A preliminary study on the inorganic carbon sink function of mineral weathering during sediment transport in the Yangtze River mainstream

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This study proposed that the dissolution of calcium and magnesium minerals in river sediment could sequester CO2 and function as a carbon sink. Based on the published study, “the contents and chemical and mineral compositions of the suspended particulate materials in the Yangtze River and their geological environmental implications” by Ding Tiping, the contents of CaO, MgO, calcite and dolomite in suspended sediment collected from 25 sampling points in the mainstream and 13 sampling points in the tributaries of the Yangtze River in 4 sampling campaigns during 2003–2007 were used to calculate the total inorganic carbon sink (TCS) capacity and nonsubstantial and substantial inorganic carbon sink (NSCS and SCS) capacities of suspended sediment along the river. Due to the reduction in the sediment yield, the TCS, NSCS and SCS of the Cuntan–Datong section during 2006–2019 decreased by 18.52 × 10⁶ tons, 12.24 × 10⁶ tons and 8.72 × 10⁶ tons, respectively, compared to the period before 2002. The average annual sedimentation of the Three Gorges Reservoir (TGR) was 114.5 × 10⁶ tons, and the related TCS and SCS losses were 6.76 × 10⁶ tons and 2.29 × 10⁶ tons, respectively, which were equivalent to 7.9 and 2.7 percent of the 85.8 × 10⁶ tons of CO2 emissions reduced by the clean energy production of the Three Gorges Hydropower Station. The TCS of global rivers was estimated as 757 × 10⁶ tons (the SCS was more than one quarter of the TCS), which is equivalent to 71.6% of the TCS by global rock weathering with 1.06 × 10⁹ tons of sequestered CO2. The collision and erosion of river sediment caused by turbulence in the processes of sediment transport (off-site rock weathering) could promote the dissolution of minerals. Therefore, it is reasonable that the dissolution rate of calcium and magnesium minerals for offsite rock weathering was much higher than that for in situ rock weathering.

The weathering of rocks containing silicate and carbonate minerals consumes CO2, which is an important inorganic carbon sink in the global carbon cycle1. An entire rock weathering process includes in situ weathering in the crust and off-site weathering during sediment transport. Atmospheric and aquatic CO2 is consumed by the weathering of silicate and carbonate minerals to form soluble bicarbonates in solution, which are transported into the sea through rivers. Some of the CO2 in the bicarbonates is deposited as Ca–MgCO3 (biological or chemical deposition) in the sea and is called the "Substantial Inorganic Carbon Sink", and some of it is released back into the atmosphere and can be called the "Nonsubstantial Inorganic Carbon Sink"2. The chemical equations for Ca–Mg ions in calcium and magnesium silicates to consume and release CO2 during the weathering and deposition processes are expressed as follows:

\[
(Ca-Mg)_2SiO_4 + 4CO_2 + 4H_2O \rightarrow (Ca-Mg)_2(HCO_3)_4 + H_4SiO_4
\]

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\[ (\text{Ca}{}^{\text{–Mg}})_2(\text{HCO}_3)_4 \rightarrow 2(\text{Ca}{}^{\text{–Mg}})\text{CO}_3 + 2\text{CO}_2 \uparrow + \text{H}_2\text{SiO}_4 \] (2)

In Eq. (2), the \( \text{CO}_2 \) deposited via \((\text{Ca}{}^{\text{–Mg}})\text{CO}_3\) is a substantial carbon sink (SCS), and the \( \text{CO}_2 \) that is released is a nonsubstantial carbon sink (NSCS). In this manuscript, all the carbon sink terms refer to inorganic carbon sinks.

The chemical equation of absorbing and releasing \( \text{CO}_2 \) by the \( \text{Ca}{}^{\text{–Mg}} \) carbonate compounds during the weathering and deposition processes is expressed as follows.

\[ (\text{Ca}{}^{\text{–Mg}})\text{CO}_3 + \text{CO}_2 + \text{H}_2\text{O} \rightarrow (\text{Ca}{}^{\text{–Mg}})(\text{HCO}_3)_2 \rightarrow (\text{Ca}{}^{\text{–Mg}})\text{CO}_3 \downarrow + \text{CO}_2 \uparrow + \text{H}_2\text{O} \] (3)

\( \text{CO}_2 \) consumed by carbonate weathering is a nonsubstantial carbon sink (NSCS), and it is released after entering the sea through rivers.

Suchet and Probst concluded that the \( \text{CO}_2 \) consumption by rock weathering was mainly affected by the flow rate on the rock surface, atmospheric temperature and rock type\(^1\). They analyzed the data of surface runoff and major dissolved elements in 232 monolithologic basins in France and established a GEM-CO\(_2\) model to estimate the amount of atmospheric \( \text{CO}_2 \) consumed by rock weathering based on the empirical relationships. The model was considered one of the main achievements of the international geological correlation program (IGCP) 404 project. Gaillardet et al. collected the hydrochemical data of 60 major rivers around the world and calculated that the global silicate weathering carbon sink amount was \( 1.4 \times 10^8 \) t C per year and the carbonate weathering carbon sink amount was \( 1.48 \times 10^8 \) t C per year through an inversion model\(^6,7\). It has been largely reported that calcium and magnesium minerals in sediment can dissolve \( \text{CO}_2 \) and function as carbon sinks during river sediment transport, but the effects of human activities (such as damming) on the potential carbon sink capacity during sediment transport have not been reported until now\(^8–11\). Therefore, the objectives of this research are to (1) elucidate the mineral compositions and transport dynamics (off-site rock weathering) in the Yangtze River, (2) estimate the potential carbon sink capacity of suspended sediment transported in the Yangtze River, and (3) evaluate the effects of damming on the potential carbon sink capacity of suspended sediment.

Materials and methods

This study analyzed the chemical element and mineral composition data of suspended sediments at 25 sites and 13 sampling points in tributaries from the upper reaches to the estuary of the Yangtze River from 2003 to 2007 according to Ding Tiping’s publication\(^12\). Twenty-five sampling sites in the mainstream and 13 sites in the tributaries of the Yangtze River were sampled 4 times (July 2003, April 2004, July 2005 and July 2007) during 2003–2007, as shown in Fig. 1 and Table 1. The variations in the \( \text{CaO}, \text{MgO} \) (during 4 campaigns), calcite and dolomite contents (one campaign in July 2005) in suspended sediment of the Yangtze River along the river are shown in Fig. 2.

The suspended sediments were not measured at some sampling sites in April 2004 because the sediment concentration in water was too low to be collected in the dry season of April 2004. Furthermore, the sediment yields in the flood seasons of May–October account for more than 75% of the yield for a year; therefore, the mean values of the chemical and mineral contributions of the three campaigns in July were used for the following calculation. However, the value in July 2005 at Zhenjiang was irregular and eliminated from the calculation.

The carbon sink effects of silicate and carbonate mineral weathering during the sediment transport processes were estimated based on the variation in the \( \text{CaO}, \text{MgO}, \text{calcite and dolomite contents} \) in suspended sediments along the mainstream of the Yangtze River. In this study, we defined the \( \text{CO}_2 \) consumed per unit weight by the dissolution of \( \text{CaO} + \text{MgO} \) in silicate and carbonate minerals of suspended sediment to bicarbonate forms as the total carbon sink (TCS) capacity of suspended sediment \( (C_1, \text{t/t}) \). In more detail, the molar masses per unit mass of \( \text{CaO}, \text{MgO}, \text{calcite} (\text{CaCO}_3) \) and dolomite \( (\text{CaCO}_3{}^{\text{–Mg}})\text{CO}_3 \) were calculated based on the contents of \( \text{CaO}, \text{MgO}, \text{calcite and dolomite} \) in the measured sediment samples at each site, and the respective carbon sink capacities (which consumed \( \text{CO}_2 \) per ton during sediment transport) were calculated based on the same molar mass of \( \text{Ca/Mg} \). According to the definition and Eq. (2) mentioned above, the \( \text{CO}_2 \) consumed by the weathering of \( \text{Ca/Mg} \) carbonate minerals is a nonsubstantial carbon sink (NSCS \( C_c \)); this yields approximately one mole of \( \text{CO}_2 \) from one mole of weathered \( \text{CaCO}_3 \), which is released again when carried into the oceans. Moreover, from Eq. (1), we infer that one mole of the \( \text{CO}_2 \) consumed by the weathering of one mole \( \text{Ca/Mg} \) silicate minerals is a substantial carbon sink (SCS, \( C_s1 \)) and the other mole is a nonsubstantial carbon sink (NSCS, \( C_s2 \)):

\[ C_1 = C_2 + C_3 \] (4)

\[ C_2 = C_{s1} + C_{s2} \] (5)

\[ C_3 = C_{s2} \] (6)

where \( C_1 \) is the TCS capacity (t/t); \( C_2 \) is the NSCS capacity (t/t); \( C_3 \) is the SCS capacity (t/t); \( C_{s1} \) is the NSCS capacity of Ca/Mg carbonate minerals (t/t); \( C_{s2} \) is the SCS capacity of calcium-magnesium silicate minerals (t/t); and \( C_{s2} \) is the NSCS capacity of Ca/Mg silicate minerals (t/t).

In fact, the SCS capacity was calculated by subtracting the NSCS capacity (based on the molar mass of sequestered \( \text{CO}_2 \) by weathering of calcite and dolomite) from the TCS capacity (based on the molar mass of sequestered \( \text{CO}_2 \) by weathering of all minerals containing \( \text{CaO/MgO} \) in this study. Subsequently, the influence of sediment yield changes on the carbon sink contributed by off-site rock weathering in the Yangtze River was preliminarily evaluated via an “ideal mainstream segment” method, especially for comparing the two periods.
of preimpoundment (1956–2000) and postimpoundment (2003–2017) of the Three Gorges Reservoir (TGR), which was gradually impounded from 2003 to 2008.

Results and discussions
CaO, MgO, calcite and dolomite contents of suspended sediments in the Yangtze River and its main tributaries. Figure 2 shows a declining tendency of the CaO + MgO and calcite + dolomite of suspended sediments in the mainstream of the Yangtze River from upstream to downstream. The total CaO + MgO contents along the Yangtze River were as follows: Tuotuo River, 16.33%; Yibin, 11.43%; Cuntan, 10.35%; Yichang (below the Three Gorges Dam), 6.17%; Wuhan Industrial Port, 6.61%; Datong, 4.80%; and Wusongkou, 4.60%. The total calcite + dolomite contents also decreased along the river as follows: Tuotuo River, 16.8%; Yibin, 9.1%; Cuntan, 6.2%; Yichang, 4.1%; Wuhan Industrial Port, 7.4%; Datong, 4.2%; and Wusongkou, 1.5%. The three stations closest to the estuary were dominated by dolomite and free of calcite.

Due to the dramatic terrain changes in the upper reaches of the Yangtze River, strong gravity erosion and physical weathering, the CaO + MgO and calcite + dolomite contents were high in the mainstream section of the Jinsha River above Yibin and decreased from the headwater to the estuary, which clearly illustrated the dissolution of calcium-magnesium silicate and carbonate minerals during the process of sediment transport in the river. The declining rates of CaO + MgO and calcite + dolomite contents in the upper reaches of the Yangtze River above Yichang were 0.12%/100 km and 0.29%/100 km, respectively, while the rates below Yichang were 0.09%/100 km and 0.15%/100 km, respectively. The declining rate of calcite and dolomite contents was higher than that of CaO + MgO contents, which indicated that carbonate minerals were more likely to be dissolved than calcium-magnesium silicate minerals during sediment transport. Because the upstream reaches had greater slope gradients, faster flow velocities and consequently higher mineral dissolution rates, the CaO + MgO and calcite + dolomite contents of suspended sediments in the upper reaches had a higher declining rate than those in the middle and lower reaches.

The CaO + MgO and calcite + dolomite contents of the suspended sediment in the main tributaries of the Yangtze River were as follows: Minjiang River: 9.75% and 6.3%; Jialing River: 5.40% and 5.5%; Wujiang River: 10.87%; Xiangjiang River: 4.75%; Hanjiang River: 4.41%; and Ganjiang River: 2.87% (only CaO + MgO contents and no calcite + dolomite content data for the last four tributaries). Except for the Wujiang River, CaO + MgO contents and calcite + dolomite contents in the Minjiang River were higher than those in other tributaries and close to the Jinsha River (Yibin site) because the Minjiang River basin had similar environments for erosion and sediment transport to the Jinsha River Basin. The CaO + MgO contents of suspended sediments in the Wujiang
River were quite different between July 2003 and July 2007, i.e., 6.67% and 15.06%, respectively. The relatively high contents might be due to its widespread distribution of carbonate rock.

Carbon sink capacity during suspended sediment transport in the Yangtze River mainstream. According to Eqs. (1)–(6), the calculated TCS capacity ($C_1$) decreased gradually from the headwater to the estuary (Fig. 3) in the following order: Tuotuo River, 0.271 t/t; Cuntan, 0.151 t/t; Yichang, 0.117 t/t; Wuhan Industrial Port, 0.127 t/t; Datong, 0.092 t/t; and Wusongkou, 0.091 t/t (Table 2). As CaO + MgO contents

| Sampling point | Station name | River/lake | Location | Distance from source (km) |
|----------------|--------------|------------|----------|--------------------------|
| M01            | Tuotuo River | Yangtze River mainstream | Under the Tuotuo River Bridge in Qinghai | 130 |
| M02            | Tongtian river | Yangtze River mainstream | Yushu Zhimenda Observation Station | 980 |
| M03            | Shigu        | Yangtze River mainstream | Lijiang Shigu Observation Station | 1820 |
| M04            | Panzhihua    | Yangtze River mainstream | Panzhihua Observation Station | 2754 |
| M05            | Yibin        | Yangtze River mainstream | Yibin Observation Station | 3480 |
| M06            | Luzhou       | Yangtze River mainstream | Luzhou Observation Station | 3580 |
| M07            | Cuntan       | Yangtze River mainstream | Chongqing Cuntan Observation Station | 3855 |
| M08            | Qingxichang  | Yangtze River mainstream | Chongqing Qingxichang Observation Station | 4020 |
| M09            | Wanxian      | Yangtze River mainstream | Chongqing Wanzhou Observation Station | 4200 |
| M10            | Fengjie      | Yangtze River mainstream | Chongqing Fengjie Observation Station | 4300 |
| M11            | Badong       | Yangtze River mainstream | Badong Observation Station | 4400 |
| M12            | Yichang      | Yangtze River mainstream | Yichang Nanjinguan Observation Station | 4515 |
| M13            | Shashi       | Yangtze River mainstream | Shashi Brick and Tile Factory Observation Station | 4620 |
| M14            | Luoshan      | Yangtze River mainstream | Honghu Luoshan Observation Station | 4850 |
| M15            | Zhuankou     | Yangtze River mainstream | Wuhan Zhuankou Observation Station | 5030 |
| M16            | Industrial Port | Yangtze River mainstream | Wuhan Industrial Port Observation Station | 5157 |
| M17            | Huangshi     | Yangtze River mainstream | Huangshi Observation Station | 5260 |
| M18            | Juijiang     | Yangtze River mainstream | Juijiang Observation Station | 5426 |
| M19            | Datong       | Yangtze River mainstream | Chizhou Datong Observation Station | 5650 |
| M20            | Nanjingxian  | Yangtze River mainstream | Nanjing Jiangning River Observation Station | 5880 |
| M21            | Nanjingxia   | Yangtze River mainstream | Nanjing Shili Changgou Observation Station | 5950 |
| M22            | Zhenjiang    | Yangtze River mainstream | Zhenjiang Observation Station | 6020 |
| M23            | Nantong      | Yangtze River mainstream | Nantong Observation Station | 6130 |
| M24            | Shidongkou   | Yangtze River mainstream | Shanghai Shidongkou Observation Station | 6250 |
| M25            | Wusongkou    | Yangtze River mainstream | Shanghai Wusongkou Observation Station 23 km | 6300 |
| T01            | Chumar River | Chumar River | Under the Chumar River Bridge in Qinghai | 430 |
| T02            | Mianning     | Yalong River | Along the river in Yarlung, Mianning | 2874 |
| T03            | Gaoshan      | Minjiang River | Yibin Gaoshan Observation Station | 3480 |
| T04            | Fushun       | Tuojiang River | Fushun observation station | 3580 |
| T05            | Linjiangmen  | Jialing River | Chongqing Linjiangmen Observation Station | 3850 |
| T06            | Wulong       | Wujiang River | Chongqing Wulong Observation Station | 4020 |
| T07            | Changsha     | Xiangjiang River | Changsha Observation Station | 4720 |
| T08            | Nanju        | Dongting Lake | Nanjia Observation Station | 4720 |
| T09            | Chenglinggi  | Dongting Lake | Yueyang Chenglinggi Observation Station | 4720 |
| T10            | Danjiangkou  | Danjiangkou Reservoir | Danjiangkou Reservoir Dam Observation Station | 5157 |
| T11            | Jiiazui      | Han River | Hankou Jiiazui Observation Station | 5157 |
| T12            | Nanchang     | Ganjiang River | Under Ganjiang Bridge in Nanchang | 5465 |
| T13            | Xieshan      | Poyang Lake | Juijiang Xieshan 1 km south | 5465 |

Table 1. Sampling points of suspended sediment in the main stream and tributaries of the Yangtze River.
decreased, so did the TCS capacities. This result verified that CO₂ was consumed by the dissolution of Ca–Mg minerals during sediment transport from upstream to downstream and that a carbon sink function existed. The TCS capacities at Cuntan and Wusongkou were 0.151 t/t and 0.091 t/t, respectively. A total of 0.060 tons of CO₂ per ton of suspended sediment was dissolved during transport from Cuntan to the sea.

The SCS capacities (C₃) of silicate minerals in the sediment were in the range of 0.027–0.047 t/t and had little variation, except for the Tuotuo River (0.061 t/t). The NSCS capacity (C₂) was consistent with the variation in the TCS capacity, and both had a gradual decreasing tendency from the headwater to the estuary (Fig. 3), as follows:

Figure 2. The variations of CaO, MgO, calcite and dolomite contents in suspended sediment along the mainstream of the Yangtze River.

Figure 3. The variation of carbon sink capacities of suspended sediment in the Yangtze River.
Tuotuo River, 0.210 t/t; Cuntan, 0.104 t/t; Yichang, 0.078 t/t; Wuhan Industrial Port, 0.097 t/t; Datong, 0.065 t/t; and Wusongkou, 0.051 t/t. The silicate carbon sink capacity (SCS) was smaller and showed a smaller reduction than the NSCS along the Yangtze River, mainly due to the slower dissolution rate of silicate minerals or greater contribution of silicate rock clastics from the watersheds in the middle and lower reaches, which also limited CO₂ consumption in comparison with carbonate minerals. Obviously, the decrease in TCS capacity from upstream to downstream was due to the intense dissolution of carbonates in the Yangtze River.

An “ideal mainstream segment” refers to a segment where there was no sediment input from the tributaries or the amount of sediment supply from the tributaries was equal to the amount of sedimentation in the segment (meaning that the suspended sediment yields at the inlet and outlet were similar), and the calcium and magnesium mineral contents of suspended sediments in the tributaries and mainstream were similar. The carbon sinks via CO₂ consumption by dissolution of calcium and magnesium minerals in the sediment transport process can be expressed as follows:

\[ W_{h1-2} = W_{s1-2} \times (C_{h1} - C_{h2}) \]  

(7)

where \( W_{h1-2} \) is the consumed CO₂ via the dissolution of calcium and magnesium minerals in the segment (\( 10^8 \) t/yr); \( W_{s1-2} \) is the mean suspended sediment transported at the segment (\( 10^8 \) t/yr); \( C_{h1} \) is the carbon sink capacity of the suspended sediment at the inlet of the segment (t/t); and \( C_{h2} \) is the carbon sink capacity of the suspended sediment at the outlet of the segment (t/t).

The Yangtze River has a drainage area of \( 1785 \times 10^6 \) km², in which the upper reaches above Yichang have an area of \( 1.05 \times 10^6 \) km². The average sediment yield from 1956 to 2000 was \( 5.01 \times 10^8 \) t/yr at Yichang, while it was \( 4.33 \times 10^8 \) t/yr at Datong, with a drainage area of \( 1.705 \times 10^6 \) km². In addition, it was \( 4.39 \times 10^8 \) t/yr at Cuntan with a drainage area of \( 0.867 \times 10^6 \) km². Although there is a large drainage area of the river segment between Cuntan and Datong (\( 0.838 \times 10^6 \) km²), the sediment yields at Cuntan and Datong, 0.051 t/t, were very similar, namely, 4.39 \( \times 10^8 \) t/yr, and 4.33 \( \times 10^8 \) t/yr, respectively, because sediment deposition in the channels of the segment offset the sediment supply from the tributaries. The contents of CaO and MgO in the suspended sediment in the tributaries are nearly the same as the values in the mainstream of the Yangtze River (Hankou station)\(^{12}\). Thus, we regarded the mainstream segment between Cuntan and Datong as an ideal mainstream segment, with Cuntan being upstream of the TGR dam as an ideal mainstream segment, with Cuntan and Datong as the two sites during the TGR damming effects. The CaO + MgO contents of suspended sediment samples for the three campaigns (July 2003, July 2005 and July 2007) and the calcite + dolomite contents of the sediment (July 2005) at the two sites (Table 2) were used to calculate differences in TCS, NSCS and SCS capacities for the segment. Taking the mean sediment yield of the two sites during the period from 1956 to 2000 for reference, the annual net TCS, NSCS and SCS between the two sites were 26.45 \( \times 10^6 \) tons of CO₂, 17.51 \( \times 10^6 \) tons of CO₂ and 8.94 \( \times 10^6 \) tons of CO₂, respectively. After 2001, due to hydropower exploration (especially the TGR project), ecological mitigation and soil conservation, the sediment yields at the two sites have been decreased and lower. Since 2006, by comparison to the period before 2000, the sediment yields at Cuntan and Datong decreased by 72.4% and 71.6%, respectively, during the period of 2006–2019\(^{16}\). Due to the reduction in sediment yields, the annual net TCS, NSCS and SCS in the segment decreased by 18.52 \( \times 10^6 \) tons of CO₂, 17.51 \( \times 10^6 \) tons of CO₂ and 8.94 \( \times 10^6 \) tons of CO₂, respectively (Table 3).

### Carbon sink capacities of the global rivers and their implications

The amount of deposited sediments of the Three Gorges Reservoir (TGR) from June 2003 to December 2017 was 1.669 \( \times 10^9 \) kWt, and the average sedimentation rate was 114.5 \( \times 10^8 \) t/yr\(^{15}\). According to the differences in the TCS, NSCS and SCS capacities of the suspended sediments between Cuntan and Datong, the losses of annual TCS, NSCS and SCS by sedimentation in the TGR were estimated to be approximately 6.756 \( \times 10^8 \) tons of CO₂, 4.466 \( \times 10^8 \) tons of CO₂ and 2.290 \( \times 10^8 \) tons of CO₂, respectively. The power generation of the Three Gorges Hydropower Station exceeded 100 \( \times 10^9 \) kWt in 2018, equivalent to saving 31.9 \( \times 10^9 \) tons of standard coal and reducing 85.80 \( \times 10^9 \) tons of CO₂ emissions\(^{16}\). The reduction in inorganic carbon sinks from the sedimentation in the TGR was equivalent to a limited amount (TCS for 7.9% and SCS for 2.7%) of the reduced CO₂ emissions by the

### Table 2. The variation of carbon sink capacity and potential of suspended sediment along the Yangtze mainstream.

| Sampling point | Station       | Basin area (10⁶ km²) | Average annual sediment flux (10⁶ tons) 1956–2000 | Average CaO content of the three campaigns (%) | Average MgO content of the three campaigns (%) | TCS capacity (t/t) and potential (10⁴ tons) | Calcite content in July 2005 (%) | Dolomite content in July 2005 (%) | NSCS capacity (t/t) and potential (10⁴ tons) | SCS capacity (t/t) and potential (10⁴ tons) |
|----------------|---------------|----------------------|---------------------------------------------------|-----------------------------------------------|-----------------------------------------------|------------------------------------------|----------------------------------|-----------------------------------|----------------------------------------|----------------------------------------|
| M01            | Tuotuo River  | –                    | –                                                 | 14.09                                         | 2.24                                          | 0.271                                    | 15.6                             | 1.2                               | 0.210                                  | 0.061                                  |
| M07            | Cuntan        | 86.7                 | 4.39                                             | 4.92                                          | 3.35                                          | 0.151/6629                               | 3.8                              | 2.4                               | 0.104/4566                             | 0.047/2063                             |
| M12            | Yichang       | 100.5                | 5.03                                             | 2.94                                          | 3.23                                          | 0.117/5885                               | 0                               | 4.1                               | 0.078/3923                             | 0.039/1962                             |
| M16            | Wuhan Industrial Port | 148.8               | 4.04                                             | 3.59                                          | 3.19                                          | 0.127/5131                               | 4                               | 3.4                               | 0.097/3919                             | 0.030/1212                             |
| M19            | Datong        | 170.5                | 4.33                                             | 2.26                                          | 2.56                                          | 0.092/3984                               | 1.8                              | 2.4                               | 0.065/2815                             | 0.027/1169                             |
| M25            | Wusongkou     | –                    | 2.18                                             | 2.56                                          | 0.091                                         | 0                                           | 0.51                            | 1.5                               | 0.051                                  | 0.040                                  |

This table shows the variation of carbon sink capacity and potential of suspended sediment along the Yangtze mainstream.
Table 3. Reduction in the carbon sink caused by the reduction in sediment transport in the reach between Cuntan Station and Datong Station after 2006.

| Station     | Average annual sediment flux (10⁸ tons/yr) | Carbon sink reduction (10⁶ tons of CO₂/yr) |
|-------------|------------------------------------------|---------------------------------------------|
|             | 1956–2000  | 2006–2019  | Total carbon sink | Nonsubstantial | Substantial |
| Cuntan      | 4.39       | 1.21       | 1852             | 1224           | 628         |
| Datong      | 4.33       | 1.23       |                   |                |             |

Three Gorges Hydropower Station. Moreover, the sediment deposited by the TGR could bury and store vast quantities of organic carbon⁶, and particulate organic carbon (POC) contents in the TGR in recent reports¹⁷–¹⁹ varied from 0.26 to 9.2%. An average of 1.5% of POC in buried sediment was used to estimate annual buried organic carbon, and the relatively permanent sedimentation of organic carbon was equivalent to 6.30 × 10⁶ tons of CO₂ sequestration. The losses of annual TCS and SCS via silicate weathering by the TGR project could also offset 107.28% and 36.36% of its annual CO₂ sequestration (6.30 × 10⁶ tons) via permanent sedimentation, respectively.

From a global perspective, 4462 rivers with basin areas of more than 100 km² showed that the current annual sediment flux of global rivers into the sea was 12.61 × 10⁹ t/a⁸. Taking the preimpoundment period TCS of 0.060 t/t for the stream segment between Cuntan and Wusongkou (the mouth of the Yangtze River) into consideration, the total inorganic carbon sink amount of 7.57 × 10⁸ tons of CO₂ was derived from global rivers, which is equivalent to 71.6% of the total inorganic carbon sink of global rock weathering (1.056 × 10⁹ tons of CO₂), with weathered silicate being more than 26% of the total weathered rocks⁴,¹⁰. The enhanced silicate rock weathering (ERW) strategy proposed by Beerling et al.¹ would create a higher annual SCS, reaching 2 × 10⁹ tons of sequestered CO₂. To achieve this goal, there is no doubt that the inorganic carbon sink amount contributed by the dissolution of calcium and magnesium minerals in the processes of river sediment transport accounted for a great portion of the carbon sink amount via global rock weathering. The collision and abrasion of river sediments combined with stirring and mixing could promote the dissolution of minerals during sediment transport processes (off-site weathering of the rock). Therefore, it was suggested that the dissolution rate of off-site rock weathering was higher than that of in situ weathering. In comparison to the periods with limited anthropogenic influences, the global sediment fluxes to the sea decreased by approximately 10%²⁰, and the corresponding total carbon sink loss in a year was estimated to be 0.757 × 10⁹ tons of CO₂, which was still less than the amount of CO₂ emission reduction contributed by hydropower exploration and the associated buried organic carbon per year.

Conclusions

The rock weathering processes included in situ weathering during the development of weathering crust and off-site weathering during sediment transport. The dissolution of silicate and carbonate minerals in river sediment consumed CO₂ in river water. From June 2003 to December 2017, the average annual sedimentation of the Three Gorges Reservoir (TGR) was 114.5 × 10⁶ tons, and the related reduction in inorganic carbon sinks from sedimentation by the TGR was only equivalent to a limited amount (7.9% for the TCS and 2.7% for the SCS) of the reduced CO₂ emissions by the Three Gorges Hydropower Station. The TCS of global rivers was estimated at 757 × 10⁶ tons, which is equivalent to 71.6% of the TCS by global rock weathering with 1.06 × 10⁹ tons of sequestered CO₂, among which the SCS was more than one quarter of the TCS. The dissolution of calcium and magnesium minerals during river sediment transport accounted for a great portion of the carbon sink amount by global rock weathering. The collision and abrasion of river sediments combined with stirring and mixing could promote the dissolution of minerals during sediment transport processes (off-site weathering of the rock). Therefore, it is suggested that more attention should be given to dissolution processes and rates of off-site rock weathering, which might be more significant than in situ weathering, especially in the upper reaches of large rivers.

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X.Z., X.W., J.T., T.P. proposed the idea and provided useful insights. J.L. collected data and prepared all figures. All authors drafted the manuscript and reviewed the manuscript.

Competing interests
The authors declare no competing interests.

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