Role of Rivers in the Carbon Cycle and the Impact of Anthropogenic Activities

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Abbreviations

C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Matter
GHG	Greenhouse Gas
HCO_3	Bicarbonate
NASA	National Aeronautics and Space Administration
OM	Organic Matter
POC	Particulate Organic Matter
SGD	Submarine Groundwater Discharge

1 Introduction

The water that runs across rivers supports the flora and animals together with the inhabitants of its banks. Rivers are described as "the gutters down which flow the ruins of continents" in Leopold et al. (1964). The statement refers to how rivers affect the geomorphology of continents, which digests the majority of images of the global carbon cycle. The global carbon cycle controls the amount of atmospheric CO_2, which in turn controls the temperature and habitability of our planet. By dispersing silt and organic matter across the landscape, rivers play a significant role in the carbon cycle. Around the world, rivers have undergone extensive man-made modification, which has an impact on important biogeochemical cycles. In the coastal regions of the world, rivers transport and transform enormous amounts of carbon. For instance, the breakdown of vascular plant-derived OM to CO_2 is boosted

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by up to six times in the Amazon River when algae-rich tributaries mix with the silt and terrestrially generated OM-rich main channel (Ward et al., 2017). Globally, a sizable amount of carbon is transported and changed in the coastal regions. This transformation and transfer of carbon, which is caused by mechanisms such as altering hydrology, water temperature, and in-stream metabolic rates, clearly demonstrates the effects of urbanization and climate change. Changes in sources and exports have an impact on ecosystem activity, food webs, and greenhouse gas emissions (Smith & Kaushal, 2015). By connecting the oceans and mountain rocks while traversing the floodplains, they become the Earth's circulatory system. Major rivers' banks served as the starting point for the development of major civilizations. Rivers have supported a variety of other activities, while the chronicles eventually contributed their essence through the location, history, and cultural heritage. Some of them are agriculture, aquaculture, transportation, industrial development, and entertainment (Borthakur & Singh, 2016). Although there are numerous nutrients that are part of the living processes, one important ingredient that is transported by river waters is carbon, which is a necessary component of all life on Earth. The human population that is concerned about climate change develops strategies to sequester surplus atmospheric carbon dioxide in the Earth. The rivers are among the most comprehensible sources of carbon export from the boundaries of continents. They produce a significant flow, which may be calculated from estimations of water output and aqueous carbon concentrations. Considering the recent increases in CO_2 concentrations in the atmosphere, it is essential to comprehend the carbon cycle and CO_2 exchange among the environment's many reservoirs. The movement of carbon from the land to the oceans and atmosphere is facilitated by rivers and estuaries. Numerous estuarine processes have a significant influence on these fluxes because carbon participates in a variety of organic and inorganic processes, including "biological productivity, oxidation/degradation of organic carbon, dissolution and precipitation of calcite, and CO_2 exchange with the atmosphere."

Recent studies, for instance, show that there is a significant "outgassing of riverine carbon to the atmosphere" due to the "high pCO_2 of river waters" in comparison to the atmosphere. In a study on the three main Himalayan rivers—the Ganga, Brahmaputra, and Meghna Rivers—the carbonate systems, the direct release of carbon dioxide from river water into the atmosphere has been examined. They discovered pCO2 levels higher than the atmospheric pCO2 level in the lower reaches of these rivers, where deep soils have developed and high air temperatures drive active soil respiration, despite the fact that the upper portions of these rivers are known to have low pCO2 levels due to active chemical weathering. An easy mixing calculation shows that subsurface water fluxes control seasonal fluctuations in these river water carbonate systems. During the rainy season, the majority of the lowlands are submerged, increasing the input of subsurface flow to river water carbonate systems and raising pCO2 concentrations (Manaka et al., 2015).

2 River and Biogeochemical Linkages

A complex interaction of "physical, chemical, and biological processes" taking place on the land, in the riparian zone along the banks, in the surface waters upstream, and in the channel sediments, results in the chemical composition of the water collected from the river at any point along its course. Element cycles can be significantly impacted by biogeochemical processes, particularly for elements that are present in trace levels yet are essential for biosynthesis. Therefore, "biogeochemistry" refers to the changes in element cycles that involve interactions between the biota and the geochemical features of the watersheds. The atmospheric CO_2 is changed into dissolved bicarbonate ions (HCO_3^-) in water, which is then transported by rivers to the oceans via weathering of both carbonates and silicates caused by the interaction of terrestrial rocks with water. Normal conditions result in 21% oxygen and 0.03% carbon dioxide by volume in the dry atmosphere at sea level; however, these percentages may vary in soil due to OM decomposition.

$$\{CH_2O\} + O_2 \rightarrow CO_2 + H_2O \tag{1}$$

As a result, the oxygen concentration of the soil's air may drop as low as 15%, and its carbon dioxide content may increase by a few percentage points as a result of this process, which also produces carbon dioxide while consuming oxygen (Manahan, 2001). The groundwater's dissolved CO_2 levels significantly rise as a result of this OM degradation, which lowers pH and speeds up the weathering of carbonate minerals, particularly $CaCO_3$. Rivers' biogeochemistry depends on energy storage from photosynthesis or the decomposition of organic materials to support biosynthesis and respiration. The biogeochemical cycling of carbon between its two main pools, land and ocean, depends on rivers entering the ocean. Physiologically inert metal complexed humic compounds, polyphenols, and polysaccharides, as well as more unstable chemicals including polypeptides, fatty acids, and carbohydrates that disintegrate quickly in the riverine environment, may be found as carbon molecules in these pools (Gupta et al., 1997). The total amount of organic carbon estimated to have been transferred annually from the rivers to the oceans ranges from 0.03×10^{15} g Ca^{-1} to 1.0×10^{15} g Ca^{-1} with the global average being around 0.5×10^{15} g Ca^{-1} organic carbon. The distribution of the river load's dissolved and particle fractions defines this transfer. Other ions like calcium and magnesium, minerals from organic matter, and particles from the land are also transported by rivers to the oceans, enhancing biological production and consuming CO_2, especially in coastal areas.

2.1 Carbon as the Element

One of the most plentiful elements in the universe, carbon is responsible for the structure of our entire biological system, encompassing both water and land. Biological things are mostly composed of carbon in its organic form. The atmosphere, lithosphere, and hydrosphere are the three components of the biosphere where carbon can be found. By converting, outgassing, and storing more than half of the C they take in from terrestrial ecosystems before transferring it to the seas, inland rivers make a large contribution to the global carbon cycle. Terrestrial carbon imports into freshwaters are frequently comparable to the net output of terrestrial ecosystems (Hotchkiss et al., 2015). Large rivers' carbon and nutrient fluxes are assumed to reflect the processes occurring in their tributaries, floodplains, and watersheds. Due to their physical size and logistical issues, large rivers make it difficult to determine carbon dynamics. Over the past 20 years, researchers have looked into a number of prominent rivers in temperate and tropical nations, including "the Amazon; major North American, Russian Arctic, and Siberian rivers; the Parana and Orinoco; and major African rivers." Long-term investigations of the world's major rivers are lacking, nevertheless, and are necessary to comprehend their nature as non-steady-state systems characterized by episodic events.

2.2 Biogeochemical Processes of Carbon

Carbon is everywhere, making it difficult to comprehend how it moves above and below, or how it is emitted or stored by the Earth system. It is said that the carbon cycle is a complicated process wherein carbon is converted from organic to inorganic and vice versa. A process of recycling, almost through the process of respiration, which involves the breakdown and release of energy from complex carbon-containing compounds, both living things—animals and plants—release CO_2 into the atmosphere. Getting a Handle on Carbon Dioxide–Climate Change: Vital Signs of the Planet (nasa.gov)) report that the atmospheric concentration of carbon dioxide (CO_2) is approximately 412 parts per million as of the year 2021. This is the most fundamental process of carbon uptake, in which plants and specific microbes absorb water and CO_2 to produce sugars and starch. Photosynthesis is a process that is fueled by sunlight and enzymes. As a waste product, oxygen is emitted here.

$$6CO_2 + 12H_2O \Leftrightarrow C_6H_{12}O_6 + 6H_2O + 6O_{2\ldots} \tag{2}$$

Every ecosystem, including river systems, maintains the biogeochemical link between the elements C and O through photosynthesis, aerobic respiration, and breakdown. The process of turning inorganic carbon into light-dependent organic matter is known as photosynthesis. Because the process is reversible, biosynthesis takes place on the right while respiration and breakdown take place on the left. Fast oxidation of stored organic matter by industry, agriculture, forest fires, and internal combustion engines may have a significant impact on the global climate because photosynthesis is so pervasive that it affects the composition of oxygen in the atmosphere. Because of this, organic material that has been stored by industry, agriculture, forest fires, and internal combustion engines is oxidizing at a startling rate, which could have a huge impact on the climate. In respiration (aerobic respiration), organic matter is oxidized in the presence of molecular O_2.

$$\{CH_2O\} + O_2(g) \rightarrow CO_2 + H_2O\ldots \tag{3}$$

Use of oxidants other than O_2 during anaerobic respiration, such as NO_3^- and SO_4^{2-}, is considered. As part of the process of exchanges of matter and energy in the form of food from organism to organism, animals can access organic carbon by consuming plants or other animals. The decomposers, which break down dead plants and animals during the decomposition process, accompany further processing. Some features of chemical reactions are controlled by the significant contribution of microbes to the carbon cycle. As a result of algae, which are carbon-fixing organisms in water, consuming CO_2, the pH of the water rises, resulting in the precipitation of $CaCO_3$ and $CaCO_3.MgCO_3$. By reducing organic C, N, S, and P to simple organic forms that plants may use, the biomass breakdown by bacteria and fungi prevents the buildup of excessive water residue.

This process, together with the residual humus residue, is crucial to the biogeochemical cycling of the elements and is necessary for maintaining the soil's ideal physical condition. Another factor is methane formation, which is the last stage of anaerobic breakdown of organic matter. Methane-forming bacteria, including *Methanobacterium*, are found in anoxic (oxygen-free) sediments, and they play a significant role in local and global carbon cycles. About 80% of the methane that reaches the atmosphere comes from this source. Higher hydrocarbons are oxidized under aerobic circumstances by Micrococcus, Pseudomonas, Mycobacterium, and Nocardia, which is an important environmental mechanism for removing petroleum waste from soil and water. The treatment of municipal wastewater includes another process known as

$$\{CH_2O\} + O_2(g) \rightarrow CO_2 + H_2O + \text{biomass}\ldots \tag{4}$$

Burning biomass releases carbon back into the atmosphere as well. Thus, this carbon is also stored in living things, particularly in plants with longer life spans, like trees. Another illustration is the fossilization of plants and animals, which results in the storage of carbon in the rock itself and, under the appropriate circumstances, the formation of fossil fuels. Moreover, the carbon that is present in non-living things, such as rocks, shells, the atmosphere, and the oceans, is known as inorganic carbon. Its trip downstream begins with the natural acid rain droplets, dissolving the minerals in the rocks. The acid is further neutralized, changing into carbon dioxide and subsequently bicarbonate, which flow into the water and eventually into rivers. While carbon dissolved into rivers is transported to the oceans, where it is then stored in the deep-sea sediments for millions of years, this process helps to remove carbon dioxide from the atmosphere on a large scale. While several activities have an impact on the carbon that flows down the river or is discharged back into the atmosphere, we must measure the quantity of carbon that enters the water in order to lessen its effect on the climate. The drainage basin where the total amount of carbon received in the water consists of the mixture of all the components from diverse sources is where the biogeochemical activities of major rivers can be combined. Different amounts of rainfall and runoff affect hydrology, which in turn affects the biogeochemistry of carbon. Rivers start to play a more active role in the basins' overall carbon balance (Richey et al., 2009).

2.3 Forms of Riverine Carbon

As shown in Fig. 1, the major three types of carbon in river waters—DIC, POC, and DOC—come from various natural inputs. River eutrophication is a crucial cause for algal POC that adds to near-anoxic conditions when it comes to the coastal zonation, along with the expanding anthropogenic components. Dissolved inorganic carbon, often known as DIC (carbonate + bicarbonate + CO_2), is the main form of carbon released into many rivers and streams around the world. Numerous physical and chemical factors, including "pH, temperature, alkalinity, dissolved oxygen, etc., and biological activities occurring inside the river's watershed," determine the chemical composition of the river. For instance, during the dry season, the Godavari river's upper reaches witness fresh and autochonous Particulate Organic Matter (POM), whereas the lower reaches see deteriorated content and a rise in inorganic suspended matter. Heavy rainfall causes a flushing of humus across the entire basin, which favors allochthonous, degraded POM. It is crucial to interpret the biotic processes because they influence water quality, fish production, and the global carbon budget. They also provide a detailed, "integrated record of natural and anthropogenic activities within the drainage basin" (Balakrishna & Probst, 2005) (Fig. 2).

Since they not only transfer carbon from terrestrial sources to the marine environment but also encourage a variety of in situ activities that can significantly affect the carbon content, fluvial systems are exceptional in their contribution to monitoring the biosphere's global carbon budget. Changes in carbon concentrations and forms can happen naturally as a result of processes like atmospheric gas exchange (particularly carbon dioxide degassing), storage in sediments at the bottom of rivers (via organic matter microbe decomposition), and an increase in plankton production, which is primarily brought on by human activities like increased nutrient input from agricultural land, sewage, and industrial activities. According to a study published in the journal *Nature*, dissolved organic carbon (DOC), which is mostly created by plant decomposition, is a "very dynamic and reactive component" of the Earth's overall carbon cycle in freshwater river systems. Contrarily, DIC is created

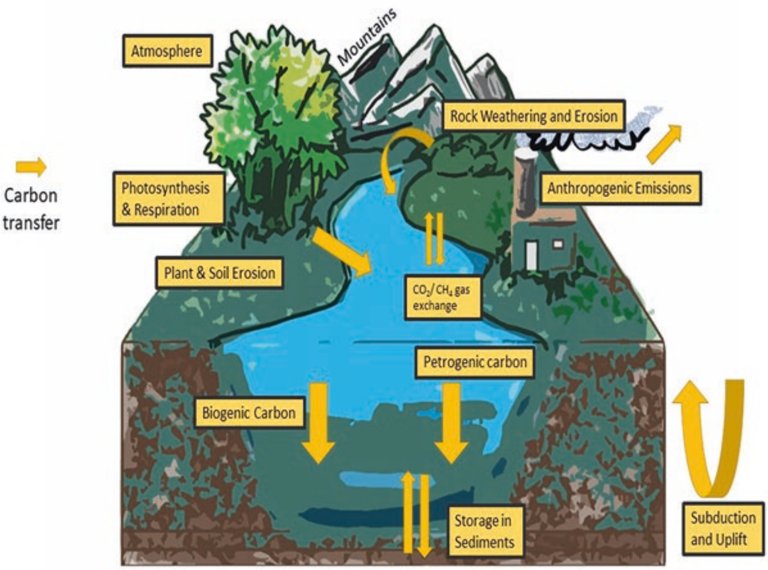

Fig. 1 The Carbon Cycle: The sequence of processes through which carbon compounds are interconverted in the environment, involving the incorporation of carbon dioxide into living tissue via photosynthesis and its return to the atmosphere through respiration, the decomposition of dead organisms, and the combustion of fossil fuels. Transportation of carbon from rivers to the sea. Some part of it settles on the seafloor and is buried and disconnected from the atmosphere for millions of years which eventually makes its way back to the surface in the form of rocks. Simultaneously, the river also erodes the carbon-containing rocks into the particles which are carried downstream. This process exposes the carbon to the air that oxidizes the previously locked-up carbon into carbon dioxide that can leak back out to the atmosphere (https://www.whoi.edu/press-room/news-release/river-carbon/)

from atmospheric CO_2 through the weathering of silicates, the creation of carbonate from rock, the consumption of SOM, and other processes. A comprehensive understanding of the carbon cycle can be developed by measuring the amount of carbon dioxide absorbed from the atmosphere during the weathering of rocks and by learning more about biogeochemistry and carbon cycling to identify the sources of inorganic carbon in river water. Assessing C isotope in DIC is one of the most accurate methods to determine the different sources of DIC in rivers because aspects of fractionations of different carbonate species and gaseous CO_2 in dissolved river water are well documented. The weathering of minerals, soil and root respiration, mineralization of in-stream DOC, and other activities that function as carbon sinks on land all contribute to the creation of DIC in streams and rivers. The CO_2 dissolved from terrestrial respiration, which includes soil and roots, contributes to the DIC pool in the stream via groundwater or shallow soil flow channels. Bicarbonate is produced when carbonate rocks dissolve in the presence of carbonic acid or any other acid, and it is also a result of the reaction between carbonic acid and silicate rocks. Depending on a specific region of land's temperature, vegetation, and

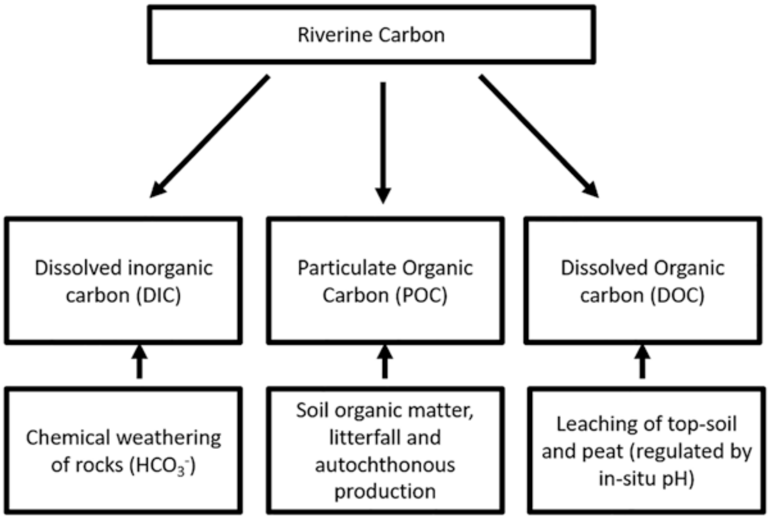

Fig. 2 Flow chart showing different forms of riverine carbon

underlying geology, a variety of terrestrial processes take place at varying rates. The amount of dissolved inorganic carbon (including carbon dioxide) produced by "ecosystem respiration (ER = heterotrophic + autotrophic respiration)" in streams varies significantly and is mainly regulated by "temperature, organic carbon intake, stream biota," and "nutrients." "The amount of POC that is transported ranges from 0.19 to 0.23×10^{15} gCa^{-1}, of which 35% is made up of labile POC. Due to CO_2 inputs from terrestrial sources, in situ aquatic mineralization of terrestrial organic carbon (hence referred to as "internal production"), as well as abiotic CO_2 creation, inland waterways are commonly oversaturated with CO_2. As a result, changes in land cover, temperature, terrestrial ecosystem processes, the relationship between land and water, and internal CO_2 generation will cause changes in CO_2 concentrations and emissions from flowing waters. Over the past 10 years, our conceptual understanding of how freshwater ecosystems fit into larger carbon budgets has undergone tremendous change, yet the ratio of internal production to CO_2 emissions from flowing waters is still not well constrained. Most freshwater budgets evaluate carbon sequestration, emissions, and export before using these fluxes to determine the terrestrial inputs to inland rivers. Although this method has been useful for integrating land-water carbon budgets, it restricts our understanding of the functional contributions of streams and rivers to carbon budgets. According to Hotchkiss et al. (2015), it is unknown to what extent freshwater ecosystems act as passive conduits (or "chimneys") for terrestrially generated CO_2 as opposed to actively metabolizing terrestrial OC to $CO_{2.}$ River intake makes up just 7.5% of primary output, but due to its stability, it may have a considerable impact on the total amount of carbon buried in coastal regions. Because riverine carbon fluxes make up less than 10% of annual anthropogenic carbon emissions, more research into them is not necessary in terms of global carbon cycle modeling. However, studies of river carbon flow, which are directly influenced by river mass movement, may offer crucial insight into the biogeochemical cycle operating in coastal ecosystems at the regional level. In addition to directly ingesting POM, rivers also provide nutrients to the estuary that help phytoplankton grow. Extreme weather and hydrologic conditions have the power to significantly modify how rivers travel in large quantities (Degens & Ittekkot, 1985; Spitzy & Ittekkot, 1991).

3 Quantification of Carbon Transport by Rivers

Although the carbon fluxes across rivers are minor on a global scale, they frequently play significant roles in the creation of regional carbon budgets (coastal zones and deltas), underlining the lack of C sinks. This can also be applied to changes in land use and cover caused by anthropogenic activity. Whether the carbon cycle is global or regional, the inland freshwater ecosystem, including rivers, plays a significant quantitative role (Cole et al., 2007). In comparison to any other biotic pathway, the increase in CO_2 partial pressure has caused the surface ocean solution to dissolve more CO_2 into the solution, creating a significant abiotic pathway for atmospheric C sequestration into the ocean. In terms of atmospheric CO_2, rivers are net contributors. The majority of the HCO_3 transportation in the flowing waters is represented as carbon dioxide, which is changed due to the fluctuating conditions of weathering of corresponding rocks like aluminosilicate or carbonate rocks. Excess carbon dioxide is derived from groundwater contributions of organic C that is respired in either soil systems or within the stream or river. The export of DIC by riverine export, which results from the fixation of carbon from the atmosphere, is estimated to be between 0.21 and 0.3 Pg C $year^{-1}$ by Cole et al. (2007). On a global scale, around 50% of the bicarbonate carried by rivers comes from the weathering of silicate, while the remaining 50% comes from the bicarbonate that is released from CO_2 sequestration. The other half of the bicarbonate that is carried results from carbonate weathering, whereas the other half originates from the sequestration of carbon dioxide. Groundwater has npt been given much consideration in the global carbon budgets yet. Although it “comprises 97% of the world’s liquid freshwater” and includes sizable amounts of both organic and inorganic carbon, the estimation of SGD (Submarine Groundwater Discharge) indicates that it contributes just “1.4–12% of river influx, with the most accepted range between 5 and 10%.” The amount of carbon being oxidized and stored within the basin, an estimate of the organic carbon flux from rivers to the ocean, and changes in flux or storage over time are all significant elements for assessing river carbon. Even though tropical river systems provide more than 60% of all water discharge and 34% of all suspended load to the world’s oceans, they have received less attention than their temperate counterparts. The vast bulk of information about tropical river systems is restricted to a few of large river systems. Due to this, leaving inland rivers out of landscape carbon budgets could lead to an overestimation of terrestrial CO_2 absorption and storage. Rushing rivers are hotspots for CO_2 emissions, outgassing at a much faster rate than lake and terrestrial ecosystems despite their little area coverage. Understanding the rates and factors that contribute to C cycling in flowing waterways is crucial given their significant impact on C transformations, movement, and emissions in the environment.

A sizable river called the Ganges traverses the southern slopes of the Himalayas. The transboundary river runs through Bangladesh and India. The migration of current organic C from the Himalayan riverine area is responsible for 10–20% of the global flow into the oceans, according to research. The "movement of organic C in the Ganga River's headwaters" has not previously been the subject of any research (Panwar et al., 2017). The rate of continental erosion, the capacity of rivers, the amount of leaching, mineralization, and sediment deposition are just a few examples of "extrinsic and intrinsic fluvial processes" that have a significant impact on the evaluation of fluvial organic carbon flow. The Ganga-Brahmaputra River system has deposited organic carbon (OC) in the Bay of Bengal over the last 15 million years, making up 10–20% of the entire world burial flux. A total of more than 65% of sediments are transported by the Ganga River, which is formed by the "Higher Himalayan Crystalline." The "Higher Himalayan Crystalline," which creates the Ganga River, transports a total of more than 65% of the sediments. The "Alaknanda River" is a Ganges tributary that travels through the Western Himalayas of India. A study was conducted to ascertain the effects of seasonal erosivity on the dissolved organic carbon concentration and physiography of the basin, which serves as an important control parameter for the movement, oxidation, and residence time of the OM. Alaknanda provides 66% of the total DOC flow carried by the Ganga River at Devprayag. The comparison with previously published data shows that the Ganga River transfers organic carbon largely as POC downstream in the Himalayan foothills and mostly as a dissolved load upstream due to changes in physiography and chemical weathering rate. The Hooghly estuary, one of its deltaic tributaries, was the subject of research. A high-suspended sediment load is seen during the monsoon. The Sundarban mangrove forest, which becomes the main source of inorganic fertilizers, is traversed by the estuary. Typically, it is seen that the estuarine transfer of nutrients associated with litter and sediment has a significant impact on the DIC fluxes of the Hooghly river's coastal zone, which are determined by using biogeochemical modeling. The calculated annual fluxes are 2.76×10^6 t or 230×10^9mol (Mukhopadhyay et al., 2006). The goal of this research was to analyze the role of upland tributaries in the transportation mechanisms impacting the Godavari's lateral carbon and nitrogen flows. The study was conducted on the Godavari river in India. In the river basin, dissolved inorganic carbon (DIC) is by far the most significant method of carbon transfer. Up to 75% of the total carbon burden is attributable to it.

According to Sarin et al. (2002), DOC and POC fluxes account for 21% and 4% of total fluxes, respectively. Because of extensive human activity in the upper basin, DOC fluxes outpace POC fluxes. In contrast, the POC and DOC fluxes in streams in the middle basin are comparable. However, due to silt entrainment in river channels and dam sites, downstream particulate organic carbon export is 35% lower than upstream and tributary imports. We propose that for severely damaged watersheds in tropical climates, long-term monitoring of sediment and carbon flow downstream is required. The main stem and tributaries of the large tropical river Godavari (India), according to a case study of its biogeochemistry, contain an abundance of total carbon varying from 13.8 to 50.7 mg C L^{-1}. In a different study of the Godavari river system, it was found that during the high season, the soil in the lower basin of the river is the main source of organic matter (OM; C/N ratios range from 8.1 to 14), while during the other seasons, river-derived (in situ) phytoplankton serves as the main source (C/N ratios range from 4 to 8). The intermediate "C/N ratios (between 4 and 8)" show that phytoplankton and soil organic matter are cautiously combined. Larger net outputs of organic carbon are caused by deforestation, agricultural activities, intense rainfall, and considerable erosion. Due to inflow from the watershed and flood plains, OM concentrations in river channels are higher during monsoons. One percent or less of the DIC fluxes from all rivers in the globe are exported to the seas through the Godavari river. Two tropical river basins' diverse hydrological sections' water sources are revealed by the analysis of oxygen stable isotope ratios (18O) and hydrogen stable isotope ratios (2H). This is related to "the increased vapor recycling process occurring in these basins and the continental wind pattern dictating the north-east winter monsoon."

The bicarbonate is the major anion at the Alaknanda River, which is primarily owing to the rock weathering influencing the water chemistry, as seen in Table 1's representation of the bicarbonate and DOC data of several Indian rivers. As a result, the Alaknanda River and its tributaries have an alkaline pH. According to Singh and Hasnain (1998), silicate weathering and carbonate weathering both have a role in the basin's overall regulation. Similar to this, weathering regulates the slightly acidic to slightly alkaline waters of the rivers Narmada and Tapti (Sharma & Subramanian, 2008). The anthropogenic sources of bicarbonate along the river

Table 1 Bicarbonate and DOC estimates of different Indian rivers

River	Bicarbonate (mg/L)	DOC (mg/L)
Arkavathy	616 (Gogeredoddi; Max) 227 (Koggedoddi; Min)	–
Pennar	237.7 (pre-monsoon) 171.8 (monsoon) 141.5 (post monsoon)	–
Ponnaiyar	289.1 (pre-monsoon) 215.2 (monsoon) 317.7 (post monsoon)	–
Pazhayar	51	–
Periyar	12 to 25	–
Ganga (Buxar)	124.44	–
Ulhas River	59.6	–
Alaknanda (Devprayag)	68.3	0.60–1.29
Bhagirathi	42.1	0.68–1.13
Ganga (Rishikesh)	4.9–34.2	1–1.19
Yamuna	102.3	0.98–4.7 (Sharma et al. 2017)
Gomti	54.9	–
Narmada	20.5–179	1.70–33.9
Tapti	130–334	3.60–13.9

Arkavathy include limestone, which is used to raise the pH of the soil or to buffered lakes to treat acidification. As wastewater from industry and home usage contains bicarbonate from cleaning chemicals and food leftovers, human interventions like effluent from wastewater treatment plants can also increase alkalinity to a stream. According to CWC data on river water quality scenario, Department of Water Resources, River Development, and Ganga Rejuvenation, similar perturbations are seen for rivers Pennar and Ponnaiyar.

When elucidating the biogeochemical cycling of carbon during the low water-flow season, the carbon isotopic composition (13C value) of both organic and inorganic river carbon in the Swarna and Nethravati Rivers clearly demonstrates the discrete dominance of carbon from autochthonous and allochthonoussources (Muguli et al., 2013). Because there is less organic carbon in these basins, atmospheric/soil CO_2 regulates river carbon mostly through the weathering of rock. The "relative difference in the typical carbon isotopic compositions of these two rivers, with the Nethravati water mirroring the average $\delta^{13}C_{DIC}$ composition of carbon fluid containing Charnockite" serves as additional evidence for this finding.

3.1 Integrating the Rivers into the Carbon Budget

The design of two boxes—one for the ocean and one for the terrestrial realm—illustrates a streamlined picture of the carbon cycle. Additionally, the gas interacts with the third box, which stands in for the atmosphere. The underlying gaps in the global budget's imbalances were revealed by this approach, according to earlier studies on the carbon budget (Cole et al., 2007). More small compartments and the accompanying processes have been added to models as they have evolved in order to consider a more in-depth version of their interactions. The models that represent the aquatic habitats that exist on land are rarely explicit. Numerous studies conducted throughout the 1970s and 1980s have demonstrated that considerable amounts of terrestrial organic and inorganic carbon C are transported from the land to the sea. It is really intriguing that it has been described as "the pipe" that moves carbon from the land to the ocean. "A straightforward mass balance equation was developed, according to one study, to follow the fate of organic and inorganic carbon in a integrated freshwater and terrestrial C budget," where the amount of carbon imported into the aquatic system can be calculated as the net carbon gas balance of the aquatic system with the atmosphere, plus storage and export in drainage waters and rivers (along with the direct groundwater discharge) to the sea. Any export of volatile organics to the air is also taken into account here. According to reports, the amount of organic carbon exported from the river to the sea ranges between 0.38 to 0.53 Pg C^{-1}. The availability of various elements from rivers, including carbon from primarily terrestrial sources, is necessary for the "steady-state chemistry of the oceans." Although estimates of riverine organic and inorganic carbon fluxes continue to be improved by new geospatial tools and scaling and modeling approaches, these fluxes are not notably different from earlier estimates. Today, yearly carbon flows to all significant ocean basins and seas are accessible. Fluxes are often closely related to river discharge, with a few exceptions where characteristics like extensive peat and carbonate coverage as well as high rates of erosion in watersheds limit carbon inputs (Bauer et al., 2013). In comparison to their benthic NPP, mangroves are known to export enormous volumes of POC and DOC into the ocean. "Global mangroves export 86 Tg C yr^{-1} of dissolved inorganic carbon (DIC) to adjacent coastal waters, which appeared to be significantly more than the estimated total export of POC, DOC, and CO2 emission from the mangrove ecosystem's submerged flood plains." Recent research has demonstrated that mangroves contribute significantly to the global exchangeable DOC (EDOC, volatile and semi-volatile OC) flow from the ocean to the atmosphere, accounting for around 60% of the total global EDOC flow. These assessments of the organic and inorganic carbon derived from mangroves, however, are based on a scant amount of research. Uncertainty is introduced and accepted due to data upscaling because unstudied portions of mangroves are still included in global budgets (Ray et al., 2018).

Natural and human-made factors are altering the amount of water that is imported from the River C into the coastal ocean. Watershed carbon stocks and fluxes, fluctuations in the water balance (precipitation and evapotranspiration), and all of these factors might affect inputs. The management of evapotranspiration through temperature regulation and the effects of climate change on the amount and frequency of rainfall events are examples of hydrological alterations. Additionally, it is required to take land management measures like plant removal and irrigation that affect evapotranspiration rates. Recent research has demonstrated that a range of practices have been found to modify carbon stocks (biogeochemical response) and flows at the drainage-network level, including the use of sulfuric acid, agricultural practices, peatland disturbance, permafrost melting, wetland loss, and reservoir construction. The amount of water that has been discharged (precipitation less evapotranspiration) is calculated by multiplying the carbon content (hydrological and biogeochemical reaction) by the amount of water. Numerous significant activities have an impact on the sources and fluxes of carbon in estuaries. Estuaries contain a mix of "organic and inorganic carbon sources obtained from terrestrial materials carried by fresh river water (with a salinity of zero), marine sources carried by shelf seawater (with a salinity of greater than or equal to 30), and materials that are peculiar to estuaries." Salinity-induced flocculation, sedimentation, microbial respiration, and photooxidation all result in the loss of organic carbon. Whether an estuary is a net carbon source or a net carbon sink may affect how much carbon is sent to the shelf.

Physical and biogeochemical processes regulate organic carbon's origin, movement, and final location. Carbon is transferred at the point where the plume and shelf waters converge by sorption and desorption. Movable and fluidized mud layers, bioturbation, and physical resuspension all aid in transporting organic carbon to the open ocean. The benthic nepheloid layer contains substantial amounts of suspended sediment that can be deposited at and resuspended from depocenters. While upwelling zones in outer shelf waters may improve primary output, high sediment loads in plumes may limit primary production in the inner shelf waters. The abbreviations DOC, POC, and DIC stand for dissolved organic carbon, particulate organic carbon, and dissolved inorganic carbon, respectively.

4 Impact of Human Activities

There are still many gaps in our knowledge of the natural, untouched carbon cycle of the coastal ocean. It can be challenging to distinguish between natural and artificial factors that are causing changes in the coastal carbon cycle due to land use changes, river impoundments, fertilizer inputs, wetland degradation, and climate change. Despite the fact that several anthropogenic sources have been identified as perturbing river and estuarine carbon fluxes, quantitative evaluations of their impact on these fluxes are still lacking. Around 2.7 Pg of carbon are moved from terrestrial to aquatic ecosystems globally. Although 1.2 Pg of carbon is respired as CO_2 and 0.6 Pg is retained in sediments, only 0.9 Pg of carbon is deposited in the ocean. The movement of carbon from the land to the sea has been greatly accelerated by human activities such as agricultural liming, increasing soil erosion, chemical weathering, and urban wastewater inputs. Furthermore, removing riparian vegetation and fertilizer from urban and agricultural areas may boost the output of native carbon. The decomposition of organic carbon in river and estuarine sediments may be accelerated by warming caused by urban heat islands and climate change. Although river engineering modifications like flood-control levees affect how carbon is cycled through rivers, it is challenging to quantify and notice these changes. The atmospheric CO_2 is absorbed when this organic carbon is buried in ocean sediment. Organic carbon that has accumulated in floodplains may oxidize and emit CO_2 into the atmosphere (Fig. 3).

It was shown in this issue of AGU Advances that engineered river bank stabilization can increase the amount of organic carbon transported to the seas while decreasing the amount of organic carbon oxidized in floodplains. This shows that solutions for bank stabilization may allow for more efficient CO_2 removal from the environment. The way nutrients, particularly organic carbon, are cycled through rivers has been impacted by human activities and channel engineering. Floodplains' ability to store carbon is reduced as a result of agriculture and development draining the soil's carbon content. Dams reduce the quantity of organic carbon discharged into the seas by holding silt in reservoirs. By preventing rivers from overflowing, artificial levees and other bank stabilization techniques reduce the amount of silt and organic carbon that is deposited on the floodplain. Bank stabilization has the ability to reduce riverine CO_2 emissions to the atmosphere while increasing the quantity of organic carbon buried in the oceans because organic carbon deposited in floodplains may be converted to CO_2. In order to determine the global terrestrial CO_2 sink, which is defined as the flux remaining after accounting for all other components of the anthropogenic carbon budget, as well as for determining both the coastal and global carbon budgets, it is not only necessary to understand the precise direction and magnitude of various human impacts on individual fluxes. At least some of the anthropogenic carbon dioxide absorbed by terrestrial ecosystems is thought to be carried to the coastal ocean, according to researchers looking at riverine organic carbon export. The shift in terrestrial carbon storage predicted by the IPCC4 and others may be overestimated given that a sizeable portion of the displaced carbon is

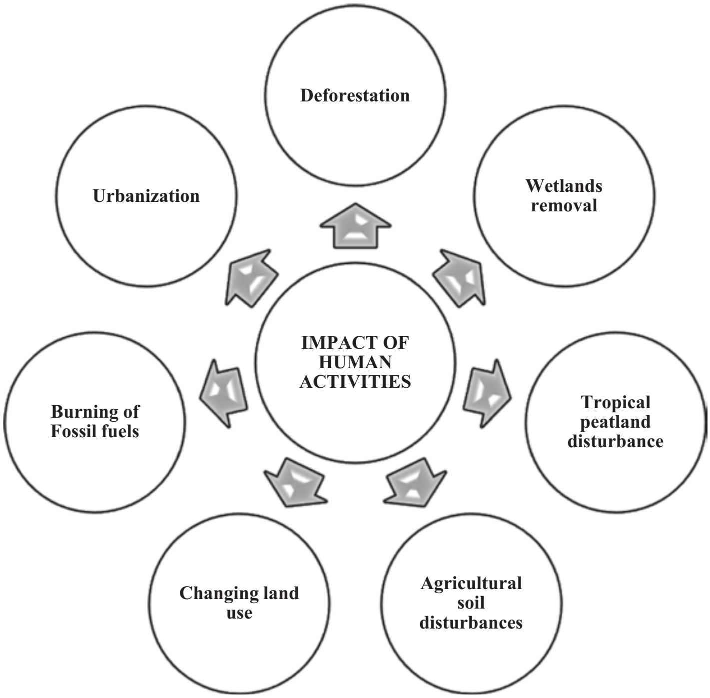

Fig. 3 Flow chart showing anthropogenic factors impacting riverine carbon

stored in coastal waters and sediments. Earth system models must include coastal carbon processes in order to support the necessary regulations and mitigation programs. It is vital to quantify the time evolution of coastal carbon transfers and fluxes and to include them in Earth system models.

4.1 Deforestation

Because deforestation lowers evapotranspiration on the land surface and increases runoff, river discharge, erosion, and sediment fluxes from the land surface, deforestation alters the hydrological, geomorphological, and biochemical states of streams. A study was carried out in the world's biggest continuous tropical forest and savannah habitat, which is located in Tanzania. This river discharge accounts for approximately 25% of total world river discharge. According to the findings of the research, almost two-thirds of the reported 25% increase in discharge has happened in the previous 50 years, which is a result of the deforestation that has occurred during that time period, was discovered. While there have been significant international attempts to conserve the Amazon rainforest, the vast majority of deforestation has taken place and continues to occur. As a result of deforestation, about 55% of the natural vegetation has been lost, and the hydrological and morphological elements of an 82,632 km^2 watershed of the Araguaia River in east-central Brazil have been significantly altered (Coe et al., 2011).

4.2 Urbanization

The Terai region of northern West Bengal (India) has experienced rapid infrastructure development as a result of economic policies put in place in 1991. This has resulted in the perceptible fragmentation of river channels, excessive in-channel sediment mining, and widespread land-use alteration of the floodplains. This study used an integrated methodology framework of remote sensing and field survey to conduct its research with the aim of examining the effects of anthropogenic interventions on the fluvial regime of the lower reaches of the Balason and Mahananda Rivers in the sub-Himalayan region over the past 30 years. In the majority of the places investigated, it was discovered that naturally vegetated zones had been transformed into built-up areas after being transformed into agricultural land and grassland, tea plantation, or barren ground. Unrestricted sediment mining and river channel embanking, which were directly linked to channel narrowing, were shown to have contributed to a considerable amount of channel narrowing between 1987 and 2017, according to research.

Cross-profiles and observed multitemporal channel width were compared, and the findings showed that the bed was significantly lowered (3.15 m) and that the channel was narrowing at an astounding rate (18.8 m/year). It has been found that rivers are beginning to show signs of losing their current equilibrium condition, which, if it happens, will cause the groundwater table to sink, flood frequency to decrease, existing river infrastructure to become unstable, and the ecology of rivers to be destroyed. Numerous recommendations have also been made with the aim of encouraging the judicious use of riverine resources by local communities and policymakers in order to restore the socio-hydrological as well as the eco-hydrological amenities of these rivers (Mitra et al., 2020). Riverine ecosystems must be preserved because they are also an essential natural habitat. A range of pressures, including as a changing water regime, increasing human intervention and biological invasion, climate change, land development, and other site-specific problems like eutrophication and urbanization, have an impact on these systems. As a result of urbanization, riparian vegetation is being replaced by impermeable and less permeable surfaces. As a result, flooding is happening more frequently, there is more surface runoff overall, and it takes less time for runoff to form. When there has been a substantial amount of rain, the entire city may have flooded. In this study, Olokeogun and Kumar (2020) used a variety of indicators generated from remote sensing data to analyze the vulnerability of riparian zones in the Indian city of Dehradun as a result of urbanization.

4.3 Burning of Fossil Fuels

The productivity of marine life may be impacted by manmade sources of nutrients to the oceans, such as rivers and air dust, but these effects are rarely investigated. Changes in marine nutrient inventories, and consequently changes in export production and ocean carbon storage, may occur if the delivery of the major physiologically limiting nutrients (nitrogen, phosphorus, ferrous, and silicon) from riverine, atmospheric, or sedimentary sources is altered, or if removal rates (such as denitrification) change. When compared to P, which is insufficient in relation to the nutrient needs of phytoplankton, the upward fluxes of significant nutrients are relatively insufficient in N on a global scale. The geographical partitioning of CO_2 uptake may be altered by a few tenths of a PgC/year since the atmospheric concentration gradients also reflect the natural fluxes brought on by weathering, the transfer of carbon by rivers, and the subsequent outgassing from the ocean. It is common to underestimate the effects of atmospheric emissions of carbon dioxide (CO_2) and methane (CH_4), particularly those resulting from incomplete fossil fuel combustion, burning of tropical biomass, and methane from tropical wetlands. As a result of their inclusion in the inversion, the latitudinal partitioning of the atmosphere is revised by up to 0.1 PgC/year (Prentice et al., 2001).

4.4 Changing Land Use

Land management is now commonly acknowledged to have a significant impact on lowering riverine carbon emissions to the coastal ocean. The release of silt and POC from the soil has increased dramatically as a result of agricultural activity. Higher carbon fluxes to the coastal ocean are not usually the result, though, as the vast majority of the terrestrial material is either redeposited on land or kept in artificial reservoirs and agricultural impoundments. According to estimates by Bauer et al. (2013), current POC flows in reservoirs, for instance, have been decreased to roughly 90% of pre-anthropogenic values. Carbon fluxes in river basins are anticipated to increase in the future, both as sources and sinks, as a result of widespread human-induced changes in land use and land cover (Sarin et al., 2002). As a result of being fertilized by river-borne inorganic fertilizers, there may be an increase in the quantity of carbon carried to and stored in marine sediments, which might represent a sizable net sink for anthropogenic CO_2. The humid tropics of South Asia are particularly susceptible to lateral C transfer due to heavy precipitation and fast land use and cover change. According to the National Institute of Environmental Health Sciences, urbanization increases the amount of organic matter in streams and soils from both natural (such as soil, leaves, and algae) and anthropogenic (such as sewage, grass clippings) sources. When flooding happens frequently, the inputs of natural particulate organic matter from riparian vegetation and soil erosion, which support the downstream DOM pool through leaching and decomposition, can rise.

By increasing food availability and reducing canopy cover (which increases accessible light), it is possible to boost autochthonous output. This biomass adds to the autochthonous DOM pool as it breaks down over time, whether on a daily or seasonal basis. Diverse point and nonpoint sources, including sewage pipe leaks and septic systems, can let dissolved organic matter (DOM) and nutrients from wastewater reach waterways. The rate at which DOM is leached from soils and benthic sediments may also be impacted by increasing stream temperatures and salinization levels.

4.5 Agricultural Soil Disturbances

The biogeochemistry of surface waters has been significantly changed as a result of human-induced increases in carbon and fertilizer inputs. Along with terrestrial sources, atmospheric deposition (AD) is a major source of carbon and nutrients for estuaries, oceans, coastal regions, and freshwaters. Numerous variables, like as light, temperature, metabolic activity occurring inside the system, and fertilizer input from the airshed and watershed, have an impact on the carbon cycle in surface streams. Surface waters are extremely vulnerable to nutrient deposition from the atmosphere. In the open ocean zone, nutrient deposition from the atmosphere promotes primary production and phytoplankton growth. It has been discovered that atmospheric deposition has a significant impact on the quality of surface water due to the increase in the autochthonous carbon pool and the increase in the allochthonous carbon input from the watershed. Overall, the effects of these actions include eutrophication and a change in the regional carbon budget. Surface water bodies that are remote from emission sources may be affected by nutrients that are delivered by the air. The availability of nutrients in the atmosphere will therefore continue to promote autotrophy throughout a greater variety of geographical areas, despite major efforts to prevent eutrophication (Singh & Pandey, 2019).

4.6 Tropical Peatland Disturbances

With a total carbon content of over 89,000 teragrams1 (one teragram is equal to one billion kilos), tropical peatlands hold one of the greatest stocks of terrestrial organic carbon in the entire planet. Peatlands provide enormous carbon reserves that may be held for hundreds of years because of their high water tables and low breakdown rates. The results of a study indicate that it is possible to quantify the annual export of fluvial organic carbon from peat swamp forests that are both intact and that have previously experienced human disturbance. The overall fluvial organic carbon flow from disturbed peat swamp forests was found to be almost 50% higher than the overall fluvial organic carbon flow from intact peat swamp forests in this study. The leaching of dissolved organic carbon from intact peat swamp forests is primarily derived from recent primary production (plant growth), rather than from older primary production (plant decay), according to carbon-14 dating of dissolved organic carbon (which accounts for more than 91% of total organic carbon). On the other hand, the majority of the dissolved organic carbon from disturbed peat swamp forest is made up of considerably older (hundreds to thousands of years) carbon that was generated from deep within the peat column. According to the study, the estimate of total carbon lost from disturbed peatlands is increased by 22% when the generally ignored river carbon loss component of the peatland carbon budget is taken into account. More accurate calculations reveal that wetland disturbance has increased river organic carbon flux from Southeast Asia by 32% since 1990. This increase accounted for more than half of the total yearly fluvial organic carbon flux from all European peatlands during that time. These results highlighted the requirement for improved analyses of the impact of drainage and deforestation on tropical peatland carbon balances, as well as the requirement for measuring river carbon losses (Moore et al., 2013).

4.7 Wetland Removal

Wetlands rank among the most significant ecosystems in the climate change response plan in terms of carbon sequestration (CS), and they are the most important ecosystems overall. Despite this, human interference is reducing their current CS capability, and further reductions are anticipated under scenarios of global population expansion and climate change, among other things. In order to boost wetlands' capacity to store carbon, numerous strategies have been proposed in the literature (Were et al., 2019). This will help to ensure that wetlands continue to be important for maintaining the global carbon (C) balance and reducing climate change. Wetlands can enhance water quality by removing contaminants from surface streams. Because they offer three different types of pollution treatment—sediment trapping, nutrient removal, and chemical detoxification—wetland pollution removal techniques are especially important. A bog is formed when water from a stream channel or surface runoff enters a wetland and grows in volume while passing through dense vegetation. Water suspended particles may settle on the marsh surface and become stranded there because the flow velocity has reduced. After being deposited, sediments can be held together by the roots of marsh plants. It is possible that up to 90% of the sediments present in runoff or stream flow will be removed from the system as the water passes through wetlands in the case of runoff or stream flow. Additionally, because soil particles are linked to contaminants like heavy metals, the settling of sediment in wetlands contributes to an improvement in the water quality. Pet waste, wastewater treatment and disposal systems, agricultural and lawn fertilizers, and a number of other sources of nitrogen and phosphorus can act as plant fertilizers in natural water bodies, leading to an overabundance of algae, cyanobacteria, and other species. Such growth might cause the extinction of nearby plant and animal species as well as the release of hazardous substances into the environment. Before entering a water body, runoff and stream flow may pass through wetlands where plants may take up the nutrients and deposit them in less dangerous chemical forms, lowering the risk of contamination. The natural equilibrium of the wetland habitat is restored when marsh plants rot and release nutrients into the environment. Due to wetland areas' ability to effectively remove excess nutrients from the water, many towns have created wetland areas specifically for the purpose of treating effluent from secondary sewage treatment facilities. It is not advised to use naturally occurring wetlands for this purpose since there is a maximum amount of additional material that can be put to a wetland before the natural plant and chemical processes become overburdened and cease to function properly. Along with the settling soil particles, some of the toxic substances that runoff brings into a wetland are also retained. Some of these toxins may be buried in the sediments as a result of biological activity and constant exposure to sunlight, while others may be changed by the action of microbes or by sunlight exposure into less hazardous chemical forms. The likelihood is that the plants will take in more pollution.

5 Balance for Climate

The main sources of atmospheric nutrient supply are chemical emissions from industry and agricultural practices, and changes in these sources are largely responsible for the regional trend in AD inputs. Throughout the Ganga River Basin, there has been a steady increase in the amount of nutrients deposited in the atmosphere. According to the results of this study, the 37-kilometer part of the river grid under consideration receives "32.65 tonnes of organic carbon per year from atmospheric sources." The sub-watershed, which includes surface water, is thought to have an annual AD-OC concentration that varies between 84.94 and 270.30 tons. Surface water data on carbon sources, sinks, and their connections to air- and watershed features are essential inputs for "regional climate modeling and river management methods." Finding out whether seasonality and human activities/processes have an effect on the spatiotemporal variability of carbon and nutrient intake to the river was one of the study's key objectives. River DOC saw significant oscillations over time, and these variations cannot be entirely attributed to phytoplankton-associated DOC. In addition to DOC's allochthonous and autonomous contributions to rivers and other water bodies, increased availability of nutrients from the atmosphere also benefits these bodies of water. The fact that DOC increases noticeably during the rainy season and that there is a significant correlation between runoff DOC and AD-nutrients raises the possibility that changes in the air-watershed interaction brought on by people will significantly increase DOC in the Ganga. The terrestrial decomposition of organic matter (DOC) (DOC) alters the productivity of watersheds, community structure, and ecosystem metabolism. It has a detrimental effect on both the accessibility of dissolved nutrients and metals in the water and the carbon cycle. Over the past 10 years, DOC levels have increased significantly throughout much of the northern hemisphere, especially in the Arctic. The quantity and quality of runoff, changes in land use, and the chemistry of atmospheric deposition are only a few of the variables that have an impact on the concentrations of DOC in surface waters. The transfer of river carbon to the coastal ocean is known to be impacted by climate. Due to the significance of transport restrictions, watersheds with high precipitation have higher river discharge rates, and several studies have long shown that discharge is the primary factor controlling the dynamics of carbon fluctuation. Temperature has an impact on both abiotic and biotic mechanisms that alter "water throughput, flow patterns, dissolution rates, and watershed carbon stocks." As a result, the overall impact of temperature on carbon fluxes differs depending on the region and whether the carbon is biological or inorganic. It is now clear that hydrologic "events," such as heavy rainfall from tropical storms, play a significant influence in the disproportionate transport of riverine organic carbon in addition to annual precipitation and temperature. The erosive power of violent storms, especially in mountainous locations, is responsible for the majority of POC transfer from watersheds to the coastal ocean. Increases in riverine dissolved organic carbon (DOC) concentrations and, consequently, yearly riverine DOC export to coastal systems are possible outcomes of these events. For instance, a single tropical storm may be responsible for more than 40% of a typical annual river DOC export. On a decadal time scale, a single large flood event can export between 80% and 90% of POC from mountainous areas. The most intense storms would probably become more frequent, influencing DOC and POC of the river transfer to coastal waters, even if the change in storm frequency is difficult to anticipate. Now, it is possible to predict the riverine transport of terrestrial carbon to the coastal ocean with moderate to high precision. On the other hand, future river carbon dynamics and related uncertainty are anticipated to be significantly impacted by climate change. Today, a number of studies point to precipitation—rather than, instance, temperature—as having the greatest influence on these fluxes in the next decades. In addition, under "future climate change scenarios, swift river transportation time is associated with large hydrological events that will contribute to the sidestepping of terrestrial C processing in rivers, as well as episodic disruption of carbon budgets of coasts, and a modification in the timing of delivery of terrestrial carbon to the coastal ocean." It is challenging to estimate the magnitude of these changes because the current generation of Earth system models does not simulate oscillations in river carbon.

6 Conclusion

River networks have a large amount of control over key carbon cycle activities. They become essential for evaluating carbon emissions created by humans and for furthering the impact of the atmosphere. Changes are made to the timing, character, and size of carbon flows. The results paint a clear picture of the crucial role played by rivers in the global cycling of carbon, which is accompanied by the release of various greenhouse gases into the atmosphere. Rivers move about 200 million tons of carbon annually. Terrigenous OM for the ocean primarily comes from this source. The majority of the carbon dioxide released by rocks and plants is absorbed by rivers. The remainder is broken down and released back into the atmosphere, while a portion is carried downstream to the open waters. River-based land-based transfer is the origin of DOC. When it enters the ocean, it is stored in the deep water for millions of years. Because of their variability, the systems that control GHG emissions from river networks are not fully understood by our current study. We can better understand the changing climate and land use with further research.

This overview talks about the many carbon inputs that help rivers create their elemental cycles. We must investigate how much carbon enters the ocean and the processes it undergoes in rivers in order to fight the effects of a changing climate. This could lead to the creation of a significant method for modifying the climate. The process by which rivers transmit carbon may be significantly impacted by chemical changes and river route variations. Residential sewage flow, in particular, seasonal fluctuations brought on by flood plains and river catchment soils, might intensify the anthropogenic impact on DOC concentrations.

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