



## Article

# Flux of organic carbon burial and carbon emission from a large reservoir: implications for the cleanliness assessment of hydropower

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## ABSTRACT

Accurately quantifying the budget of carbon sources and sinks in hydropower reservoirs is important for evaluating the cleanliness of hydroelectricity. However, current research on carbon emissions from reservoirs has rarely taken into account the organic carbon (OC) buried in sediment. Only greenhouse gas emissions from the water-air interface at reservoirs have been examined, which would result in an over-estimation of the greenhouse effect of reservoirs. In November 2017, this study investigated the distribution of sediment in the Hongfeng Reservoir (HFR) in southwest China, a typical large hydropower reservoir, by using an underwater seismology monitoring system. We estimated the flux of OC into sediment using the results of a sediment survey and a dataset compiled from references. Our results show that, the HFR retained 200,715 t of OC in the sediment since its impounding after dam construction to the sampling year of 2017, when the average burial flux was  $3,521 \text{ t-C a}^{-1}$  ( $10^6 \text{ g C a}^{-1}$ ) and the modern burial flux was  $5,449 \text{ t-C a}^{-1}$ . After excluding the exogenous OC, the modern valid carbon sink of the sediment was 4,632 t per year. Under the current state of the reservoir, taking the modern valid carbon sink value, the carbon emissions from the reservoir's surface, and the discharge water from the dam into consideration, the net carbon sink of the HFR is found to be  $1,098.9 \text{ t-C a}^{-1}$ . If the hydroelectricity generated by the reservoir is converted to a carbon sink, then the total net carbon sink becomes  $12,972.9 \text{ t-C a}^{-1}$ . This work argues that both reservoir sediment and hydroelectricity are important carbon sinks and both should be included in assessments of the greenhouse effects of reservoirs.

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## 1. Introduction

Since the beginning of the twenty-first century, the potential for greenhouse gas (GHG) emissions from artificial reservoirs and their impact on climate change has increasingly gained the interest of scientists and some international organizations. Controversy surrounding this issue has been ongoing for more than a decade. During this period, a series of articles regarding the release of large amounts of GHGs from artificial reservoirs have been widely published (Refs. [1–4]), and the cleanliness of hydropower production has been strongly questioned. Some groups, such as the International Rivers Network (IRN) and Save the Mekong Coalition (SMC) disagree with the necessity of water energy development. However, this belief has not been widely recognized and on the contrary, some research teams have suggested that the carbon emissions from hydropower reservoirs are greatly exaggerated.

Some reservoirs are believed to be carbon sinks ([www.synapse-energy.com](http://www.synapse-energy.com) and Refs. [5–7]). This disagreement in research findings indicates that the carbon source/sink effect of reservoirs has obvious spatial heterogeneity. Furthermore, the scientific community has no unified methodology regarding how to evaluate the carbon source/sink effect of these reservoirs. In 2009, the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Hydropower Association (IHA) jointly recommended a set of guidelines called Greenhouse Gas Measurement Methods and Assessment Guidelines for artificial freshwater reservoirs [8]. These guidelines suggested a comprehensive method for assessing the carbon emissions of reservoirs by investigating various possible carbon sources and carbon sinks within the reservoirs. Unfortunately, such integrated research reports remain lacking.

There are several problems regarding estimating the global carbon emissions of reservoirs: (1) Existing studies of carbon emissions from reservoirs involved only the total GHG flux from water-air interface of the reservoir area (Refs. [1,4,9]), but the release of GHG from the discharged water of the reservoir was

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not included in the estimation; (2) Previous studies generally stressed GHG emissions of reservoirs, but ignored the organic carbon burial into sediment. The latter reached  $160 \text{ Tg C a}^{-1}$  in the early estimation [10], which has been significantly higher than the latest estimate of the carbon emission of the reservoir,  $51 \text{ Tg C a}^{-1}$  [11]. In this sense, reservoirs may even be net carbon sinks; (3) Most of the artificial reservoirs are hydroelectric reservoirs, and the annual electricity generation should be included in the total carbon emission budget of the reservoir in the form of carbon sinks. Integrated studies are currently scarce. Therefore, an understanding of the carbon emission of the reservoir should be based on the carbon budget of the reservoir, which is also the main basis for evaluating the cleanliness of the hydropower. The most direct way to evaluate the carbon budget of reservoirs is to analyze the variation in carbon flux of water into and out of reservoirs, but this requires long time-series and high-frequency monitoring data support. Most reservoirs lack such monitoring. Furthermore, it is difficult to obtain these data from local authorities, particularly reservoir sedimentation data. The newly-developed underwater seismological method provides a good solution for the quantitative assessment of reservoir the accumulation of sediments [11], and assists with the estimation of sedimentary organic carbon sinks. If combined with the carbon emissions data of reservoirs, the budget of carbon sources and sinks of reservoirs can be better quantified. In this study, a typical hydropower reservoir in a subtropical area, the Hongfeng Reservoir (HFR) in southwest China was investigated to determine carbon burial and carbon emissions. The main objectives of this study were: (1) to understand the sediment accumulation and OC burial, (2) to evaluate its carbon source/sink effect based on the carbon balance relationship of the reservoir, and (3) to further convert the electricity generated by this reservoir into a carbon sink to overall understand the carbon sink effect of the HFR.

## 2. Study area and methods

### 2.1. Study area

The Wujiang River, located in the southwest of China, is an important tributary of the Yangtze River. The Maotiao River, located in the middle and upper reaches of the Wujiang drainage basin, is also an important tributary of the Wujiang River. A series of cascade reservoirs has been constructed since 1958 on the Maotiao River, and the entire basin hydropower development is now complete. The Hongfeng Reservoir (HFR) ( $106^{\circ}20'10''$ – $106^{\circ}27'00''$  E and  $26^{\circ}24'37''$ – $26^{\circ}34'17''$  N) is the largest and also the first-level reservoir (Fig. 1). Built and impounded in March 1960, the HFR lies in a fault basin and belongs to a canyon reservoir. Inflow to this reservoir is primarily from the Houliu, Maxian, Yangchang and Taohuanyuan Rivers, with a range of discharge from 5.7 to 6.6, 2.2 to 4.2, 5.8 to 34.5 and 3.1 to  $13.9 \text{ m}^3 \text{ s}^{-1}$ , respectively [12]. The first three rivers contribute to 72.5% of the total inflow (Fig. 1). The normal water storage level of the reservoir is 1,233.2 m, and the storage capacity is 602 million  $\text{m}^3$ . The average depth of the water is 10.5 m, and the maximum water depth reaches 45 m. For the description of climate and lithology, see [Supplementary materials](#).

The Maotiao River is the first river in China to complete the development of cascaded hydropower in its entire river basin. The river is 181 km long and forms a hydropower utilization pattern of six hydropower stations and four reservoirs in a small area. Therefore, the distance between the reservoirs is short. After the HFR discharges a short distance, it is injected into the next-level reservoir (Baihua Reservoir) (Fig. 1), points A and B are the site of outflow from the dam of HFR and the upper edge of the Baihua Reservoir Backwater Zone, respectively.

### 2.2. Sampling and processing of acoustic data

In this study, a high-precision shallow bottom profiler (Strata-Box, SyQuest) was used to observe the deposition of reservoir sediments. This model is equipped with two frequency band transducers and hydrophones of 3.5 and 10 kHz. Both frequency band soundwaves can penetrate a certain thickness of sediment, in which low-frequency sound wave penetration is stronger than high-frequency soundwave penetration. Before the construction of the reservoir, the original river bed was composed of exposed bedrock and soil layers. After impounding, particulate matter transported by rivers settles in the reservoir and forms loose, high-water-content sediments accumulated in the reservoir. This is clearly distinguishable in acoustic characteristics from the base of the river bed before the construction of the reservoir. Therefore, the thickness of sediments since the reservoir was built can be determined by acoustic reflection signals (Fig. S1 online). In November 2017, this study investigated the distribution and thickness of sediment in the HFR by means of continuous underwater observations, and used a differential global positioning system (DGPS) for positioning. The raw data of water depth and sediment thickness were recorded by the laptop during the cruising process. The cruising path attempted to keep an equal interval grid, while avoiding the islands in the lake. Sediment core was randomly collected and was mostly used to verify the result observed by the instrument.

The raw data were processed and interpreted using HYPACK® – Standard version software. The sound speed was  $1,500 \text{ m s}^{-1}$  for freshwater. Sediment thickness was determined by the depth difference between the surface of sediment and the base before the dam was constructed. After obtaining information on the sediment thickness and the coordinated position of each point, an interpolation was conducted using the inverse distance to a power algorithm with Surfer 9 software (Surfer 9, Golden Software, Inc., USA). The sediment thickness of the reservoir boundary and the boundary part of the islands in the lake was set to zero because there is no sediment accumulation in the boundary area of the reservoir [11].

### 2.3. Collecting and processing the relevant parameters of surface sediments and sediment cores

During approximately the past decade, much work has been conducted regarding the sediments of the HFR for different research purposes. This study collected and collated this research data (Fig. S2 online) including the OC content of surface sediments in different areas of the reservoir, the OC content along sediment cores in typical areas, and the porosity of sediment cores. The samples of surface sediments were generally collected by small grabs that usually obtained sediments within 10 cm of the surface layer. Therefore, this study defines surface sediments as sediments within a range of less than 10 cm. Using OC data of surface sediments and using the same number of grids as the sediment thickness interpolation, the OC contents of surface sediments were subjected to lake-wide interpolation. The interpolation data of surface sediment OC contents and sediment thickness were integrated to form a dataset in a uniform coordinate format for the calculation of OC mass in the surface layer within 10 cm.

Data of sediment cores from the past decade or more were collected for this study. It is reported that after water pollution during the 1980s and 1990s, total phosphorus and total nitrogen in the water of the HFR had no significant increase over the past ten years [13], indicating that there was no significant change in the external input and endogenous primary productivity of this reservoir. Therefore, these data can be processed in a uniform manner. After integrating the OC content data of the sediment cores from



Fig. 1. Location map of studied reservoir.

different regions [12,14–23], we calculated the OC mass of the sediment column in four sections according to the change in porosity on the sediment profile [24]: surface sediments (0–10 cm), sediments between 10 and 20 cm, sediments between 20 and 30 cm, and sediments between 30 cm to the original riverbed (Fig. S3 online). See [supplementary materials](#) for detailed description.

The total OC burial in sediments is the sum of the OC mass in each section of sediment. The annual average cumulative flux of OC is divided by the total OC burial by reservoir age. The reservoir is 57 years old (1960–2017). Considering the current eutrophic state, which indicates the greater OC flux to sediment, we calculated the modern organic carbon burial flux by the average annual cumulative weight of sediments by multiplying the OC average value of the surface sediment (within 10 cm) (see [supplementary materials](#)).

#### 2.4. Calculation of gaseous emissions of carbon and the conversion of hydroelectricity to carbon sink

The GHGs data used in this study was derived from the published literature and personal communications. Those studies adopted seasonal or monthly monitoring frequencies, and the sampling sites covered the major areas of the reservoir. This included Wang et al. [18], who sampled the areas covering the central south lake and central north lake of the HFR in January, April, July and October 2001 and January and August 2002. Both Wang et al. [25] and Yang [26], using a monthly sampling frequency from July 2007 to June 2008, collected samples at the central reservoir area of the Hongfeng Reservoir and its discharge. In these studies,  $p\text{CO}_2$  in water was calculated from alkalinity, which was deter-

mined by in-situ acid titration. The analysis of  $\text{CH}_4$  was conducted using headspace-chromatography.

Reservoir discharge is also an important conduit for GHG release. However, there are few reports on this aspect, mainly because areas affected by reservoir discharge are difficult to define and so it is difficult to accurately calculate the GHG emissions. The estimation method adopted in this study is as follows: the difference between the average GHG concentration in the water discharged from the dam, and the GHG concentration in the water entering before the next reservoir, multiplied by the average annual discharge flow.

According to the conversion coefficient of electricity and standard coal, we calculated the hydropower carbon sink capacity of the HFR. The conversion coefficient of electricity to standard coal is as follows: 1 kW h electricity = 324 g standard coal, and 795.9708 g  $\text{CO}_2$  is released, which is converted to 217.08 g-C [27]. Public information suggests that the annual average generating capacity of the Hongfeng Hydropower Station is  $5.47 \times 10^7$  kW h  $\text{a}^{-1}$  (<https://baike.baidu.com>), which is close to the design index of the reservoir ( $6.89 \times 10^7$  kW h  $\text{a}^{-1}$ ). In this study, the annual average power generation was used to calculate its carbon sink effect.

### 3. Results

#### 3.1. Water depth and sediment thickness of the HFR

The HFR is a medium-depth artificial reservoir in the karst mountain area. The terrain of the reservoir area is complex and mountainous and the average slope of the river is 1.3%. The north

lake of this reservoir is relatively open and its topography is relatively flat. The topography of the south lake is relatively steep and the mountains are high, resulting in many islands in the south lake region. The isobath map (Fig. 2a), shows that the deepest area of the reservoir is located in the north lake area, and the south lake is relatively shallow. The deepest point of the reservoir is located at the intersection of the north and south lakes, where water depth reaches nearly 40 m. The water depth of the reservoir bays around the rivers flowing into the reservoir is very shallow, and these areas are often exposed during low water-level operation. It is difficult for these areas to form effective sediment accumulation due to the rapidly fluctuating water level.

There is a significant difference between the accumulation of sediments in the south and north lake because they are affected by the underwater terrain and size of the catchment area (Fig. 2b). Generally, the sediments of the HFR are primarily accumulated in the south lake area, and the sediments in the north lake are relatively less. Compared with the isobath map of the reservoir, we found that reservoir sediments mainly accumulated in the deep water area. In the shallow water area near the lake bank and the rivers, sediments rarely accumulated, which concurs with the field observations. The primary reason is that the hydrological regulation of the HFR leads to a large fluctuation of water level (13.5 m amplitude), which will transport the sediments in shallow water to the deep water area again. There are three rivers (Yangchang, Houliu and Maxian Rivers) transporting materials into the south lake area. However, the complex underwater topography and the many islands in this lake limit sediment transport in the rivers significantly. As a result, the sediments mainly accumulate in the south lake area, forming a thicker deposit, with some areas being more than 1.5 m thick. The central part of the south lake is the main area for sediment accumulation, and most of this area is covered with thick sediments. In contrast, the distribution of sediments in the northern lake area is relatively sparse, showing discontinuous distribution and relatively thin sediments. This is because only one river, the Taohuayuan River flows into the north lake area. In addition, the outlet from the dam of the HFR is located in the north lake area so flood discharge processes and the deep water discharge for power generation will have an important impact on the accumulation of sediment in this area. This is also the reason that there has been less research regarding sediment cores in the north lake in the past.

### 3.2. Accumulation of sediments in the reservoir

From the commencement of impounding to the sampling year (1960–2017), the total accumulated volume of sediment in the HFR is 8,260,000 m<sup>3</sup>, and the weight is 7,630,000 t. There were few long-term series reports about the water and sediment in this reservoir. However, data released by the Encyclopedia of Rivers and Lakes in China shows that the sediment transport modulus of the Hongfeng Lake Basin is 169 t km<sup>-2</sup> a<sup>-1</sup> [28], while the sediment transport modulus of Guizhou Province is 141 t km<sup>-2</sup> a<sup>-1</sup> [29]. According to these data and the basin area before the dam (1,551 km<sup>2</sup>), we calculated the average amount of sediment transporting into the reservoir as 200,000–260,000 t a<sup>-1</sup>, which is mostly concentrated in flood seasons. During a flood season, the HFR usually uses low water levels for flood control operations, which will result in the transportation of large quantities of river sediment downstream, although some sediment is retained by the reservoir. In this study, the annual sediment accumulation of the HFR was calculated as 133,000 t a<sup>-1</sup> (Table 1), which is approximately 50% of the amount of sediment transported into the reservoir. When considering the sediment deposition in the reservoir and sediment discharged from the dam, we believe that the estimation results are reasonable. Among all the sediments in the reservoir, the surface (0–10 cm range) sediment had higher water content. Although its sediment volume accounts for nearly 20% of the total volume, its total weight accounts for approximately 4%. In comparison, the volume of sediment below 30 cm accounts for 43% of the total volume, and its mass is 80%. This is due to compaction of the sediments, resulting in low water content in the lower sediments.

### 3.3. Distribution characteristics of OC content in the surface sediments

The OC content of the surface sediments is closely related to the input of terrestrial organic matter and the primary productivity level in reservoir. Since the construction of the HFR, the water quality evolved from an early oligotrophic state to a eutrophic state in the 1990s of the last century [30]. This was reflected in the rapid increase of OC content in the sediments. The content of OC in the sediments of the north lake is generally higher than that of the south lake (Fig. 3). Cage fishing in the HFR was very active from the 1990s of the last century to the early twenty-first Century. This

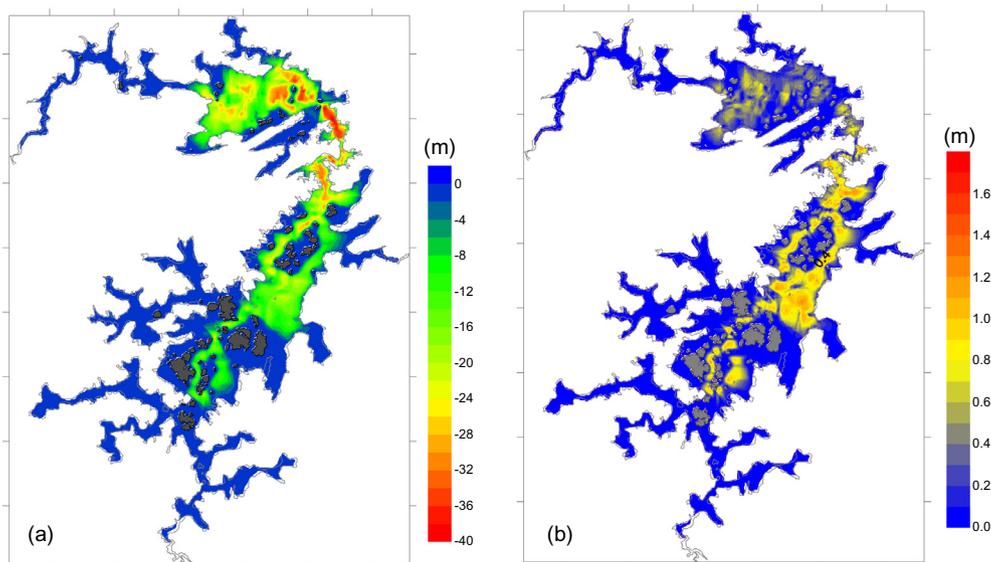


Fig. 2. Contour maps of water depth (a) and sediment thickness (b) of the HFR.

**Table 1**  
The accumulation of sediment and OC burial in the Hongfeng Reservoir.

Sections	Volume of sediment (m <sup>3</sup> )	Weight of sediment (t)	OC burial (t)
0–10 cm	1,942,997	291,450	12,714
10–20 cm	1,497,742	449,323	15,439
20–30 cm	1,240,219	620,109	14,697
30 cm to the original riverbed	3,582,751	6,269,814	157,865
Total sediment	8,263,709	7,630,696	200,715
Average <sup>a)</sup> (a <sup>-1</sup> )		133,872	3521 <sup>a)</sup>
Modern flux <sup>b)</sup> (a <sup>-1</sup> )		133,872	5449 <sup>b)</sup>
Annual burial flux <sup>c)</sup> (mg cm <sup>-2</sup> a <sup>-1</sup> )			11.7

<sup>a)</sup> Calculated by the reservoir age of 57 a.

<sup>b)</sup> The average annual cumulative weight of sediments in this reservoir was multiplied by the OC average value of the surface sediment (within 10 cm).

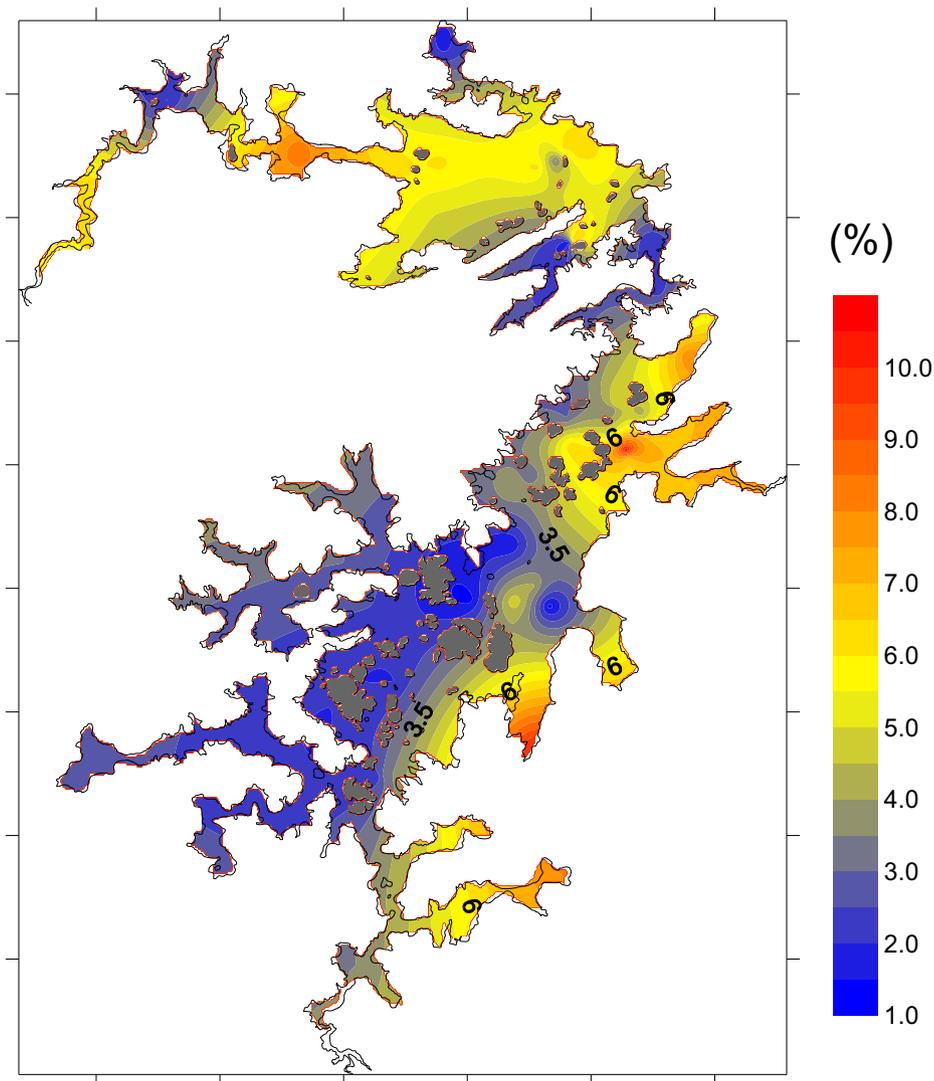
<sup>c)</sup> Calculated from modern flux. Area of reservoir surface: 46.34 km<sup>2</sup>.

significantly increased the trophic level of the reservoir and resulted in a significant increase in the content of OC in the sediment of affected regions. The high value area of the OC content correlates with the main distribution areas of historical cage fishing. From Fig. 3, it is clear that sediments in bays near the rivers flowing into the southern lake have low OC contents with values close to the average OC level of land soil, which mainly reflects the charac-

teristics of the river input and the low level of primary productivity of these areas. The content of OC in the surface sediments of the central reservoir area is significantly higher.

### 3.4. OC burial in the sediments

Due to increased trophic levels during past decades, the content of OC in the sediments of the HFR has gradually increased. Evidence from the C/N ratio and δ<sup>13</sup>C-POC demonstrate that OC gradually changed from a terrestrial signal to an algal source signal [12]. Because of the spatial heterogeneity of the distribution of sediments, it is difficult to use a uniform sediment deposition rate to calibrate the OC distribution along the sediment profile. Therefore, according to the OC content characteristics of the sediment cores in different regions, the integrated treatment was carried out based on sediment depth (Fig. S3 online). The content of OC along the sediment profile varied greatly, with the average OC content of sediments below 30 cm being 2.35%, which was close to the OC value of the local soil [31]. This indicates that the organic matter in the early accumulation stage of the reservoir is mainly exogenous organic matter. The average OC content in the 20–30 cm section was 2.37%, in the 10–20 cm layer, after increasing gradually was 3.26%, and in the 10 cm to sediment surface section, after increasing rapidly was close to the maximum value of 10%



**Fig. 3.** The distribution of OC content in the surface sediment of HFR.

(Fig. 3). It is worth noting that the variation of the OC content in surface sediment was significantly affected by the difference between the internal and external source contributions of different sedimentary regions.

Despite the high OC content in the surface sediments, the OC mass within the 10 cm range was 12,714 t, which accounted for only 6.3% of the total OC mass of the entire reservoir. Correspondingly, the 10–20 and 20–30 cm sections accounted for 7.8% and 7.3%, respectively. Under the influence of compaction, sediments below 30 cm to the original riverbed accounted for most of the total sediment quantity, of which OC accumulation amounted to 157,865 t, accounting for 78.6% of total OC burial (Table 1). With the reservoir age to 2017 of 57 years, the average annual cumulative OC of the reservoir was 3,521 t a<sup>-1</sup>. As the HFR has undergone great changes in water quality over the past few decades, it has been in a lengthy state of eutrophication and due to increasing primary productivity, the modern OC deposition flux in this reservoir is greater. In this case, if the average OC burial flux is used for carbon budget calculation, the carbon burial effect of the reservoir will be underestimated. Consequently, this study used the average annual accumulation weight of the sediment and the OC content of surface sediments (0–10 cm) to calculate the modern OC accumulation flux. The calculated result was 5,449 t a<sup>-1</sup>. According to this flux, the modern annual burial flux of OC in the HFR is 11.7 mg cm<sup>-2</sup> a<sup>-1</sup>.

### 3.5. Gaseous emission of carbon from the HFR

While reservoirs accumulate OC by retaining sediment, they also release GHGs to the atmosphere through the water-air interface. Following previous reports, this study calculated the emission flux of GHGs from reservoir water surface and discharge water from the dam (Tables 2, 3). We found that the GHGs (including CO<sub>2</sub> and CH<sub>4</sub>) released from the surface of the reservoir area were approximately 3,216.5 t of carbon, equivalent to global warming potential (GWP) conversion. This value was close to the average annual OC burial flux in sediments, but less than the modern OC burial flux.

**Table 2**  
GHGs emission from reservoir surface of HFR.<sup>a)</sup>

	Annual average emission flux	GWP [27]	Converted to carbon (t-C)	Sources
CO <sub>2</sub>	13.2 ± 3.9 mmol m <sup>-2</sup> d <sup>-1</sup> (-5.8 to 110)	1		[18]
	15 mmol m <sup>-2</sup> d <sup>-1</sup> (-9 to 70)	1		[25]
	14.1 ± 0.9	1	2861.9	Average value
CH <sub>4</sub>	25.5 ± 5.5 mmol m <sup>-2</sup> a <sup>-1</sup>	25	354.6	Personal communication
Summation			3216.5	

<sup>a)</sup> Area of reservoir surface: 46.34 km<sup>2</sup>; the values in parentheses are the range of variation.

**Table 3**  
GHGs emission from the discharge water downstream the dam of Hongfeng.<sup>a)</sup>

	CO <sub>2</sub>	CH <sub>4</sub>
Average GHGs in the outlet from the dam of the HF (site A, Fig. 1)	4,808 (1,194–11,130) (μatm)	95.07 (0.74–513.9) (nmol/L)
Average water temperature at site A (°C)	14.7 (5.6–26.2)	
Average GHGs in the upper edge of the backwater area of the Baihua Reservoir (site B, Fig. 1)	4,600 (261–10,882) (μatm)	67.3 (3.89–260.3) (nmol/L)
Average water temperature at site B (°C)	17.3 (5.9–27.7)	
Annual average flow	30.5 m <sup>3</sup> s <sup>-1</sup>	
GWP [27]	1	25
Conversion to carbon (t a <sup>-1</sup> )	308.6	8.01
Data sources	[25]	[26]

<sup>a)</sup> The values in parentheses are the range of variation.

The issue of GHG emissions from reservoirs concerns not only the emission from the reservoir surface, but also the release of GHG from the reservoir discharge. The latter was often not valued in previous estimates, including the existing global estimates of reservoir carbon emissions (Refs. [1,4]). As shown in Table 3, the release of GHGs from reservoir discharge can be converted by GWP to a carbon amount of 316.6 t-C a<sup>-1</sup>. This portion of carbon emissions is relative to 1/10 of annual carbon emissions from water surface of reservoir area, and 6% of the modern OC burial flux to sediments. Compared with the total emissions of the water surface in the reservoir area, this value is smaller, but it demonstrates that reservoir discharge is an important conduit for GHG emissions. The contribution of GHG emissions from discharge water to the total emissions of this reservoir is significantly lower than that of previous reports [32]. This is primarily because after the reservoir discharges a short distance, it enters the next-level reservoir (Baihua Reservoir) (Fig. 1), so the area affected by the discharge is relatively small. Also, as a hydropower reservoir, this reservoir uses the bottom water discharge mode to generate electricity and so downstream the dam has the characteristics of low water temperature and high greenhouse gas content. Due to the low temperature, after entering the Baihua Reservoir, the discharge of the upstream reservoir penetrates into the Baihua Reservoir through the bottom, thus avoiding the release of GHGs.

## 4. Discussion

In the initial stages of reservoir construction, the impounding process submerged the original vegetation in the reservoir area. Evidence shows that this portion of organic matter gradually decomposed during the subsequent burial process and stabilized after approximately 10 years [33]. The HFR has been operating for 57 years to 2017 and the easily degradable portion of the submerged vegetation has decomposed. Therefore, the early submergence of the reservoir was not considered in this study. Furthermore, the deposition of calcium carbonate is not usually considered as a carbon sink so this study did not take the accumulation of inorganic carbon in reservoir sediments into account.

#### 4.1. Source analysis of carbon sink in sediments

The OC burial rate of reservoir sediments in different areas varies greatly. Wang et al. [18] reported that the OC burial rate of sediments in the HFR was  $5.05 \text{ mg C cm}^{-2} \text{ a}^{-1}$ , according to a study of sediment cores. In this study, the burial rate of OC in the entire reservoir was calculated as  $11.7 \text{ mg C cm}^{-2} \text{ a}^{-1}$  based on the sediment of the entire lake. These values are all significantly lower than that of previous estimates on global reservoirs [10]. Zhang [34] estimated that the primary productivity level of HFR was  $109 \times 10^7 \text{ mol C a}^{-1}$ . According to Wang et al. [18], 70% of the newly-deposited OC will be decomposed within 12 years, and the rest will remain in sediments as refractory OCs. Based on a conservative estimation of the above results, the amount of OC buried in sediments of the HFR would be  $3,924 \text{ t a}^{-1}$ , which is close to our estimated value of modern OC storage ( $5,449 \text{ t a}^{-1}$ ). When taking into account the differences in the calculated values of reservoir water surface and the recent changes in reservoir productivity levels, our estimates are reasonable.

The OC deposited in the reservoir sediments are mainly derived from terrestrial organic matter and endogenous organic matter formed by photosynthesis in reservoirs. Among them, the part of terrestrial organic matter is mainly composed of soil organic matter, and is transported by rivers to deposit in reservoirs. This part of organic carbon is generally difficult to degrade, and its depositing in reservoir sediment is essentially the accumulation of organic matter in another place, so it cannot be regarded as the valid carbon sink. On the contrary, after the impounding of the reservoir, with the slowing of flow velocity and the reduction of water turbidity, the photosynthesis inside the reservoir gradually increases, and the dissolved inorganic carbon (DIC) in water is absorbed to form endogenous organic matter. This process is also known as biological carbon pump effects in surface aquatic ecosystems [35,36]. Traditionally, these newly formed OC is thought to be mainly from the re-photosynthetic utilization of DIC formed by the decomposition process of terrestrial organic matter (including POC, DOC) in river courses [37]. Lu et al. [38] confirmed in their research on reservoirs in Karst areas that the carbon of newly formed organic matter in reservoirs is largely derived from soil  $\text{CO}_2$ , and the photosynthetic absorption process in the reservoir prevented these  $\text{CO}_2$  from being released into the atmosphere. Consequently, this part of carbon should be regarded as the valid carbon sink.

Since the establishment of the HFR, industrial and agricultural activities in the basin have been continuously intensifying. In particular, cage fishing in the reservoir has developed rapidly since the 1980s and this has led to the gradual deterioration of the reservoir water quality. From the sediment record, the total phosphorus content in the bottom sediments was close to the background soil level, and increased several times in the surface sediments [30,39]. As a result, the water quality of the HFR has transformed from an oligotrophic to a current eutrophic state. Due to this eutrophication state, the photosynthesis resulted in  $p\text{CO}_2$  in surface water being seasonally lower than the atmospheric level, and a large amount of atmospheric  $\text{CO}_2$  was absorbed [40]. Studies have shown that the terrestrial POC flowing into the reservoir through the rivers reaches  $2.8 \times 10^7 \text{ mol a}^{-1}$ , which is less than 3% of the primary productivity of the lake [18,34] and indicates that this reservoir is an autotrophic ecosystem. The results of C/N ratio and  $\delta^{13}\text{C}$ -POC also confirmed that the main source of POC in sediment was from phytoplankton [12]. Based on an end-members mixing model, Lu et al. [38] reported that endogenous organic carbon formed by photosynthesis contributed 85% to OC in the sediments of the HFR, and the exogenous OC accounted for only 15%. Our study used this ratio of endogenous OC to calculate the valid carbon sink of the HFR and found that the valid carbon sink in the HFR is  $4,632 \text{ t}$  of carbon per year.

#### 4.2. Budget of carbon sources and sinks

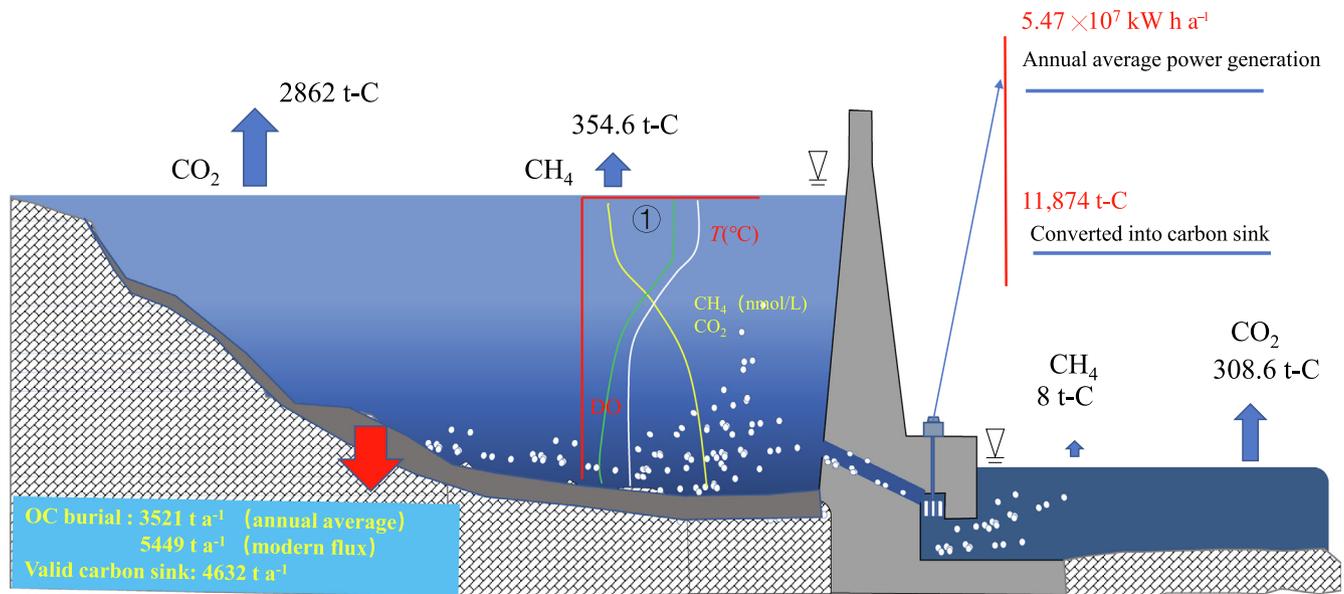
During the past two decades, GHG emissions from artificial reservoirs, and in particular hydroelectric reservoirs have been a popular area of research for the academic community (Refs. [1,41–43]). Observations in boreal and tropical regions have confirmed the release of large amounts of GHGs from artificial reservoirs [2,3,44–47]. However, most of these studies only considered carbon flux at the air-water interface of reservoirs, and lacked a comprehensive assessment of the budget of carbon sources and sinks. This is one of the most important reasons for the current disagreement about the cleanliness of hydropower. In recent years, the role of carbon burial in reservoirs has gradually gained attention from researchers [48–50]. The OC burial in sediments in the HFR shows that the average annual burial flux of OC in the sediments was  $3,521 \text{ t a}^{-1}$ , while that of the modern OC reached  $5,449 \text{ t a}^{-1}$ . Among them, the valid carbon sink is  $4,632 \text{ t}$  of carbon per year. On this basis, it is clear that this portion of OC should be included in the calculation of the reservoir's carbon budget and the evaluation of the greenhouse effect of the reservoir.

Greenhouse gas emissions are the main carbon source of reservoirs. Table 2 shows that the GHGs (including  $\text{CO}_2$ , and  $\text{CH}_4$ ) released from the reservoir area is about  $3,216.5 \text{ t a}^{-1}$  of carbon equivalent by global warming potential (GWP) conversion. Since the HFR has been built for many years and the water quality has been in a eutrophic state for more than two decades, the endogenous portion of the OC modern burial in sediments is more representative of the real carbon sink situation. Therefore, the difference between carbon emissions from the water surface of the reservoir ( $3,216.5 \text{ t-C a}^{-1}$ ), and the valid carbon sink in sediments ( $4,632 \text{ t-C a}^{-1}$ ) is  $1,415.5 \text{ t-C a}^{-1}$  which represents the net carbon sink in the reservoir area. When considering the reservoir's carbon burial, the emissions of GHGs from the reservoir's water surface can be offset, which indicates that there is no significant release of GHGs from the reservoir.

The overall carbon budget of the reservoir should also include the amount of greenhouse gas released from the discharge water downstream of the dam. According to Table 3, the GHGs released from the discharge of the HFR are converted into a carbon content of  $316.6 \text{ t-C a}^{-1}$ . By integrating the OC burial and gaseous emissions of carbon from the reservoir, it can be found that the carbon burial is larger than the carbon release, with a difference of  $1,098.9 \text{ t}$  of carbon per year. Therefore, overall, the HFR is as a carbon sink.

#### 4.3. Scenario analysis

Because there is no fossil fuel consumption in the power production of hydropower plants, hydroelectric power has long been regarded as a model of clean energy. Therefore, the power generation capacity of the hydropower station should be used as a carbon sink and included in the calculation of the carbon budget of the reservoir. Based on the conversion coefficient of electricity to standard coal, the annual average generating hydroelectricity of Hongfeng power station can be converted to  $17,722.8 \text{ t}$  standard coal per year, equivalent to a carbon sink of  $11,874 \text{ t-C a}^{-1}$ . This study integrated the main fluxes of carbon source and carbon sink, and discussed the carbon budget of the HFR in two scenes (Fig. 4). Firstly, without considering the carbon sink effect of hydropower, GHG emissions from the reservoir water surface and downstream discharge were equivalent to  $3,216.5$  and  $316.6 \text{ t-C a}^{-1}$ , respectively, and the valid carbon sink in reservoir sediment amounted to  $4,632 \text{ t-C a}^{-1}$ . Therefore, the net carbon sink was  $1,098.9 \text{ t-C a}^{-1}$ . This indicates that although the HFR has greenhouse gas emissions, it is still generally in a carbon sink state. Secondly, when



Scenario analysis 1. Net carbon sink: 12,972.9 t-C a<sup>-1</sup> (using valid carbon sink), including carbon sink of hydroelectricity

Scenario analysis 2. Net carbon sink: 1,098.9 t-C a<sup>-1</sup> (using valid carbon sink), excluding carbon sink of hydroelectricity

**Fig. 4.** Budget of carbon source and sink in the HFR. ①: The typical distribution characteristics of temperature, dissolved oxygen and GHGs along the water column.

including the carbon sink converted from hydroelectricity, under this scene, the net carbon sequestration in the HFR is 12,972.9 t-C a<sup>-1</sup>. Compared to scene 1, the amount of carbon sequestration of the hydropower is enormous. According to the scenario analysis, the Hongfeng Reservoir is currently in a carbon-sink state. This indicates that in the current state, the reservoir is not an important source of GHGs, and the released GHGs can be offset by the organic carbon sink in the sediments. Therefore, the hydroelectric carbon sink can be regarded as the net carbon sink of the reservoir.

## 5. Conclusion

Presently, most studies on carbon emissions from artificial reservoirs remain focus on GHGs emissions from the water surface of reservoirs, and there is a lack of understanding of the reservoir's greenhouse effect from the perspective of overall carbon sources and sinks. In this study of the HFR in Guizhou Province, we conducted a detailed investigation of the OC burial fluxes in sediments, the GHG emission fluxes from reservoir surface and downstream discharge, and calculated the hydroelectricity generation capacity of the power plant as a carbon sink for an overall assessment. According to estimates, modern organic carbon burial in the sediments of the HFR reached 5,449 t-C a<sup>-1</sup>, with a valid carbon sink of 4,632 t-C a<sup>-1</sup>. Our scenario analysis shows that the net carbon sink of the HFR is 1,098.9 t-C a<sup>-1</sup>, when the carbon sink of hydro-electricity is not included. When the hydropower carbon sink is included in the calculation, the net carbon sink of the reservoir is 12,972.9 t-C a<sup>-1</sup>. It is clear that, whether considering carbon sinks generated by hydropower or not, the amount of carbon sinks in the sediments of the HFR is sufficient to offset its GHGs emissions. Our results indicate that organic carbon burial in sediment is an important carbon sink, and should be included in the assessment of hydroelectric cleanliness. Furthermore, the seismological methods used also provide important rapid research tools for the investigation of reservoir sediment carbon sinks.

## Conflict of interest

The authors declare that they have no conflict of interest.

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## Author contributions

FS Wang and CQ Liu designed the program. FS Wang wrote the paper. YC Lang helped with the maintenance and use of field observation equipment. Y Qin and NX Yu participated in field investigations and sample analysis. BL Wang participated in data processing and discussion.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scib.2019.03.034>.

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