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Original Research Paper

Factors Controlling Carbon Metabolism in Riverine Systems: A Review of Hydrological, Biogeochemical, Biological and Anthropogenic Controls

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Abstract

Riverine ecosystems are important constituents of the global carbon cycle in which carbon is transported, transformed, stored and exchanged among terrestrial, aquatic and atmospheric sections. Riverine carbon breakdown is commonly defined through the balance between gross primary production (GPP) and ecosystem respiration (ER), but this balance is regulated by relating hydrological, physicochemical, biological and human induced factors. Hydrology regulates residence time, sediment transport, groundwater exchange and gas transfer, while light and temperature strongly influence photosynthesis and respiration. Nutrient accessibility can promote primary production and enhance microbial respiration. The nature and origin of dissolved organic carbon (DOC) and particulate organic carbon (POC) determine substrate availability and therefore the intensity of heterotrophic processing. Sediments play as an important role of carbon storage and transformation, including anaerobic pathways that may produce methane. Catchment land use, wastewater discharge, agriculture, urbanization, dams and channel modification can substantially alter natural carbon pathways. Climate change further modifies these controls through warming, floods, drought and altered terrestrial carbon delivery. The Ganga River illustrates the interaction of these processes under strong monsoonal hydrology, high sediment transport and intense anthropogenic pressure. An integrated understanding of carbon metabolism is essential for interpreting river water quality, greenhouse-gas exchange, aquatic habitat and ecosystem functioning.
Keywords: riverine carbon metabolism; ecosystem respiration; gross primary production; DOC; POC; carbon dioxide; Ganga River; aquatic ecology

1. Introduction

River act as contact zone between terrestrial ecosystems, inland waters, the atmosphere and the oceans. (Aufdenkampe et al., 2011; Cole et al., 2007). River receive both types of carbon (organic and inorganic) from terrestrial soils and its vegetation, weathering process, through atmospheric deposition and anthropogenic activities. River transports these carbon downwards and gradually change the chemical and biological form of carbon. So, rivers are act as an active biogeochemical reactors in which carbon is produced, consumed, transformed, stored and exchanged with the atmosphere.

Metabolic processes in river ecosystem is commonly indicate gross primary production (GPP) and ecosystem respiration (ER). GPP denotes photosynthetic fixation of inorganic carbon into organic matter, whereas ER represents oxidation of organic matter by microorganisms, plants and animals. Their difference is expressed as net ecosystem production (NEP = GPP − ER). Positive NEP indicates that production exceeds respiration, whereas negative NEP indicates a heterotrophic condition. Importantly, metabolic state does not equal total carbon balance because a river can simultaneously export carbon downstream, store carbon in sediments and release CO_2 to the atmosphere. (Odum, 1956; Hall, 2016).

All controlling factors of river ecosystem are strongly interconnected. High discharge induced by rainfall, increase the carbon inputs and it simultaneously increases turbidity and adversely affect the light penetration and photosynthesis. High nutrient input in river enhance primary productivity. So, river metabolism is the outcome of interacting constraints rather than a response to a single variable. (Battin et al., 2008; Battin et al., 2009).

The present review compile of the major controlling factors of riverine carbon metabolic activity, hydrology, flow and discharge, residence time, nutrient concentration, dissolve oxygen level, temperature, light availability, quantity and quality of organic carbon, sediments, microbial activity, land-use and climate change. The Ganga River system, where all the controlling factors operate the system simultaneously. (Battin et al., 2008; Battin et al., 2016; Battin et al., 2023).

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2. Conceptual Framework of Riverine Carbon Metabolism

In river system carbon enters as organic, inorganic, dissolve and particulate forms from various sources, like surrounding terrestrial vegetation and soils, weathering process, wastewater discharge, agricultural runoff and autochthonous source of carbon. In river carbon present in different forms, some remain dissolve, suspended particles, accumulate in sediments, some enters in microbial activity and some mineralized to dissolve inorganic carbon and gaseous exchange. (Aufdenkampe et al., 2011; Cole et al., 2007).

Organisms that carry out photosynthesis, such as phytoplankton, periphyton, benthic algae and macrophytes, add to the gross primary production. Ecosystem respiration includes microbial decomposition, plant respiration and animal respiration. Rivers in which gross primary production exceeds ecosystem respiration are relatively autotrophic, while those in which ecosystem respiration is greater than gross primary production are relatively heterotrophic. Yet these classifications refer to the local metabolic balance and do not in themselves quantify downstream export, burial or atmospheric emissions. (Odum, 1956; Battin et al., 2016).

The concentration of carbon also needs to be interpreted with care. It does not follow that a high level of DOC means that respiration is high since a considerable portion may be refractory. Likewise, a high concentration of chlorophyll does not necessarily show that net carbon fixation is high if respiratory losses are large. Thus a reliable evaluation will have to rely on complementary measurements of the carbon pools, oxygen dynamics, hydrology and gas exchange. (Battin et al., 2008; Hall, 2016).

3. Physical and Hydrological Controls

3.1 Hydrology, Flow and Residence Time

Hydrology acts as a master control since it determines residence time, sediment transport, channel connectivity, groundwater exchange and air–water gas transfer by means of discharge and flow velocity. High discharge usually leads to a greater delivery of terrestrial dissolved organic carbon and particulate organic carbon via runoff and erosion. At the same time, suspended sediments can reduce light penetration, disrupt benthic communities and inhibit photosynthesis. Floods may thus increase the supply of heterotrophic carbon while temporarily decreasing autotrophic production. (Battin et al., 2008; Battin et al., 2009).

The conditions associated with low flow create a different environment since longer residence times can improve microbial processing and nutrient uptake, while less dilution may cause the contribution from wastewater and groundwater to become more significant. In severe cases of low flow there is an increase in temperature and oxygen stress and anaerobic metabolism may be promoted. Floods that last for a short time may be responsible for a large proportion of the annual carbon export; as a result, the average annual discharge by itself is not enough to establish reliable carbon budgets.

3.2 Floods, Drought and Hydrological Pulses

Floods link up the channels of rivers with the surrounding terrestrial and floodplain areas and cause the movement of soil carbon, leaf litter, organic matter and sediments. A portion of the carbon is carried downstream, another portion is deposited and buried, and the rest is quickly broken down by microorganisms. Right after a flood, there can be high levels of DOC and POC together with low primary production. When there is a drought, the reduced discharge leads to an increase in the concentration of solutes, reduces channel connectivity and may result in a longer residence time as well as oxygen depletion and methane production in organic-rich sediments. Sampling based on individual events is therefore necessary if the annual carbon dynamics are to be understood. (Uehlinger, 2006; Battin et al., 2008).

3.3 Light, Turbidity and Suspended Sediments

Light is another important controller of GPP. Light availability to the photosynthesizing layer is a function of solar radiation, depth of the water body, riparian shade, turbidity, suspended solids, and colored dissolved organic matter. In smaller streams with forests, riparian shade may limit light availability significantly; however, in larger rivers, turbidity and suspended solids become more important. Turbidity might lower primary productivity despite adequate nutrient supply but increase the physical movement of POC. (Battin et al., 2008; Vannote et al., 1980).

3.4 Channel Morphology and River Size

Pool, riffle, side channel, wetland, and floodplain linkages generate spatial heterogeneity in metabolism. The riffle adds to turbulence and oxygen transport, while pool and deposition sites increase the chance for sediments and residence time. Through the river continuum concept, the influence of terrestrial organic material and shade becomes more prominent in small streams than larger streams where turbidity, nutrients, phytoplankton, and physical form become increasingly important. (Vannote et al., 1980; Sabater et al., 2008).

4. Chemical and Biogeochemical Controls

4.1 Temperature

The temperature plays a role in controlling enzymatic reactions, microbial actions, and physiological functions. An increase in temperature will normally cause the increase in organic matter decomposition and respiration rates in the physiological range, while the response of GPP is more complicated. In cases where ER increases relative to GPP, warming will result in heterotrophy and increased conversion of organic carbon into DIC and CO_2. Warming also lowers oxygen solubility in water, thus creating oxygen stress in river ecosystems with organic matter. (Battin et al., 2008; Marzolf & Ardón, 2021).

4.2 Nutrients: Nitrogen and Phosphorus

Both nitrogen and phosphorus control the production of autotrophs and microbes. Enrichment will have an effect on production when nutrients are limiting, by stimulating the production of algae and macrophytes. Nevertheless, increased production will cause the formation of more organic matter, which may eventually lead to higher rates of respiration. Nitrogen is involved in denitrification in oxygen limited conditions, where carbon oxidation and nitrogen metabolism are coupled together. Phosphorus can result in eutrophication and deoxygenation through the accumulation of organic matter. (Battin et al., 2008; Sabater et al., 2008).

4.3 Dissolved Oxygen and Redox Conditions

The level of dissolved oxygen (DO) is one of the products and drivers of the river metabolic cycle. Photosynthesis releases oxygen during the day while respiration requires oxygen all the time. Changes in DO levels on a daily cycle can be an effective measure of GPP and ER. Where organic carbon input is large, respiration can lead to an oxygen deficit resulting in hypoxia or even anoxia. (Odum, 1956; Hall, 2016).

4.4 pH, Alkalinity, Weathering and Groundwater

Respiration increases CO_2 concentration while photosynthesis decreases CO_2 concentration and thus affects pH and carbonate chemistry. Carbonate chemistry can be written as $CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- \rightleftharpoons CO_3^{2-}$. Alkalinity gives the buffering capability of water and is essential when discussing DIC and pCO_2. Geological processes contribute to inorganic carbon whereas groundwater can provide DOC, DIC, nutrients, and CO_2 especially under low flow conditions. Groundwater-river interactions need to be included in carbon budget assessments. (Cole et al., 2007; Raymond et al., 2013).

5. Organic Carbon Quantity, Quality and Storage

5.1 Dissolved Organic Carbon

DOC serves as a significant carbon source for microbes. Microbes convert organic molecules that dissolve into biomass and some portion is converted to CO_2. The ratio between the formation of biomass and the respiration process is determined by the quality of the substrate, availability of nutrients, temperature, and microbes. Labile DOC is able to promote rapid microbial respiration and formation of CO_2, while refractory DOC may remain in solution and be transported downstream. Thus, DOC is not a sufficient respiratory demand predictor. (Battin et al., 2008; Battin et al., 2016).

5.2 Particulate Organic Carbon and Sediments

POC is mainly moved by suspended particles, which come from soil, plants, algae, and anthropogenic sources such as eroded banks. POC is moved very fast in case of high discharge water flow, but at low flow, POC can be accumulated on the riverbed floor. Deposited POC can either be buried, resuspended or metabolized by microorganisms and animals living on the riverbed. In sediments, there is accumulation of carbon and also metabolism. Mineralization takes place where oxygen enters into the sediments, but as oxygen decreases, other processes become dominant. (Aufdenkampe et al., 2011; Battin et al., 2008).

5.3 Hyporheic Processing

The hyporheic zone is the area where surface waters interact with groundwater underneath and adjacent to the channel. Water, dissolved substances, and organic matter movement into the interface facilitates microbial decomposition due to fluctuations in oxygen levels in the substrate. The significance of the metabolism in the hyporheic zone will depend on the permeability of sediments, water pressure, the nature of the river and its flow. Large rivers may have significant hyporheic and floodplain interaction zones. (Findlay, 1995).

6. Biological Controls

6.1 Microbial Communities and Fungi

Decomposition, mineralization, fermentation, methanogenesis, and carbon fixation require bacteria, archaea, fungi and protists. Microbial community structure is influenced by the following factors: temperature, the nature of organic matter, oxygen, pH value, nutrients and pollutants. Aquatic fungi are especially significant in the decay of plant material from land ecosystems due to the fact that extracellular enzymes break down cellulose and lignin into smaller molecules. (Battin et al., 2016; Marzolf & Ardón, 2021).

6.2 Phytoplankton, Periphyton and Macrophytes

Carbon assimilation occurs through phytoplankton, periphyton, benthic algae, and macrophytes. Periphyton is particularly significant in rivers with clear, shallow water and stable substrates while phytoplankton will be significant in large and slow-moving river sections. Macrophytes help in providing temporary carbon storage and also habitats; once mature, the biomass turns to detrital carbon, which can be used for microbial decomposition. (Odum, 1956; Battin et al., 2016).

6.3 Grazing, Fish and Aquatic Animals

Transfer of carbon within trophic levels by aquatic animals occurs via consumption, respiration, and excretion. Benthic macroinvertebrates break down organic material and agitate sediments, thereby increasing the surface area for microbial colonization. Fish play their role in carbon cycling via respiration, consumption, excretion, and bioturbation. Hence, aquatic animals are both consumers and processors of carbon. (Battin et al., 2016; Sabater et al., 2008).

7. Anthropogenic Controls

7.1 Catchment Land Use

The forest, agricultural fields, urban surfaces, and wetlands provide differing amounts and forms of carbon and nutrients. Deforestation can lead to a decrease in shading in riparian zones and increased erosion, while agriculture could lead to DOC, POC, and nutrient loading. Urbanization leads to storm water and wastewater loading. Thus, the catchment processes should be considered part and parcel of the river metabolism process. (Aufdenkampe et al., 2011; Battin et al., 2008).

7.2 Wastewater and Pollution

The waste water usually consists of readily biodegradable organic carbon and nutrients. Decomposition of waste water carbon by microorganisms leads to increase in oxygen demand and thus may result in CO_2 formation. Thus, the pathway waste water carbon → microbial respiration → oxygen consumption → CO_2 formation links water pollution to carbon metabolism and aquatic ecosystem. Better management of waste water would minimize readily biodegradable carbon entering into river. (Battin et al., 2023; Upadhyay et al., 2024).

7.3 Dams and Channel Modification

Dams affect flows, residence times, sediment transport, and carbon storage. While reservoirs can be expected to store particulate carbon and nutrients, these materials may decompose within the reservoir and create CO_2 and CH_4; sediment storage does not necessarily imply long-term sequestration. The effects on downstream flows and sediment supply can impact primary productivity and habitat. Channelization and concrete lining can lower the complexity of habitat, sediment storage, and hyporheic flow. (Tranvik et al., 2009; Battin et al., 2009).

7.4 Climate Change

Climate change affects multiple controls in tandem due to warming, changed rainfall patterns, droughts, floods, and variations in terrestrial vegetation and carbon inputs. Warming could facilitate respiration in highly organic sediments, floods could cause a terrestrial carbon pulse, while drought could lead to increased residence times and oxygen stress. Extreme events occur sporadically and are difficult to detect using traditional monthly sampling; high frequency and event-driven observations are hence critical. (Battin et al., 2009; Tranvik et al., 2009; Yang et al., 2025).

8. Ganga River as a Case Study

The river Ganga exemplifies a major river system where there are strong interactions between natural and anthropogenic controls. Carbon contributions from the Himalayas and land sources, monsoon-driven hydrology, large sediment transport, agriculture, urban development, wastewater, and industrial activities all play roles in carbon transport and cycling. The middle Ganga is especially relevant since anthropogenic organic matter loading may interact with natural carbon cycling. (Upadhyay et al., 2024).

Moreover, the river system also exemplifies the significance of monsoon-induced hydrological pulse events. The increased runoff associated with the monsoon season releases organic carbon and nutrients along with fine sediments. Elevated levels of suspended sediments are likely to reduce light penetration and photosynthetic activity. As a result, the same process may lead to decreased autotrophy and increased physical export of carbon. (Upadhyay et al., 2024; Yang et al., 2025).

9. Interactions among Controlling Factors

The most important feature of riverine carbon dynamics is that of interactions among the controls. For example, temperature affects both the oxygen solubility and the microbial metabolism at the same time. An addition of nutrients will not increase GPP in case if light availability is limited by high turbidity. Addition of DOC may lead to the provision of organic substrates for the microbes and decrease the light availability because of their absorbing properties. High stream flow may bring additional carbon and reduce the residence time of the water body. (Sabater et al., 2008; Battin et al., 2023).

A valuable hierarchy for concept clarification is: Catchment features -> Carbon availability -> Hydrological transport -> Physico-chemical environment -> Metabolism of living organisms -> Carbon transformation -> Atmosphere interactions, storage, and downstream transport. It helps to combine the landscape-level processes with local metabolism and provides an effective approach to compare river segments and seasons.

10. Methods for Quantifying Riverine Carbon Metabolism

Continuous day-night DO sampling is one of the methods used most often in quantifying ecosystem metabolism. The basic oxygen mass balance equation may be stated as $\Delta O_2 = GPP - ER \pm$ gas exchange $\pm$ physical transport. Proper correction for reaeration and advective transport, when needed, is key to accurate estimation. The carbon budget approach using DIC, pCO_2, alkalinity, and CO_2 flux measurements is another tool that yields additional data about carbon metabolism. (Odum, 1956; Hall, 2016).

Stable isotopes like $\delta^{13}C$ can help in determining the sources of carbon, whereas radiocarbon can give an idea about the age of carbon. Incubation studies can help in measuring decomposition and respiration, whereas high-frequency sensors can measure DO, temperature, pH, conductivity, and turbidity. Remote sensing can give information about chlorophyll-a, turbidity, color, and temperature of water, but metabolic studies are essential in the field because the respiration of ecosystems cannot be determined from remote sensing data. (Hall, 2016).

Method	**Primary information obtained**
Continuous diel DO	GPP and ER
pCO_2 measurement	Dissolved CO_2 dynamics
Floating chamber	Direct air–water CO_2 flux
DOC/POC analysis	Organic-carbon concentration and transport
DIC and alkalinity	Inorganic-carbon dynamics
Stable isotopes	Carbon-source identification
Radiocarbon	Carbon age
Incubation experiments	Carbon degradation and respiration
High-frequency sensors	Short-term metabolic variability
Remote sensing	Spatial patterns of turbidity and primary production

11. Ecological Implications for Aquatic Ecosystems

Carbon metabolism affects aquatic organisms because of their direct relation with food and oxygen supply. Production provides food with organic carbon to the food web, while respiration requires oxygen. High amounts of organic carbon input lead to high microbial oxygen consumption and thus the creation of hypoxic conditions depending on the tolerance of fish and macroinvertebrates.DOC changes affect water clarity. (Sabater et al., 2008; Battin et al., 2016).

The carbon flow is responsible for creating linkages between the food web of the terrestrial and aquatic systems. Algal carbon produced by autochthonous algae may sustain grazers, while terrestrial DOC and POC would feed microbial and detrital carbon flows. The microbe biomass that results from terrestrial DOC may be fed into the higher trophic levels, and the terrestrial POM may be fragmented by invertebrates.

12. Research Gaps and Future Directions

Several important unknowns still exist with regard to the amount contributed by transported or locally derived carbon, the influence of flood/storm pulses, and sediment/hyporheic processing. Carbon age is another major unknown since recently fixed as well as old terrestrial and geologic carbon can be transported together. The determination of the age and source of carbon undergoing respiration and emission into the atmosphere as $CO2$ is vital in determining its importance. (Battin et al., 2023; Yang et al., 2025).

Future research should integrate hydrological, biogeochemical, microbiological, and ecological studies. Measurement of DOC, POC, and DIC should include discharge, suspended sediment concentration, temperature, DO, nutrients, and $pCO2$. When possible, direct $CO2$ flux measurements should support $pCO2$ calculations. Biological studies should include phytoplankton, periphyton, microbiota, macroinvertebrates, and fish. Monitoring should focus on monsoon, flood, drought, and heat waves because extreme events may affect the carbon balance more than any other period in the year. (Battin et al., 2023; Yang et al., 2025).

13. Integrated Research Framework

A systematic approach to investigating carbon metabolism in rivers involves five interdependent components, which include (i) catchment properties affecting carbon availability, (ii) hydrology affecting transport, residence time, sediment transport, and groundwater interaction, (iii) physicochemical factors such as light, temperature, nutrient availability, oxygen, pH, and turbidity, (iv) biological communities affecting production, decomposition, and food webs, and (v) carbon destination via transport downstream, carbon storage in sediments, and CO_2 and CH_4 emissions. The entire process chain would therefore involve: Catchment → carbon input → hydrology → physicochemical control → biological metabolism → GPP/ER → CO_2/CH_4 + biomass + sediment storage + downstream transport. (Battin et al., 2023).

14. Summary of Major Controls

Factor	Principal mechanism	Main metabolic response
Hydrology	Residence time, transport, connectivity	Alters GPP and ER
Light	Controls photosynthesis	Strong control on GPP
Temperature	Controls reaction rates	Influences GPP and ER
Nutrients	Controls primary and microbial production	Alters GPP and ER
DO/redox	Controls aerobic vs anaerobic pathways	Changes ER pathways
DOC quality	Controls substrate availability	Strong influence on ER
Turbidity	Reduces light penetration	Often suppresses GPP
Sediments	Storage and microbial habitat	Influences ER and burial
Groundwater	Supplies DOC and DIC	Influences carbon metabolism
Morphology	Controls flow and habitat	Influences GPP, ER and gas exchange
Land use	Determines carbon and nutrient inputs	Indirect metabolic control
Wastewater	Supplies labile organic carbon	Often increases ER
Dams	Modify flow and sediment transport	Alter retention and metabolism
Climate change	Changes temperature and hydrology	May shift metabolic balance

15. Carbon Pools and Major Fates

Carbon pool	Major sources	Major fate
DOC	Soil, vegetation, wastewater, groundwater	Microbial degradation and downstream transport
POC	Soil erosion, vegetation, algae, sediments	Burial, respiration and downstream transport
DIC	Weathering, respiration, groundwater	CO_2 exchange and downstream export
Sedimentary carbon	Deposited POC	Burial or remineralization
Biomass carbon	Primary production	Grazing, decomposition and respiration
CO_2	Respiration and mineralization	Atmospheric emission or aquatic transport
CH_4	Anaerobic metabolism	Oxidation or atmospheric emission

16. Conclusion

Carbon cycling in rivers is a process that involves production, transport, transformation, storage, and exchange of carbon in terrestrial, aquatic, and atmosphere pools. Basic metabolic process in river carbon cycling includes GPP and ER, but the actual balance is regulated by factors including hydrology, availability of organic carbon, sediment fluxes, nutrients, oxygen, microbes, and aquatic organisms. Hydrology acts as a major regulatory factor by controlling carbon transport, residence times, sediment flux, groundwater exchange, and gas exchange processes. Light and temperature control photosynthesis and respiration, while carbon availability controls microbes' substrate. (Aufdenkampe et al., 2011; Battin et al., 2009).

Carbon burial or release of carbon in dissolved inorganic carbon (DIC), CO_2, and methane is influenced by whether the carbon is processed in a pathway that involves either an aerobic or anaerobic process. Anthropogenic influences such as wastewater, runoff from agriculture, urbanization, damming, and channelization can disrupt natural metabolic processes favoring increased heterotrophy and oxygen consumption. Additional factors that bring uncertainty to these systems include changes in climate that cause warming and increased variation in hydrology. Ganga River is one example of these influences. (Tranvik et al., 2009; Raymond et al., 2013).

Future studies on river carbon will have to be geared towards an observatory approach that combines hydrologic and oxygen monitoring alongside the monitoring of DOC, POC, DIC, pCO2, sediment carbon, and microbial processes along with aquatic biological measurements. Such an integrated monitoring approach will help in understanding river carbon budgets, GHG fluxes, and water quality as well as aquatic habitat. (Battin et al., 2023; Upadhyay et al., 2024; Yang et al., 2025).

References

Aufdenkampe, A. K., Mayorga, E., Raymond, P. A., Melack, J. M., Doney, S. C., Alin, S. R., Aalto, R. E., & Yoo, K. (2011). Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. Frontiers in Ecology and the Environment, 9, 53–60.

Battin, T. J., Kaplan, L. A., Findlay, S., Hopkinson, C. S., Marti, E., Packman, A. I., Newbold, J. D., & Sabater, F. (2008). Biophysical controls on organic carbon fluxes in fluvial networks. Nature Geoscience, 1, 95–100.

Battin, T. J., Luyssaert, S., Kaplan, L. A., Aufdenkampe, A. K., Richter, A., & Tranvik, L. J. (2009). The boundless carbon cycle. Nature Geoscience, 2, 598–600.

Battin, T. J., Besemer, K., Bengtsson, M. M., Romani, A. M., & Packmann, A. I. (2016). The ecology and biogeochemistry of stream biofilms. Nature Reviews Microbiology, 14, 251–263.

Battin, T. J., Raymond, P. A., et al. (2023). River ecosystem metabolism and carbon biogeochemistry in a changing world. Nature, 613, 449–459.

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., Middelburg, J. J., & Melack, J. (2007). Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. Ecosystems, 10, 172–185.

Findlay, S. (1995). Importance of surface-subsurface exchange in stream ecosystems: The hyporheic zone. Limnology and Oceanography.

Hall, R. O. Jr. (2016). Metabolism of streams and rivers: Estimation, controls, and application. In Stream Ecosystems in a Changing Environment. Elsevier.

Hotchkiss, E. R., Hall, R. O. Jr., Sponseller, R. A., Butman, D., Klaminder, J., Karlsson, J., et al. (2015). Sources of and processes controlling CO_2 emissions change with river size. Nature Geoscience, 8, 696–699.

Marzolf, N. S., & Ardón, M. (2021). Ecosystem metabolism in tropical streams and rivers: A review and synthesis. Limnology and Oceanography, 66, 1627–1638.

Odum, H. T. (1956). Primary production in flowing waters. Limnology and Oceanography, 1, 102–117.

Raymond, P. A., Hartmann, J., Lauerwald, R., et al. (2013). Global carbon dioxide emissions from inland waters. Nature, 503, 355–359.

Sabater, S. (2008). Alterations of the global water cycle and their effects on river structure, function and services. Freshwater reviews, 1(1), 75-88.

Tranvik, L. J., Downing, J. A., Cotner, J. B., et al. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. Limnology and Oceanography, 54, 2298–2314.

Uehlinger, U. (2006). Annual cycle and inter-annual variability of gross primary production and ecosystem respiration in a flood-prone river. Freshwater Biology.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences, 37, 130–137.

Yang, Q., Wu, F., Wu, Q., et al. (2025). Global patterns and hierarchical controls of metabolism from headwaters to large rivers. Journal of Hydrology, 663, 134268.

Upadhyay, P., et al. (2024). Deciphering carbon dioxide fluxes and interactions in the Ganga River Basin of South Asia. Environmental Research, 252, 118902.

Reassessing riverine carbon dioxide emissions from the Indian subcontinent. (2022). Science of the Total Environment, 816, 151610.

River bed carbon and nitrogen cycling: State of play and some new directions. (2012). Science of the Total Environment, 434, 143–158.

Organic matter decomposition and ecosystem metabolism as tools to assess the functional integrity of streams and rivers: A systematic review. (2020). Water, 12, 3523.