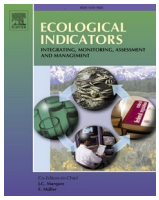
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Review



A review of reservoir carbon Cycling: Key Processes, influencing factors and research methods

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ABSTRACT

Based on the focus on the role of reservoirs as carbon sources and sinks, this article explores their impact on the global carbon cycle. Reservoirs, which are "artificial lakes" created by human activities in rivers, are reviewed in terms of the key links in carbon cycling within reservoir areas, the influencing factors, and research methods related to carbon cycling and carbon emissions. By reviewing the literature on reservoir carbon cycling, we elucidate the mechanisms of carbon inputs, decomposition and transformation, carbon emissions, and carbon burial, summarizing the biogeochemical coupling processes of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), particulate organic carbon (POC), and particulate inorganic carbon (PIC) with hydrological conditions and nutrients. The study concludes that the reservoir carbon cycling process is influenced by the characteristics of the reservoirs themselves, hydrological and hydrodynamic conditions, physicochemical and nutrient conditions, and human activities. Additionally, we further clarify the applications of field sampling and analysis, modeling, remote sensing technology, and isotope techniques in reservoir carbon cycling. In the future, it is recommended to continue monitoring and simulating the reservoir carbon cycle processes on a long-term and large-scale basis, and to deeply explore the multifactorial mechanisms of reservoir construction in the global carbon cycle.

1. Introduction

Globally, there are three processes in the carbon cycle: the inorganic carbon cycle, the short-term organic carbon cycle and the long-term organic carbon cycle (Galvez et al., 2020), and the uncontrolled exploitation and utilization of fossil energy sources by humans and the global scale of transformation activities have disrupted the natural equilibrium of the Earth's carbon cycle and the closed-loop pathway (Zou et al., 2022). This has resulted in an increase in greenhouse gases and global climate change, and plays an important role in maintaining the stability of the structure and function of the biosphere (Tranvik et al., 2009).Inland waters, particularly reservoirs, are characterized by high carbonate content and play a significant role in nutrient enrichment and storage (Sang et al., 2018), exhibiting a robust mechanism for carbon cycling. The transportation characteristics of streams, rivers, lakes, reservoirs, and other inland water bodies, alongside their continuous material exchange and energy transfer, constitute an essential component of the global carbon cycle. The construction of reservoirs has changed the river morphology and hydrological conditions to a certain extent; the storage and diversion effects of reservoirs have changed the degree of river fragmentation, affected the surrounding ecological environment, and had a significant impact on the river carbon cycle process and its impacts; and in turn, it may have altered the nutrient and carbon cycle processes of the water body-land–atmosphere. Influenced by multiple factors such as ecological environmental protection, power generation and diversity of functional services of flood control and water storage, reservoirs embody different functional value orientations in different social development contexts, and new ecosystems have been formed with the construction and development of reservoirs, so focusing on the carbon cycling process of reservoirs can help to improve the management measures of reservoirs and reduce carbon emissions, and play an important role in the effective prediction of future scenarios.

In recent years, hydropower has emerged as a crucial source of clean

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energy globally, aimed at reducing fossil fuel consumption and pollution from fuel combustion. With over 16 million dams worldwide and more than 50,000 large dams exceeding 15 m in height, the upcoming decades will witness the construction of numerous new dams primarily for energy production (Maavara et al., 2017). The spatial distribution of global reservoirs and dams is shown in Fig. 1, with data from the updated Global Reservoirs and Dams Database (GRanD, version 1.3) (GlobalDam Watch.org(Global Dam Watch)), which provides the geographic locations of 7320 dams (Lehner et al., 2011). Data on the administrative boundaries of the world's countries were obtained from the Center for Resource and Environmental Sciences and Data of the Chinese Academy of Sciences (CRESD) https://www.resdc.cn/Default.aspx. Most of the reservoirs and dams are in low and mid-latitudes and coastal areas, as well as in the river basins of large rivers. In terms of latitudinal distribution, dams at high latitudes are relatively few in number and small in size. The construction of reservoirs is more limited because of the influence of the cold climate and the sparse population, which leads to a small demand for water resources. Dams in the low latitude region are more numerous and larger in size, with high precipitation in the region, high demand for water resources, and certain requirements for flood control and water storage. The construction of dams is also influenced by topography, with valley and canyon areas being suitable for water projects due to natural height differences. The number and size of dams are also related to the country's economic and technological level, and development needs. While hydroelectricity is recognized as a technologically mature, environmentally friendly and clean source of energy, there is a growing realization that hydroelectric reservoirs are not carbon neutral (Barros et al., 2011). Herath et al. traced the sources of dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) and measured carbon dioxide (CO_2) fluxes using isotopic techniques, and the results indicated that the dam impoundment altered the carbon cycle and aquatic carbon balance in the Three Gorges Reservoir. This study reflects a global image of the contribution of hydropower reservoirs to the carbon cycle and aquatic carbon balance (Herath et al., 2020). Their water storage activities alter natural hydrological conditions, affecting the nutrient status of downstream rivers. Reservoir construction can change surrounding land use types, influencing sediment transport processes (Wang et al., 2016), and may trigger the degradation of organic matter and the release of greenhouse gases (GHGs) (Li et al., 2018b). The artificial control over the construction and operation of reservoirs allows for adjustable effects on river connectivity, yet the dynamics of aquatic environments and seasonal changes in reservoirs remain unclear (Yi et al., 2022).

Human activities have also severely disrupted the terrestrial water cycle. The most obvious example is the hydrological changes associated with the development of dams and reservoirs (Wang et al., 2011). Unlike natural rivers, reservoirs transform river dynamics from a free-flowing state to a stationary lake state. The direct physical effects include reduced river flow, increased clarity, and nutrient retention. Biogeochemically, reservoirs enhance primary production, reduce the proportion of terrestrial dissolved organic matter (DOM), and increase the efficiency of organic carbon (OC) burial. Global organic carbon burial in lakes and reservoirs is 0.15 (range 0.06–0.25) Pg C per year, of which about 40 % is stored in reservoirs (Mendonça et al., 2017). The impact on light conditions and hydraulic residence time (HRT) and may lead to varied degrees of changes in organic matter transport and transformation (Yi et al., 2022). Reservoir construction promotes DOM deposition and sequestration, enhancing DOM flow from land to rivers, human disturbance may have increased carbon fluxes from land to inland waters by 1.0 Pg / yr (Nai et al., 2023), thereby influencing carbon burial and cycling processes (Wang et al., 2021a). Moreover, transformations and fluctuations of carbon sinks and sources in reservoirs are more pronounced than in natural lakes (Phyoe and Wang, 2019). As a pivotal artificial water ecosystem, the carbon cycling process in reservoirs is a research topic of considerable interest.

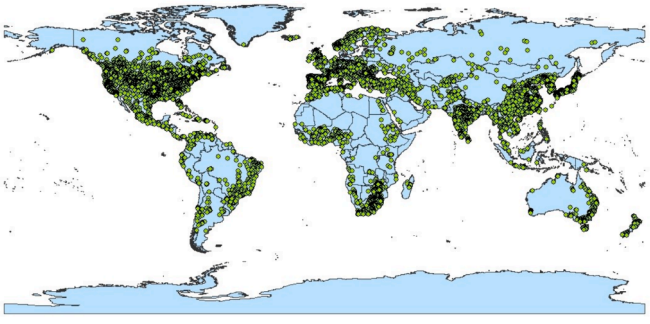


Fig. 1. Global spatial distribution of reservoirs and dams (Data from the updated Global Reservoirs and Dams Database (GRanD, version 1.3), the Center for Resource and Environmental Sciences and Data of the Chinese Academy of Sciences (CRESD)).

The global importance of reservoirs as sources and/or sinks of greenhouse gases remains hotly debated, with the construction of dams and reservoirs altering the processes of carbon fixation, mineralization and organic carbon burial in rivers, impeding the flow of essential nutrients, including carbon, phosphorus, nitrogen and silica, along the river network and leading to enhanced nutrient transformation and elimination (Maavara et al., 2020; Maavara et al., 2017). In this study, we have sorted out the key links, influencing factors and research methods of the carbon cycle in reservoirs, and elaborated on the main participating substances, influencing factors and monitoring methods involved in the core links of carbon input, carbon decomposition and transformation, carbon emission and carbon burial in reservoirs. We propose the possible impacts on the carbon cycle in the future construction and development of reservoirs in a comprehensive and multidimensional way, and provide suggestions for realizing carbon emission reduction and carbon neutrality.

2. Key aspects of the reservoir carbon cycle

2.1. Carbon sources and input pathways

Carbon inputs include terrestrial carbon input, biological carbon sequestration, atmospheric carbon input, human activities carbon input, and carbon input from flora and fauna. Terrestrial carbon can enter reservoirs through upstream river input, runoff erosion, and groundwater input (Zhang et al., 2021). Reservoirs exhibit more dynamic carbon transport and deposition processes than lakes, primarily due to their higher water mobility and human-managed fluctuations in water levels. Some of the organic carbon entering rivers is unstable and may undergo mineralization, oxidation, or sedimentation during migration, leading to potential losses along the way (Bowen et al., 2024). Endogenous organic carbon is typically derived from the photosynthesis of aquatic flora and fauna and some autotrophic microorganisms within rivers (Pace et al., 2004). In contrast, carbon inputs to lakes are typically more influenced by the stability of natural ecosystems and have a relatively greater capacity to sequester carbon (Yang et al., 2008). Gases such as CO_2 and CH_4 in the atmosphere can dissolve into water bodies through rainfall, and organic carbon particles in the atmosphere can also settle onto the water surface through similar mechanisms (Bao et al., 2017). The discharge of industrial wastewater, agricultural water, and domestic sewage generated by human activities is also one of the main sources of exogenous carbon outside the reservoir (Zhang et al., 2021). Leaves and branches falling from vegetation around the reservoir, animal excrement and carcasses, and other biomass directly contribute carbon to the water body (Page et al., 2002).

2.2. Carbon decomposition and transformation processes

The decomposition and transformation of carbon involve aspects

such as biological decomposition, chemical conversion, photosynthesis, respiration, and nutrient cycling, mainly focusing on four substances: dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), particulate organic carbon (POC), and particulate inorganic carbon (PIC) (Dreybrodt, 1988) (Table 1).

Organic carbon primarily participates in microbial metabolic processes through respiration. Under aerobic conditions, microorganisms undergo aerobic respiration, converting organic carbon (DOC and POC) into CO_2 and water (Zhang et al., 2022a)(Fig. 2). In the hypoxic environment of the bottom layer of reservoirs, microbial anaerobic respiration converts electron acceptors such as nitrate and sulfate into CH_4 and CO_2. Methanogens convert organic carbon into methane (Ma et al., 2024). Photosynthesis is another major pathway for the transformation of inorganic and organic carbon in reservoir carbon cycling. Aquatic plants and algae utilize CO_2 to produce organic carbon and energy while releasing oxygen, providing a usable carbon source for aquatic organisms. Inorganic carbon (DIC and PIC) mainly participates in chemical reactions such as carbonate formation and dissolution, directly affecting the water's acid-base balance and long-term carbon storage (Wang et al., 2022c). Chemical transformation processes also include photodegradation (Liu et al., 2023), chemical oxidation, etc., for the decomposition or oxidation of organic carbon. The products of microbial decomposition of organic carbon also include some simple inorganic nutrients such as nitrogen and phosphorus. Remineralization processes convert organic forms of nitrogen and phosphorus into inorganic forms, promoting nutrient cycling. The nutrient environment of reservoirs affects microbial activity and the rate of organic matter decomposition, thereby altering the decomposition and transformation processes of carbon.

Yi et al. used various tracer methods to track changes in the composition and properties of POC and DOC (Yi et al., 2021). The results indicate that the vertical distribution of DOC and POC concentrations and compositions during the stratification period in the reservoir area shows a typical carbon cycle pattern: organic carbon generation and degradation are more active in the surface layer, while in-situ generation is lower in the subsurface layer, but remineralization is significant. The mesopelagic layer has less organic carbon transformation, and the bottom layer has significant microbial transformation and/or sediment dispersion. This is generally consistent with our mapping of carbon flow processes (Fig. 2).

2.3. Reservoir carbon emission and carbon source functions

Reservoirs typically exhibit a strong capacity as carbon sources, especially during their initial construction phase. Due to the inundation of substantial organic matter and water body eutrophication, reservoirs release significant amounts of greenhouse gases (Tremblay et al., 2004). In this paper, we focus on the emissions of CH_4 and CO_2 among the greenhouse gases, as these two gases are closely related to the carbon cycle process. The differences between reservoirs and natural rivers or lakes promote greenhouse gas emissions from the reservoir surface and carbon accumulation in sediments through high sedimentation rates and larger watershed-to-reservoir area ratios (Phyoe and Wang, 2019). Compared to natural lakes, reservoirs usually display more pronounced physical and chemical heterogeneity and shorter water residence times. Additionally, because their inflow and outflow rates are generally higher than those of natural lakes, reservoirs may receive more inputs of external materials. The differences in carbon emissions between reservoirs and lakes are closely related to variations in temperature, dissolved organic matter quality, and bacterial production (Tadonléké et al., 2012). In contrast, rivers primarily function as carbon transport systems, showing relatively weaker overall carbon source capabilities. Therefore, reservoirs are playing an increasingly important role as carbon sources, which is particularly significant in the context of global climate change.

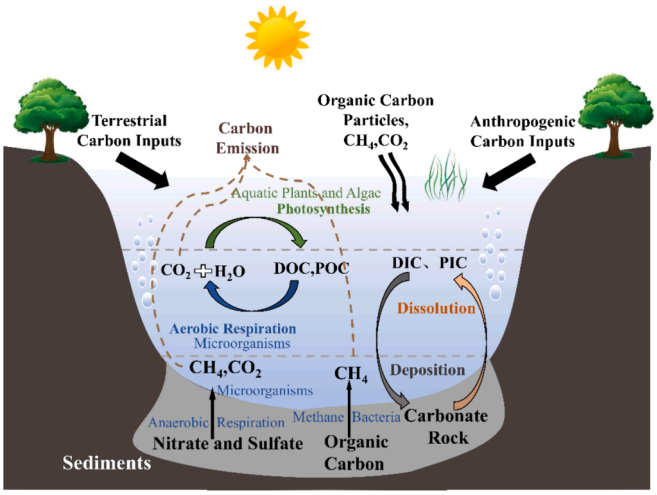


Fig. 2. Schematic diagram of carbon flow in reservoir storage area.

The total global GHG emissions from reservoirs amount approximately 0.38 Pg CO_2 equivalent (CO_2eq. yr^{-1}) per year, constituting 1.0 % of global anthropogenic emissions. Of this, the GHG emissions from hydropower reservoirs represent 68.4 % of the emissions from all types of reservoirs (Li and He, 2022). In hydropower reservoirs, GHGs can be

Table 1
Elaboration of the Decomposition and Transformation Processes of Four Major Substances.

	DOC	DIC	POC	PIC
Components of the Carbon Cycle Involved	Involved in microbial metabolism, mineralization produces greenhouse gases such as CO_2 and CH_4 (Rohlfs et al., 2016).。	Buffering components, involved in the formation of endogenous organic carbon and carbon deposition (Li et al., 2022).	POC primarily exists in suspended particulate matter and sediments, serving as a bridge for the transformation between DOC and DIC.(Ji et al., 2016).	A major component of carbon deposition, enhancing the carbon sink function of reservoirs. (Wang et al., 2022c)
Source	Exogenous sources include soil organic matter and domestic sewage discharge, endogenous sources include the release from phytoplankton, metabolism of zooplankton, and bacterial activity.	Water-gas exchange, chemical weathering processes, photosynthesis and respiration, degradation and mineralization of organic matter(Huang et al., 2023),soil carbon loss(Zhou et al., 2023).	Terrestrial plants, aquatic phytoplankton, microbial biomass (Wang et al., 2020).	Terrigenous sources: physical erosion of carbonate rocks; authigenic sources: in-situ carbonate precipitation.(Li et al., 2021).
Transformation Pathways	Photodegradation, biodegradation, and other physical loss processes (e.g., sedimentation) (Imtiazy et al., 2023).	CO_2 outgassing, carbonate precipitation, transfer to organic matter through photosynthesis (Cui et al., 2017).	Microbial decomposition, promotes the accumulation and emission of CH_4.(Zhang et al., 2022c)	Converted to other small molecules such as DIC and CO_2.
Main Factors	Inputs of carbon from terrestrial sources (Graeber et al., 2012), human activities (Shao et al., 2019) ; seasonal variations (Zhuang et al., 2023).	Photosynthesis and respiration of aquatic organisms, biological Production(Wang et al., 2019b)..	Adsorption capacity of sediments, degree of biological production and degradation(Wu et al., 2020).	Dissolved concentration of CO_2 in water; sedimentation rate

emitted through various pathways, including diffusion, bubbling, plant-mediated emissions, degassing from turbines and spillways, and downstream river discharge. CH_4 is primarily emitted by bubbling and, to a lesser extent, by diffusion, while CO_2 and N_2O emissions mainly occur through diffusion. The diffusive flux at the surface layer and the bubbling flux in the shallow layer are predominantly the result of carbon emissions from biodegradation processes occurring beneath the reservoir's surface (Yang et al., 2024). Moreover, about 99 % of CO_2 and more than 50 % of CH_4 are released into the atmosphere via the diffusive pathway (Huang and Li, 2023). Dam outlets, the primary site for mixing of water flows, result in the degassing of GHGs due to pressure and temperature changes in the water flow after passing through low-level outlets, such as turbines and spillways (de Faria et al., 2015). The degassing flux from turbines is primarily due to the rapid release of dissolved GHGs as a result of the water's rapid depressurization. The carbon emission processes in the river downstream of the dam should also be considered as part of the reservoir carbon cycle. Carbon emissions from downstream rivers are mainly influenced by dissolved CO_2 concentrations in the water flow and water turbulence and are also related to factors such as flow rate and outflow depth. Seasonal variations and dam management practices significantly affect peak carbon values, which may vary by two orders of magnitude (Calamita et al., 2021)(Fig. 3).

There are four main carbon sources that contribute to carbon emissions: flooded biomass, allochthonous dissolved OC, allochthonous particulate OC, and autochthonous carbon. Flooded biomass, consisting mainly of vegetation, humus, and microorganisms, served as the primary source of carbon emissions in the early stages of reservoir construction. Carbon release from sediments is relatively common, with CH_4 produced mainly by anaerobic microorganisms that decompose organic matter in sediments under specific anoxic conditions (Ometto et al., 2013). In karstic areas, the weathering of carbonate-rich sediments releases large amounts of DIC into the water column, forming inorganic carbon that, in turn, releases CO_2 (Wang et al., 2024a). Additionally, the mineralization of organic matter (OM) is a significant source of CO_2 in reservoirs and leads to low phosphorus ion concentrations and a decrease in the pH of the released water, which accelerates the dissolution of carbonate rocks and leads to elevated pCO_2. Thus, the lithology of the reservoir is crucial when estimating CO_2 emissions (Wang et al., 2021b). Primary carbon accumulated from primary production within the reservoir is a significant source of CO_2 emissions. Comparison of the relative contributions of internal (ecosystem metabolism) and external (tributaries and groundwater) sources to reservoir carbon emissions shows that internal production consistently sustains most of the measured CO_2 fluxes, with groundwater and tributaries making a small but non-negligible contribution (Barbosa et al., 2023).

The peak of carbon emissions from reservoirs appeared in the 1980 s, and with the increase in reservoir age, CO_2 emissions have shown a decreasing trend. Some studies and analyses indicate that the carbon emission pathway from reservoirs is shifting from CO_2 diffusion flux to CH_4 bubbling and degassing flux (Soued et al., 2022). This decrease in CO_2 emissions may be related to factors such as changes in land cover and land use, with reductions in agricultural land leading to decreased soil erosion and terrestrial carbon inputs. For example, the return of farmland to forests may reduce dissolved CO_2 concentrations and thus carbon fluxes (Ran et al., 2021). Compared to CO_2, CH_4 has a more pronounced effect on climate change (Beaulieu et al., 2019), with the global warming potential (GWP) of reservoirs primarily due to CH_4 contributions, which are generally lowest in winter and spring and highest in summer and fall (Samiotis et al., 2018).

The development of terraced hydropower leads to the interconnection of multi-terrace river reservoirs, producing superimposed and cumulative effects on ecosystems at both temporal and spatial scales (Maavara et al., 2020). Numerous studies have shown that constructing large reservoirs in river upper reaches significantly alters river hydrodynamics and sediment nutrient transport, an important cause of spatial and temporal GHG partitioning upstream and downstream of rivers. It is generally accepted that dam construction accumulates organic matter and increases water body eutrophication, thereby increasing GHG emissions from rivers. However, by expanding the study scope from individual reservoirs to the entire river basin, such as the 4300-kilometer section of the Yangtze River, some studies have shown that the construction of the Ming Three Gorges Dam significantly reduced GHG emissions (Ni et al., 2022). The regulation of global physical, chemical, and biological equilibrium by large dams under terraced hydropower development raises concerns about the mechanisms of carbon emissions.

2.4. Reservoir carbon sequestration and sink function

Regarding carbon sink functions, reservoirs can effectively sequester organic carbon in their early stages, particularly under nutrient-rich conditions that promote plant growth. Reservoirs function as carbon sinks due to their unique habitat conditions and strong productivity (Knoll et al., 2013). Although reservoirs and lakes cover only about 1 per cent of the Earth's surface, they accumulate one to four times more OC than the oceans, owing to high sedimentation rates and burial efficiencies. During the early stage of reservoir construction, the impoundment process floods the original vegetation in the reservoir area, creating in situ burial of organic matter. The buried primary PIC and OC in the sediments do not participate in the short-term carbon cycle process but enter the long-term geological cycle. This attenuates the impact of carbon release from the sediments, and this portion of organic matter can be directly regarded as the carbon sink of the formed reservoir. However, over time, the carbon sink capacity of reservoirs may gradually decline, closely linked to the evolution of the ecosystem. In comparison, wetlands generally provide a more stable carbon sink function, maintaining high carbon storage capacity over longer periods. Additionally, while natural lakes also possess some carbon sink functionality, their potential and stability are typically lower than those of reservoirs (Jia et al., 2022). Thus, under specific conditions, reservoirs can serve as effective carbon sinks, but their long-term efficacy depends on ecological management and hydrological conditions.

Organic carbon deposited in reservoir sediments mainly originates from land-source organic matter and endogenous organic matter formed by photosynthesis within the reservoir. Land-source organic matter, primarily consisting of soil organic matter, enters the reservoir area under the scouring effect of runoff. It is generally difficult to degrade because land-source organic matter is rich in lignin, aliphatic polymers, and humus, which are resistant to anoxic decomposition. Land-based organic matter essentially represents an accumulation from elsewhere and therefore cannot be considered an effective carbon sink. The burial of terrestrial carbon and oxygen compounds in reservoirs constitutes a new carbon sink only if the burial is more efficient than in other depositional environments. Inland waters are more efficient at burying carbon than oceans because the high sedimentation rates in reservoirs

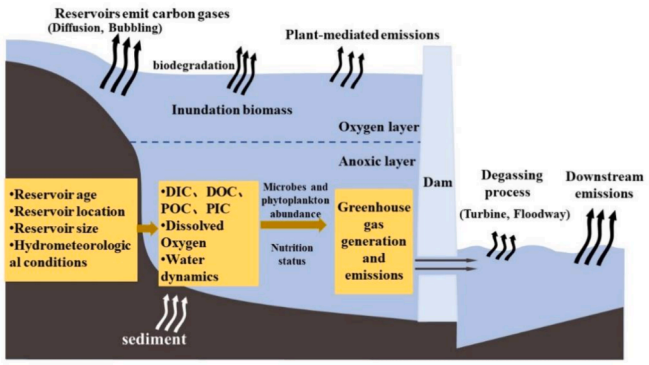


Fig. 3. Schematic diagram of carbon emission processes in reservoirs.

result in the rapid burial of deposited organic carbon on the bottom, thus preventing it from oxidizing. More of the organic carbon that settles escapes mineralization and remains in the sediment. The effectiveness of dams in trapping sediments, combined with the often low dissolved oxygen in bottom waters, typically results in reservoirs accumulating organic carbon at higher rates than natural lakes. Terrestrial sources of organic carbon may be buried more efficiently in reservoirs than in other depositional environments (Mendonça et al., 2017). Several studies have shown that terrestrial organic carbon is more likely to be buried with higher efficiency in anoxic environments. Reservoirs are susceptible to anoxia due to slowed water flow and increased primary production, reinforcing the view that reservoirs are an effective anthropogenic carbon sink (Isidorova et al., 2019).

And the flow rate decreases, the photosynthesis of aquatic plants gradually increases, absorbing DIC in the water to form endogenous organic matter, such as POC and DOC (Wang et al., 2019a). Since photosynthesis fixes atmospheric CO_2 to form sediments, it is evident that the carbon sink function in sediments can offset the carbon source function of carbon emissions by fixing CO_2. This underscores the importance of considering the full lifecycle of the carbon cycle. Additionally, some power generation reservoirs do not consume fossil fuels during operation, and their contribution to power generation should also be factored into the calculation of carbon sinks.

Globally, human activities have increased river sediment transport through enhanced soil erosion. However, the sediment reaching the coast is significantly trapped in inland water bodies due to anthropogenic dam construction (Zheng et al., 2020). It is reasonable to infer that a significant amount of POC has been sequestered in the catchment. High eutrophication is likely to result in increased soil erosion and greater terrestrial sources of OC entering reservoir waters, particularly during agricultural runoff. Smaller reservoirs with high eutrophication exhibit higher sediment OC accumulation, whereas larger reservoirs tend to show the opposite effect (Phyoe et al., 2020).

Furthermore, reservoirs increase the overall conversion of organic carbon to CH_4 in river systems, as damming creates environments poor in oxygen at the bottom. Thus, the role of reservoirs in the global carbon balance is significant, given their high carbon burial rates and GHG emissions. The classification of reservoirs as carbon sinks and sources can vary over time and depends on factors such as age, latitude, primary production, and morphometry (Phyoe and Wang, 2019).

3. Elements affecting carbon cycle processes in reservoirs

3.1. Reservoir characteristics

The influence of reservoir characteristics on carbon emission is reflected in factors such as the age of the reservoir, its location and latitude, depth, and capacity. It has been shown that newer reservoirs emit more carbon than older ones, likely due to the rich inundated biomass in younger reservoirs. The areal emissions of both CO_2 and CH_4 from hydroelectric reservoirs were significantly negatively correlated to reservoir latitude. Tropical reservoirs exhibit higher carbon intensity compared to those in temperate and tundra regions, as tropical rivers may have higher water temperatures and richer carbon loads from terrestrial sources. Reservoirs with higher water temperatures produce greater carbon emissions (Hou et al., 2013). In addition, higher flooded biomass in tropical regions leads to higher emissions, and may increase the ratio of GHGs that are released (Barros et al., 2011). Greenhouse gas emissions per unit area tend to be higher in small hydropower reservoirs than in large reservoirs. This is mainly small reservoirs are widely used for agricultural purposes, are subject to soil disturbance, fertilizer inputs and anthropogenic disturbances, and are more prone to increased sediment and nutrient runoff into the reservoir due to the small areas of inundation and the low buffering capacity of the shallow. The size of the water body is negatively correlated with the rate of sediment organic carbon accumulation, so that exogenous inputs of degradable organic matter become the main source of carbon emissions in larger reservoirs when the original accumulated carbon sources are completely degraded, and the corresponding exogenous inputs per unit of reservoir capacity in large reservoirs are not as large as in small reservoirs (Wang et al., 2024b). Nutrient conditions and water depth are also significant factors influencing carbon emissions. Highly eutrophic reservoirs exhibit high carbon intensity, and shallow reservoirs have a greater carbon intensity than deeper ones (Li and He, 2022). Exogenous inputs are an important factor in the alteration of nutrient composition in reservoirs, and the distance between the location of dam construction and the location of terrestrial inputs affects the degree of carbon decomposition during migration (Basso et al., 2020). Future hydropower development plans should aim to minimize overall environmental impacts and reduce carbon dioxide emissions through careful selection of reservoir locations, designs, and operations (Wang et al., 2024a).

Stratification and mixing result from changes in water temperature and density in natural water bodies, influenced by seasonal meteorological conditions, and tend to occur in lakes and reservoirs. Reservoirs under thermal stratification typically evolve into three layers: epilimnion, thermocline, and hypolimnion (Yang et al., 2019). Generally, stable thermal stratification occurs during the summer months, limiting the penetration of light and affecting CO_2 uptake by photosynthesis (Pu et al., 2020).

Differences in water density during the thermal stratification period prevent material exchange between the upper and lower water bodies. The bottom water body cannot be replenished with oxygen, resulting in anoxic or hypoxic conditions, which lead to the release of nutrients and organic matter and morphological transformation at the water–sediment interface. Furthermore, under suitable light, temperature, and nutrient conditions, phytoplankton colonize the less mobile surface water and produce large amounts of endogenous DOM during metabolism (Wei et al., 2022). The mixing process, on the other hand, alters the overall water quality of the reservoir area and stimulates the emission of CO_2 from the remineralization of organic matter in the bottom water column. Another study found that CO_2 emissions were much higher during mixing than during thermal stratification (especially during the transition from stratification to mixing) due to the release of dissolved CO_2 (CO_2aq) and oligomeric anions (Li et al., 2022).

3.2. Hydrological and hydrodynamic conditions

The operation of reservoirs under specific scheduling, such as for flood control and power generation, significantly affects their hydrodynamic conditions, including water level, flow, and surface turbulence. Compared to natural rivers, the construction of reservoirs transforms rivers from hydrologically connected systems into lakes in a still-water state, exhibiting lake-like characteristics such as weakened currents, increased water transparency, and more favorable conditions for the growth of aquatic plants. Some studies have indicated that reservoirs with short hydraulic residence times may exhibit higher carbon content (Delwiche et al., 2022). The longer the water body's residence time and the slower the flow rate, the higher the carbon emissions from the reservoir (Zhao et al., 2017).

The carbon cycle processes in reservoirs are also related to the capacity for treating transformed exogenous carbon and the flow of endogenous carbon in the water column, all of which are directly influenced by hydrological and hydrodynamic conditions (Yang et al., 2023). Driven by both hydrodynamics and water management, the water level in reservoirs is constantly changing, and flooded land is periodically exposed to the water surface in a special area known as the fallout zone. When the effects of the waning zone are considered, global CO_2 emissions from reservoirs increase by 53 %, with reservoirs preferred as a source of carbon (Keller et al., 2021). Changes in water level directly alter soil pH, the anaerobic–aerobic environment, and microbial activity, which, in turn, affects organic matter production, organic carbon accumulation, and conversion (Ren et al., 2022; Zhao

et al., 2020). There is a positive correlation between hydraulic load and sediment microbial carbon sequestration rate. Meanwhile, the stability of water flow and HRT are crucial factors for plankton growth and reproduction (Travaini-Lima et al., 2016). Water flow and velocity are determinants of reservoir depth and HRT, significantly related to the formation of thermal stratification in reservoirs (Yang et al., 2020). Hydraulic conditions serve as important physicochemical parameters for studying the reservoir carbon cycle, representing objective conditions that regulate and govern the distribution and trophic state of biological communities (Wang et al., 2022a).

3.3. Physicochemical and nutritional conditions

Temperature directly influences the carbon cycle by affecting the respiration and primary production of aquatic organisms. Different temperature dependencies of respiration and photosynthesis may result in decreased carbon fixation and increased carbon emissions (Kosten et al., 2010). Specifically, higher the temperatures are associated with greater carbon emissions (Kosten et al., 2010; Xiao et al., 2022). Conversely, the processes of respiration and organic decomposition are stronger, and partial pressure of CO_2 (pCO_2) levels in reservoir water bodies are higher when the water temperature is lower (Li et al., 2018a). Furthermore, CO_2 participates in a greater number of biological metabolic processes in warmer environments, and the carbon fluxes at the water–air interface of reservoirs exhibit a positive correlation with temperature (Yan et al., 2018).

Additionally, the pH of the river serves as an indicator of the relative proportions of bicarbonate (HCO_3^-), carbonic acid (H_2CO_3), and CO_2 components, thereby reflecting the carbon buffering capacity of the reservoir water (Wang et al., 2015). Some studies have highlighted the important role of calcite precipitation as a carbon source to the atmosphere, which acts as an alkalinity sink regulating the pH of the upper water column of the reservoir and as an important driver of CO_2 fluxes. Alkalinity can reflect the metabolic status of inorganic carbon and sediments to some extent (Khan et al., 2020; Khan et al., 2022).

In general, reservoirs with high levels of eutrophication exhibit high carbon intensity. The nutrient status of a reservoir has a complex and variable effect on its carbon cycle, with nutrients formed mainly by the input of exogenous organic carbon and the decomposition and transformation of grasses and phytoplankton. As the reservoir ecosystem matures and nutrient levels increase, the CO_2 transported to the atmosphere will decrease, and atmospheric carbon will be absorbed, transformed, and transported downstream, eventually flowing into the sea. This process may lead to a shift from a reservoir being a carbon source to a carbon sink (Colas et al., 2021; Pacheco et al., 2014). Eutrophication affects the cycle of DOM by altering its chemical composition, structure, molecular formula, and biogeochemical processes. In some eutrophic reservoirs, the transport and transformation of organic matter at the land–water-air interface may be greatly enhanced, accelerating the input and release of DOM and leading to significant impacts on the carbon cycle and balance. The correlation between carbon emission capacity and nutrient status is related to temporal and spatial scales and is influenced by physicochemical indicators such as temperature and dissolved oxygen.

3.4. Human activities

The assessment of anthropogenic changes in the river water environment is a critical factor in the carbon cycle mechanism of reservoirs. The growing population and urban construction involve land drainage, dam construction, inter-regional water transfers, and river diversions, and land use changes, which affect the composition of water body materials as well as flow processes (She et al., 2022). Terrestrial carbon inputs in the form of organic matter promote accelerated carbon emissions from in-situ carbon decomposition in reservoirs, land use types change, watershed nutrients increase, and reservoirs are subjected to more disturbances from terrestrial sources as well as inputs from other watersheds.

Nutrient inputs from agricultural production and urban expansion can lead to increased eutrophication of reservoirs, with the accelerated application of synthetic fertilizers and centralization of municipal wastewater treatment thus increasing pollution from nutrients (N, P). The increase in human production activities then leads to greater photodegradation and biodegradation of the complex dissolved organic matter fraction in the water column, potentially leading to an acceleration of the global carbon cycle (Liu et al., 2022). Sites with large inputs of exogenous materials from sewage discharge and upstream runoff tend to be hotspots for CO_2 emissions from reservoirs. Large inputs of exogenous carbon may lead to spatial heterogeneity of CO_2 emissions from coastal reservoirs and alter the biogeochemical cycle of CO_2 (Zhang et al., 2021).The average and total emissions of CO_2 and CH_4 are two and three times higher, respectively, in sediments from agricultural activities (Pinheiro et al., 2022).

Dams and reservoirs reduce river sediment fluxes, which are trapped behind dams and in reservoirs, and particulate organic carbon fluxes are reduced (Zhang et al., 2009). To reduce sedimentation, governments have adopted anthropogenic management measures. The China Yellow River Conservancy Commission (CHRCC) has implemented the Water-Sediment Regulation Scheme (WSRS) to alleviate downstream siltation, upliftment of the riverbed, enhance flood control, and maintain reservoir capacity. However, this affects the hydrological processes and sediment transport patterns of the river, changing the relationship between water and sand fluxes and other environmental factors, and inevitably affecting the state of nutrients in the reservoir and its downstream reaches (Zhang et al., 2013; Zhao et al., 2022). Furthermore, a study suggests that human intervention has significantly altered carbon transport within the inland water continuum, involving dramatic changes in carbon transport from rivers to coastal oceans (Lu et al., 2022).

4. Research methods of reservoir carbon cycle

4.1. Field sampling and analysis

Field sampling and analysis is one of the primary research methods for studying the carbon cycle in reservoirs, playing a crucial role in revealing the mechanisms and influencing factors of reservoir carbon cycling. The location of field sampling must consider both the vertical and horizontal distribution of the water body to ensure the representativeness of the samples. Sampling sites typically include the reservoir's inlet and outlet, and also consider areas with different water depths and flow rates to comprehensively understand the distribution and transformation of carbon within the reservoir. The following are the main methods of field sampling and analysis in reservoir carbon cycle research.

Research methods for studying carbon emissions in reservoirs primarily include the floating chamber method, eddy covariance method, sediment respiration dynamics assessment, and modeling approaches. The floating chamber method involves measuring GHG concentration changes via gas chromatography. The eddy covariance method is used to measure vertical wind speed and GHG concentration in turbulent atmospheric boundary layers (Kumar et al., 2023). Sediment respiration dynamics assessment evaluates the contributions of sediments to carbon emissions through in-situ measurements and the virtual incubator method (Gao et al., 2024; Yang et al., 2022). Modeling approaches, such as the GRAT and G-res tools, are utilized to predict long-term GHG emissions (Kumar et al., 2023).

The research methods for carbon burial in reservoirs include underwater seismology, sediment core analysis (Ran et al., 2022), and the use of high-precision shallow bottom profilers (Wang et al., 2019a). Underwater seismology is used to estimate sediment thickness and distribution, providing detailed data on sediment characteristics. Sediment

Table 2
Models related to estimation and monitoring of carbon cycle processes in reservoirs and their applications.

Model Name	Categorization	Typical model	Application	Applicable area
Empirical Model	Statistical Regression Model	Single linear regression model (L), multiple linear regression model (ML), and generalized additive model (GA), etc.	Assessing carbon transport and deposition in large-scale reservoir systems.	Globe
	Machine Learning Model	Random Forest Model	Estimating CO_2 emissions using a data-driven stacked random forest algorithm(Zhang et al., 2021).	Globe
Process-driven Model	Aquatic Biogeochemical Model	WET Model	WET is a fully modular aquatic ecosystem model developed under the Framework Syntax for Aquatic Biogeochemical Modeling (FABM-PClake) based on the FABM-PClake model that can be coupled to multiple physical models in zero to three dimensions.	Danish
	Biogeochemical Model	NICE-BGC	The coupling of hydrological water features and biogeochemistry is integrated in the carbon cycle estimation (Nakayama, 2022).	Globe
	Integrated Ecosystem Model	AQUATOX	A modeling framework for ecological risk assessment to study the potential accumulation and biomagnification of organic pollution(Scholz-Starke et al., 2013).	Europe and China
Water Quality Model	1D Model	DYRESM	Modeling the physical processes of reservoir stratification, including temperature and density changes(Etemad-Shahidi et al., 2010).	North America and Europe
	2D Model	CE-QUAL-W2	Modeling two-dimensional water quality and biogeochemical processes in reservoirs(Delwiche et al., 2022).	Globe
	3D model	Delft3D	Used for three-dimensional flow and water quality modeling, it allows for dynamic monitoring of carbon in the water column(Brown et al., 2014).	Globe
Integrated Model	Integrated terrestrial-hydrological Basin Model	INCA-C Model	A carbon integrated watershed process model that integrates terrestrial components, hydrological channels and climate change modules, focusing on the dynamics of organic carbon in the watershed between terrestrial systems and surface water environments (Oni et al., 2012; Sharma et al., 2023)	Globe
	Global Nutrient Cycle Model	Global-NEWS	Modeling and predicting nutrient export from watersheds and their impacts on water body ecosystems.	Globe
Carbon Emission Model	G-res Model		Calculation of net biogenic GHG emissions from hydropower reservoirs (Levasseur et al., 2021).	Globe
	ResME (reservoir Methane Emissions)		The model predicts CH_4 release through boiling and diffusion, plant emissions, and downstream emissions by estimating carbon inputs and methane production.	Globe

core analysis involves directly measuring the carbon content in core samples to calculate total organic carbon (TOC) burial rates and assess long-term carbon sequestration dynamics. High-precision shallow bottom profilers are used to observe sediment deposition, combining acoustic signals with sediment core verification to quantify sediment accumulation and organic carbon burial (Wang et al., 2019a).

The methods for studying carbon flux in reservoirs encompass sampling and analysis from various perspectives, including water samples, plankton, and microorganisms. Water sample analysis involves techniques such as high-temperature catalytic oxidation, liquid chromatography, and UV–visible spectrophotometry to measure carbon concentrations. In the analysis of plankton, commonly used methods to determine biomass and carbon content include biovolume conversion, drying, and weighing (Silva et al., 2014). These methods are used to evaluate the role of plankton in carbon fixation. For microbial analysis, DNA extraction and PCR techniques can be used to examine the microbial community structure. Additionally, respirometry chambers and gas analyzers are employed to measure microbial carbon metabolic activity, such as the production rates of CO_2 and methane CH_4. Alternatively, the Water Quality Index (WQI) and Shannon-Wiener Diversity Index can be used for water quality evaluation (Nguyen and Huynh, 2023).

4.2. Numerical simulation and modeling

Reservoir carbon cycle models are key tools for understanding and predicting the dynamics of carbon in reservoirs, and are used to simulate and analyze the processes of carbon production, transformation, storage, and loss. The main types of models include empirical models, process models, water quality models, carbon emission models, and integrated models (Tables 2, 3). Empirical models provide rapid estimates of carbon fluxes through statistical methods. Process models describe in detail the physical, chemical and biological processes of the carbon cycle and reveal the mechanisms of carbon production and consumption. The water quality model focuses on the concentration and distribution of carbon in the water body, and simulates the carbon transport process by combining with the hydrological and hydrodynamic conditions. The carbon emission model focuses on accounting for and projecting methane and carbon dioxide emissions. The integrated model combines the modules of the previous models to comprehensively predict the carbon cycle process.

Global-scale models usually aim at estimating global reservoir carbon transport fluxes. Nakayama, T. and Pelletier et al. used the Coupled Ecohydrology and Biogeochemical Cycling Model (NICE-BGC) to estimate the impacts of 82 major reservoirs on hydrological and biogeochemical cycling globally (Nakayama and Pelletier, 2018). The results showed horizontal carbon transport (DOC flux = -66.4 TgC/yr, POC flux = -11.8 TgC/yr, DIC flux = -43.5 TgC/yr) and vertical fluxes (CO2 escape in the presence of reservoirs = 76.6 TgC/ yr, carbon burial = 45.0 TgC/yr). Weissenberger et al. explored the impact of the continental water cycle on climate using a semi-empirical carbon cycle model, and showed that the construction of reservoirs leads to an increase in hydraulic residence time and thus an increase in atmospheric carbon fluxes (Weissenberger et al., 2010). In addition, there was a study on the effect of precipitation on the carbon cycle process in the reservoir, and the results showed that in the Three Gorges Reservoir rainfall less than 10 mm d^{-1} promoted the carbon sink effect in the reservoir; when rainfall exceeded 24 mm d^{-1}, surface runoff began to disrupt the carbon balance (Li et al., 2024).

In the future, with advances in remote sensing technology and sensor networks, access to high-resolution and real-time data becomes more feasible, providing rich data support for models. Scholars have conducted research on model improvement and development to quantify carbon fluxes accurately, enhance model applicability in specific

regions, and improve simulation accuracy. Multiple neural networks are often used to construct machine learning models, such as the convolutional neural network and long-short-term memory neural network hybrid model (CNN-LSTM) (Qin et al., 2022), which employs CNN and LSTM neural networks for data feature extraction of reservoir water quality parameters, respectively, and Deep Neural Network (DNN) for CO_2 flux regression to achieve prediction of carbon fluxes. Ouyang et al. used Random Forest (RF) and Support Vector Machine (SVM) machine learning algorithms as well as Convolutional Neural Network (CNN) and Long Short-Term Memory Neural Network (LSTM) deep learning algorithms to predict CO_2 and CH_4 diffusion fluxes at the water–air interface of a reservoir through environmental factors (Ouyang et al., 2023). The results showed that the deep learning algorithms all had better prediction results, and the RF prediction among the classical machine learning algorithms was significantly better than the SVM. The LSTM and RF produced the optimal prediction accuracies for the CO_2 diffusion flux and CH_4 diffusion flux, respectively. Simulation and monitoring data of the reservoir carbon cycle are also built using coupled models with biogeochemical models, such as the 3D hydrodynamic-biogeochemical-carbon cycle coupled model, Flooded Forest Denitrification Decomposition model (FF-DNDC) (Kim et al., 2016), etc. Carbon estimation models for regions, specific watersheds, and individual units also include dynamic mass balance model, etc. The application of artificial intelligence and machine learning technologies will significantly improve the predictive accuracy of models and their ability to handle complex data.

4.3. Remote sensing techniques

Satellite observations provide relatively high-frequency, continuous, large-scale, and long-term data compared to, for example, in situ surveys and studies. Remote sensing technology enables the exploration of targets from a distance and identifies changes in their morphology, concentration, or content, etc., with the help of electromagnetic radiation and its reflection. In alpine regions, characterized by complex terrain and harsh climatic conditions where in situ monitoring of the river water environment is challenging, remote sensing technology based on hyperspectral satellite data holds significant development potential (Wang et al., 2022b). At high latitudes, the use of remote sensing to detect CH_4 emissions from water bodies also presents greater potential (Engram et al., 2020).

Chromatic dissolved organic matter (CDOM) is an important organic matter in aquatic ecosystems and the main component of DOM in natural water bodies. It is closely linked to carbon, water, and light, serving as an effective tool for capturing the DOC footprint, from which the total carbon content of the water body can be further inferred. CDOM is also recognized as a direct contributor to the carbon cycle budget that produces CO_2. Remote sensing techniques for CDOM have significant applications and importance in carbon cycle studies. Since CDOM may originate from anthropogenic releases, it also served as a reliable indicator for monitoring water quality. On a large scale, based on the optical properties of CDOM, the inversion of the absorption coefficient of CDOM using remote sensing images is an effective method to estimate the concentration and distribution of CDOM (Zhu, 2012).

Inversion algorithms are utilized to infer carbon component concentrations, carbon flux values, etc., and to visualize long-term data monitoring fluctuations in the form of graphs (Kutser, 2012). This approach offers the advantages of comprehensive coverage, large scale, and multi-temporal analysis. The methods of remote sensing inversion can be broadly classified into three categories: model analysis, empirical method, and semi-empirical analysis (Li et al., 2020). Remote sensing techniques are sometimes combined with optical algorithms to enhance inversion accuracy and identify component content through optical effects (Xu et al., 2021). Optical remote sensing, primarily used to monitor inland water bodies using its color information data, is also known as water color remote sensing. It has advanced in water body distribution extraction, atmospheric correction of remote sensing data of water bodies, and nutrient status evaluation.

However, daily and seasonal variations in reservoir water bodies are significant, spatial variability is high, and the resolution of satellite data acquired is often low. These factors make it somewhat challenging to use satellite monitoring to estimate the distribution of DOC in inland water bodies and the emissions of CO_2, CO, and CH_4, among others.

Table 3
Comparison of the application and advantages and disadvantages of the four models.

Model	Application	Advantages	Disadvantages
Empirical Model	Large-scale reservoir systems	Rapid estimates	Less accurate
Process-driven Model	Carbon production and consumption	Detailed process description	Complex
Water Quality Model	Carbon transport and distribution	Focus on water quality	Limited to water quality
Integrated Model	Comprehensive prediction of carbon cycle processes	Combines multiple modules	Requires extensive data
Carbon Emission Model	Methane and carbon dioxide emissions	Focus on GHG emissions	Failure to consider its impact mechanisms

4.4. Carbon isotope determination method

In recent decades, the GHG effect, exacerbated by climate change, has drawn increasing attention, positioning the river carbon cycle as a core research area due to its close relationship with global carbon reduction. However, the sources of carbon and its transport processes are influenced by multiple factors and links, complicating the accurate assessment of carbon's origins and destinations.

Stable isotope determination technology, known for its high precision in tracing, traceability, and indication characteristics, serves as an important tool for revealing the biogeochemical processes of carbon, nitrogen, and other elements in reservoir ecosystems. Carbon stable isotopes (δ13C) are minimally affected by energy flow, material circulation, and spatial and temporal changes, and are often used as indicator substances. These indicators help identify the source of dissolved carbon in water bodies, assess the degree of eutrophication, and analyze disturbances in reservoir water bodies by human activities, playing a crucial role in exploring carbon cycle pathways in reservoirs. Research has shown that the δ13C technique can effectively reveal the mechanism of PIC production by phytoplankton in hydropower reservoirs, its influencing mechanisms, and the processes of PIC production, migration, and transformation (Li et al., 2021). The δ13C technique also facilitates the study of POC processes and associated carbon cycling within the reservoir area through POC/chl-a ratios, combined applied carbon isotope ratios (δ13CPOC and δ13CDIC), and water CO_2 content (Bueno et al., 2020).

Natural radioisotopes of carbon (Δ14C) are powerful tracing tools for studying biogeochemical carbon cycle processes and carbon exchange among carbon pools. Δ14C applications in reservoir ecosystems include tracing organic carbon sources, determining the contributions of atmospheric dispersion, fossil fuels, etc., to reservoir carbon mass (Blattmann et al., 2018), analyzing dynamic distribution differences in the vertical direction of water bodies (Joung et al., 2019), and further understanding aquatic ecosystem functions and global carbon cycle mechanisms. Studies on Δ14C in the riverine carbon cycle are less frequent compared to δ13C, primarily because radiocarbon collection and processing are difficult and expensive. Fortunately, the development of accelerator mass spectrometry (AMS) has made Δ14C measurements more accessible (Chen et al., 2021).

Carbon isotopes can delineate carbon spatial trends across

space–time and material forms. Dual-isotope (δ13C, Δ14C) measurements are commonly employed to systematically investigate carbon sources and carbon cycling processes (Shan et al., 2021). The combined and complementary use of both isotopes limits the interplay of sources and cycling of organic and inorganic carbon in the surface environment and eliminates errors in results from individual metrics, representing a promising approach. In one study, carbon isotope content provided insights into the source of DOC through δ13C and the age of DOC through Δ14C, facilitating the exploration of hidden DOC movement in the ocean (National Academy of, 2014). The construction of reservoirs introduces discontinuities in river systems, and isotope measurement methods can track changes in carbon concentrations in three longitudinal zones—riverine, intermediate, and lacustrine—and in the vertical carbon distribution of the water column (surface and deep layers) (Wang et al., 2022c). Additionally, the impact of damming on carbon flow can be analyzed to explore the role of different forms of carbon mass in regulating and balancing the carbon cycle processes. Continued reservoir construction underscores the significant influence of reservoirs on the carbon cycle as sites of carbon transformation and storage. Measurements of surface and deep particle deposition, organic carbon dissolution, and inorganic carbon release can monitor the dynamics of potential carbon sources' input and explore the transport mechanism of dissolved carbon in the reservoir.

5. Conclusions and future perspectives

5.1. Conclusion

(1) The study of carbon cycle in reservoirs provides an in-depth discussion of its key links and influencing factors, which provides an important basis for the management of reservoir ecosystems.
(2) Reservoir carbon cycling mechanisms are elucidated, highlighting their crucial role in the global carbon cycle and providing a foundation for future research on reservoir management and carbon reduction to promote ecosystem health.
(3) Further exploring the research methods and techniques of carbon cycle in reservoirs will help improve the monitoring and management of the carbon cycle process and realize the sustainable use of reservoir resources.

5.2. Foresight

(1) In-depth exploration of the multi-factor influence mechanism: fully explore the interactions between the influencing factors and their combined effects on the carbon cycle. Provide a more comprehensive view of carbon cycle dynamics.
(2) Long-term monitoring of the reservoir carbon source/sink function: Establish a comprehensive long-term monitoring network for the reservoir carbon cycle, including regular monitoring of indicators such as carbon concentration in the water body, sedimentation rate of bottom sediment, and greenhouse gas emission fluxes, in order to obtain more comprehensive and long-term data. Reveal the position of reservoir carbon source/sink role in the carbon cycle.
(3) Ecosystem service value: Based on the in-depth study of the carbon cycle in reservoirs, comprehensively assess the carbon storage and emission of reservoir ecosystems as well as their contribution to climate regulation and ecological balance. An ecosystem service value assessment model is established to quantify the contribution of reservoir ecosystems to the society and economy, and to provide scientific basis for ecological compensation, eco-compensation and ecological compensation.
(4) Establishment a Life Cycle Assessment (LCA) of Carbon Footprints: It is recommended to strengthen multi-scale and multi-region joint data sharing, establish a unified carbon income and expenditure evaluation system, and provide scientific basis for reservoir management and policy formulation.
(5) Research on model integration and prediction: Combine the existing reservoir carbon cycle models, carry out research on model integration, and improve the accuracy and reliability of simulating the reservoir carbon cycle process.

CRediT authorship contribution statement

Chunhui Li: Methodology, Conceptualization. **Yihan Wang:** Writing – original draft, Software. **Yujun Yi:** Writing – original draft, Funding acquisition. **Xuan Wang:** Investigation, Data curation. **Celso Augusto Guimarães Santos:** Writing – review & editing. **Qiang Liu:** Writing – original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Further reading

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