by the middle and late 21st century (Tangang et al., 2020). The DOC concentration will likely increase in the Mekong and Rajang due to the positive relationship between these parameters. However, the changes in LULC as well as the presence of riverine structures, such as dams, may result in future DOC projection due to change in sources and pathways and nutrient retention (T. Liu et al., 2021). The increased discharge in Rajang is expected to have an

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impact on the erosion of C from peatland areas, resulting in higher concentrations of DOC in the deposited sediments (Müller-Dum et al., 2019; Staub et al., 2000). Based on this evidence, the DOC load is expected to decrease in the cold-drier climate as in the Chinese rivers, but increase in the tropics.

6. Conclusions

Asia's vast river basins contribute significantly to the oceans' freshwater supply while also exporting a substantial amount of C to the oceans. Our synthesis shows that most riverine DOC concentrations in Asia are generally lower than in equatorial and high-latitude regions (>40°N), with tributaries showing greater variation and higher levels. This study revealed nonlinear precipitation signals, divergent temperature responses across basins, and a consistently positive role for soil moisture (especially in the Mekong and Yangtze). However, the DOC input to the oceans from Asian river basins are experiencing changes over time. Further, climate change projections indicate both increases and decreases in river discharge volumes depending on their locations. Thus, DOC transport is expected to decline in arid-temperate climates such as northern Chinese rivers while rise in tropical regions. With ongoing global climate change, it is crucial to investigate how such events will affect the hydrological drivers and the transport of DOC through changes in rainfall extremes, monsoons, typhoons, and wildfires.

In addition, adding geomorphological context (e.g., slope, soil type, land-cover type) to the investigations will sharpen interpretation, especially in regions undergoing rapid climate-driven shifts such as tropical rainforests and high-latitude river basins with high mean DOC values. We also recommend applying machine learning (ML) approaches to ingest and process the large volumes of data sets encompassing the vast Asian landmass.

Our synthesis relies on published concentrations data set rather than primary measurements, so inter-study analytical differences may remain. Spatial coverage is uneven (denser in some Chinese river basins; sparser elsewhere) and many records are short (<3 years), which can dampen trend detection. Binning by basin-specific terciles or quartiles improves comparability, but it can be sensitive to small sample sizes in some seasons. Finally, hydroclimatic drivers were aggregated using gridded products at finite resolution, which may mismatch local sampling conditions. We therefore interpret effect sizes conservatively and emphasize pattern direction and consistency across basins rather than their precise magnitudes, highlighting where added observations would most reduce uncertainty.

In data-sparse river basins, integrating remote sensing approach holds great potential. Several indicators related to photosynthesis and microbial metabolic processes, such as leaf area index (LAI), normalized difference vegetation index (NDVI), chlorophyll-a (Chl-a), land surface temperature (LST), gross primary production (GPP), and net primary production (NPP), can aid in increasing the predictability of riverine DOC. It is equally crucial to consider the hydrological aspects of the watershed, as they play a significant role in controlling the movement of DOC due to the intricate interplay between the water and the carbon cycles. While remote sensing techniques are predominantly applied in locations with large water surface areas such as lakes, coastal areas, and oceans, extending these methods for large Asian rivers offers a promising avenue for capturing DOC transport. Applying ocean color products at river outlets, then pairing them with basin-scale hydrologic metrics, enables first-order estimates of the timing and flux of DOC reaching estuaries. This approach should be coupled with targeted in situ calibration (at select anchor stations) to handle the turbidity and bottom effects and to maintain cross-sensor continuity.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data used in this study are publicly available. The compiled riverine DOC Dataset S1 is archived and is publicly available in Figshare (Septiani & Akanda, 2025). Observational DOC values were extracted from previously published studies; the complete list of the source studies is also provided in Dataset S1. Observational DOC values were extracted from previously published studies; the complete list of source studies is provided in the Figshare record associated with the data set. Precipitation data are from GPM IMERG Final Run V07 Daily and TRMM 3B42 Daily V7 (Huffman et al., 2016, 2024). Temperature data are from FLDAS2 Noah-MP,

MERRA-2 Single-Level Diagnostics v5.12.4, and AIRS/AMSU AIRX3STD v7.0 (AIRS project, 2019; GMAO, 2015; Slinski & Sarmiento, 2023). Soil-moisture data are from the GRACE/GRACE-FO data assimilation product (Rodell et al., 2022). A methodological description of the GRACE assimilation framework is provided by Li et al. (2019). Full data set citations are listed in the References.

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