Potential effect of upstream sediment trap by a dam on dissolved organic matter transported into the Three Gorges Reservoir, China

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Abstract. This paper demonstrates how suspended sediment trapped by dam construction may impact the quantity of dissolved organic matter (DOM) exported discharge entering the Three Gorges Reservoir (TGR). Suspended sediment and water samples were collected along the upper Yangtze River and its major tributaries, and their water and sediment properties determined. The results provided evidence of the more organic polluted nature of the tributaries compared to the upper mainstream Yangtze River. However, the measured DOM concentration in the waters within the TGR downstream from the tributary confluence, was 14% — 25% lower than that estimated just from mixing runoff. In contrast, the measured contents of particulate organic matter (POM) along the main Yangtze River increased by around 20%, whilst the partitioning coefficient of organic matter between sediment and water peaked $2.99 \times 10^3$. The results indicated that the sediment from the upper Yangtze River possibly absorbed the DOM sourced from the tributaries with the organic contamination. The annual DOM load which equals the average concentration of DOM multiplied by exported runoff, entering the TGR has been predicted to increase by 15% — 23% during the operation period of another dam named after Xiluodu constructed upstream from the TGR.

1. Introduction
Suspended sediment load from upper Yangtze River basin has been increasingly reduced in the last decade due to large-scale implementation of eco-restoration projects and dam construction[1]. It is estimated that the scheme could reduce 47% of the sediment load imported for the Three Gorges Reservoir (TGR) from 2013 onwards when the Xiluodu hydropower plant located at nearly 1,100km upstream of the Three Gorges Dam is fully operated[2].

It is a fact that a lot of fishes were found dead on the downstream of the Xiluodu Dam in 2014 after the full operation of the Xiluodu hydropower plant. The water quality of TGR that had been problematic involved organic contaminants since the TGR was impounded in 2003. The different types of organic pollutants such as substituted benzene derivatives were identified in the Chongqing section with the high number of dissolved organic contaminants detected slightly less than those in Nanjing and Shanghai – mega-cities in the estuary of the Yangtze River. Higher levels of dissolved organic pollutants were detected in the base-flow season with the lack of sediment in water column rather than the flood-flow season[3].
Suspended sediment strongly controls the transfer, dispersal and fate of DOM associated with organic contaminants drained into river systems[4-6]. Adsorption and biodegradation of DOM highly correlated with organic contaminants are two interrelated processes occurring in sediments. For most organic contaminants, the partition coefficient for sediment-water systems was recorded in the range of 10-10³ so that they can accumulate in the sediment to much higher levels as compared to those in the water column[7-17]. It reported that the sediment plays a part role in water quality improvement, evidenced by the fact that the concentrations of some dissolved organic contaminants discharged into the rivers suddenly dropped below detection limits due to their adsorption by suspended sediment[18-23].

There is a knowledge gap in quantitative understanding of the role of upstream sediment trapping on the fate of the downstream DOM associated with the organic contaminants. Such information is needed to inform the development of reservoir management strategies aimed at controlling sediment-associated contaminants. For instance, the sediment from the upper Yangtze River, which is mostly generated by gravity erosion, is relatively uncontaminated before that sediment entering the TGR, which may function as a sort of geoadsorbent[24].

Against the background that the TGR faces the high risks of anthropogenic organic pollution and sharp decline of the load of suspended sediment that might be a sort of functional adsorbent to organic contaminants, this paper demonstrates how suspended sediment trapped by dam construction may impact the quantity of DOM exported discharge entering the TGR.

The main objectives of the study were: 1) To examine the spatial variation of organic matter concentration in the sediment and water sampled from the mainstream of Yangtze River and its tributaries (the Min River and the Tuo River), and to assess the partitioning behavior of organic matter between sediment and water. 2) To quantitatively predict the potential effect of upstream sediment trapped by the Xiluodu Dam on the annual DOM load, which equals the average concentration of DOM in the water column multiplied by exported runoff, entering the TGR.

2. Materials and methods

2.1. Study area
The Three Gorges Reservoir (29°16’-31°25’N, 106°50’-111°50’E) stretches a 600km valley from Chongqing City to Yichang City, boasting a capacity of 39.3 billion m³ and a total area of 1084 km² (see Figure 1). The water level of the TGR operates at 145m in summer and up to 175m in winter. The Xiluodu Dam with a capacity of 12.7 billion m³ is located at nearly 1100km upstream of the Three Gorges Dam, 124km upstream of the Pingshan hydrological station, and 189km upstream of Yibin City where the Min River flows into the Yangtze River[25].

![Figure 1. Study area and sampling sites](image-url)
The Yangtze River flows through Yibin and Zhutuo, then into the Three Gorges Reservoir. The Zhutuo hydrological station is located at the upper end of the Three Gorges Reservoir. The distance from the Xiluodu Dam to the Zhutuo hydrological station is 426 km. The Jinsha River, the main reach of the upper Yangtze River, drains a catchment area of 485,100 km² above the Pingshan station and 454,400 km² above the Xiluodu Dam. The hydrological data from Pingshan has been used for the dam design and research.

The Jinsha River contributes about 50% of the flow and 76% of the suspended sediment load to the TGR, the first-order tributary of the Min River contributes 31% and 14%, and the second-order tributary of the Tuo River contributes 4% and 3%, respectively (see Table 1).

| River | Station | Catchment area (km²) | Runoff (billion m³) | R_w (%) | Sediment load (million tons) | Rs (%) | Average sediment concentration (kg/m³) |
|-------|---------|----------------------|---------------------|----------|----------------------------|--------|--------------------------------------|
| Jinsha | Pingshan | 485,100 | 142.6 | 50.4 | 255 | 76.3 | 1.79 |
| Min | Gaochang | 135,400 | 86.6 | 30.6 | 48.4 | 14.5 | 0.56 |
| Tuo | Lijiawan | 23,300 | 12.4 | 4.38 | 9.8 | 2.93 | 0.79 |
| Chishui | Chishui | 20,400 | 8.2 | 2.89 | 7.3 | 2.19 | 0.93 |
| Heng | Hengjiang | 14,900 | 9.2 | 3.26 | 8.3 | 2.50 | 0.92 |
| Yangtze | Zhutuo | 694,700 | 283 | 100 | 334 | 100 | 1.18 |

Notes: R_w is relative contribution of runoff to the Zhutuo station at the Yangtze River; Rs is relative contribution of sediment load to the Zhutuo station at the Yangtze River.

Both of the tributaries drain the Sichuan Basin which is dominated by urban and industrial land use in their middle and lower reaches, whereas the Jinsha River drains a rural catchment which is dominated by high mountains and sloping agricultural land. Chongqing, which is the largest city in the TGR, is subject to considerable organic pollutants due to its developed industry and high urbanization. A reference site (Zhongxian, S5) in the middle of TGR, downstream from Chongqing Urban Section of the Yangtze River and Jialing River, provided useful background information that we need to quantitatively assess accumulation of organic pollutants on sediment.

2.2. Sampling procedure and analytical methods
Before the Xiluodu Dam stopped the flow, water samples were taken from seven sites: S1, S2, S3, S4, S5 on the main stem of the Yangtze River; S6 on the Min River; S7 on the Tuo River. Suspended sediment samples of around ten grams for each sampling site were immediately online collected by the novel sediment sampler (national patent number 201621269967.0), which is a desirable and low-costing alternative to a centrifuge or filtering separation system[26].

Figure 2. Schematic view of sediment sampler
All samples were collected in Nov, 2006 when the water lever of TGR was 156m, just before the Xiluodu Dam constrained the flow of the upstream Yangtze River in 2007.

The 20L surface waters sampled from the rivers were refrigerated at 0-4 °C in Teflon barrels and 100mL filtered through a membrane with 0.45 μm apertures for determination of pH, conductivity, K₂Cr₂O₇-H₂SO₄ Chemical Oxygen Demand (COD₇)[27]. The suspended sediment samples filtered from the water samples were air-dried at room temperature, gently disaggregated.

The grain-size distribution and specific-surface-area (SSA) of the sediment samples were measured using a Digisizer laser diffraction granulometer. The pH value of the sediment samples was determined on the sediment-to-water ratio of 1: 2.5. The content of organic matter in the sediment was determined by the method of capacity titration following K₂Cr₂O₇-H₂SO₄ digestion[27]. The contents of total nitrogen (TN) and total carbon (TC) in the sediment samples were measured by Carlo ErbaNA2500 C/N instrument.

2.3. Data analysis
The concentrations of organic matter both in the water and sediment samples were measured by the method of capacity titration following K₂Cr₂O₇-H₂SO₄ digestion, but the former was calculated on oxygen versus the latter on carbon. To compare the distribution diversity of organic matter between water and suspended sediment, COD₇ in the water is transformed to the content of dissolved organic matter (DOM) in the water by the formula listed below.

\[ DOM = COD_7 \times 0.375 \times 1.724 \]  

(1)

Where DOM represents concentration of dissolved organic matter in water column (mg/L); COD₇ represents concentration of K₂Cr₂O₇ chemical oxygen demand (mg/L); 0.375 represents shift coefficient from oxygen to organic carbon, 1.724 represents transfer coefficient from organic carbon to organic matter [27].

The partition coefficient (KP) of organic matter for sediment-water systems was calculated as the ratio between the concentration of dissolved organic matter (DOM, mg/L) in the water and the content of particulate organic matter (POM, mg/g) in the suspended sediment.

\[ K_P = POM \times 1000 / DOM \]  

(2)

The annual load of DOM (A_DOM, million t/a) or POM (A_POM, million t/a) was estimated respectively as:

\[ A_{DOM} = DOM \times Q_w \times 10^{-3} \]  

(3)

\[ A_{POM} = POM \times Q_s \times 10^{-3} \]  

(4)
Where $Q_s$ represents annual mean runoff at each sampling site (billion m$^3$/a), $Q_i$ represents annual mean sediment load at each sampling site (million t/a).

The contribution ratio of organic matter individually from water and suspended sediment was calculated as below in each study stream-section.

$$R_{DOM} = \frac{A_{DOM}}{A_{TOM}} = \frac{A_{DOM}}{(A_{DOM} + A_{POM})}$$  \tag{5}

$$R_{POM} = \frac{A_{POM}}{A_{TOM}} = \frac{A_{POM}}{(A_{DOM} + A_{POM})}$$  \tag{6}

Where $R_{DOM}$ represents the contribution ratio of dissolved organic matter sourced from the runoff (%); $R_{POM}$ represents the contribution ratio of particulate organic matter originated from the sediment load (%).

Assuming that the property value of suspended sediment would be a simple mixture of the properties of the upstream catchments, the POM content entering the TGR downstream from the confluence of the tributaries is estimated in proportions defined by mixing sediment yield from the tributaries joining the Yangtze River mainstream. If the estimated value of POM is less than the measured value of POM, there may be a case for invoking the biogeochemical transformation such as adsorption of organic matter by suspended sediment to explain the minus between the estimated and the measured value of POM.

$$POM_s = POM_{measured} - POM_{estimated}$$  \tag{7}

The potential increase ratio of annual DOM load ($R_i$) entering the TGR was introduced, assuming that the organic pollutants due to shortage of sediment absorption would turn to the water column as well as both the runoff and organic pollution remain at the present level.

$$R_i = D_s \times Q^p_s \times POM_s / A^Z_{DOM}$$  \tag{8}

Where $D_s$ represents decreasing ratio of sediment trapped by the Xiluodu Dam; $Q^p_s$ represents annual mean sediment load at the Pingshan station where the Xiluodu Dam located (million t/a); $POM_s$ represents content of organic matter absorbed by the sediment (mg/g); $A^Z_{DOM}$ represents annual mean DOM load at the Zhutuo station at the head of TGR (million t/a).

3. Results and discussion

3.1. Spatial variation of DOM and POM

Concentrations of DOM in the waters are listed in Table 2. The lowest DOM was found downstream from the Xiluodu Dam in the upper Yangtze River. The relatively high DOM was observed in the tributaries of Min River and Tuo River, which is approximately 1.5 times of the average level in the mainstream of Yangtze River. Evidently, both of the tributaries were more polluted than the Yangtze River. Downstream of the confluence of both tributaries with the main Yangtze River, the concentration of DOM increased slightly but had decreased slightly further downstream at Zhutuo Station (S4) at the head of TGR. Similar trends in DOM levels were observed between each of the sites.

| River | Sites | pH DOM (mg/L) | pH POM (mg/g) | TC (%) | TN (%) | SSA (m$^2$/g) |
|-------|-------|---------------|--------------|--------|--------|--------------|
| Yangtze | S1 | 8.23 | 5.48 | 7.75 | 9.22 | 2.54 | 0.06 | 0.178 |
|       | S2 | 8.25 | 5.69 | 7.77 | 9.88 | 2.71 | 0.07 | 0.197 |
|       | S3 | 8.26 | 6.23 | 7.69 | 15.1 | 2.64 | 0.06 | 0.137 |
|       | S4 | 8.30 | 5.61 | 7.84 | 13.8 | 2.93 | 0.08 | 0.200 |
|       | S5 | 8.10 | 7.05 | 7.10 | 21.1 | 2.61 | 0.10 | 0.895 |
| Min   | S6 | 8.36 | 7.50 | 7.55 | 19.6 | 2.70 | 0.10 | 0.188 |
| Tuo   | S7 | 8.18 | 11.2 | 7.65 | 29.2 | 1.90 | 0.13 | 0.342 |
With the exception of finer sediment in both the sampling sites of S5 within the TGR and S7 in the Tuo River, the sediment samples showed a similar grain-size distribution (see Figure 2). The median grain size of the sediment sampled from the Pingshan Station (S1) and Zhutuo Station (S4) was found to be 0.013mm and 0.012mm, respectively, which was analogous to that of the suspended sediment recorded in the Zhutuo station [28-29]. That means the sediment samples in this paper can be representative of the suspended sediment within the study area.

![Figure 4. Grain-size distributions of sediment samples](image)

In the sediment samples of the Yangtze River and its tributaries, the lowest concentration of organic matter was measured downstream from the Xiluodu Dam in the upper Yangtze River (see Table 2). In accordance with more organic matter in the water of both the tributaries, the contents of organic matter in their sediments were one or two times higher than those in the mainstream Yangtze River. The concentration of organic matter in the sediment doubled downstream from the Xiluodu Dam (S1) to the middle of the TGR (S5), displaying a sharp increase downstream along the Yangtze River.

In terms of total nitrogen (TN) in the sediments, only small differences in levels were observed between the sites, which are in accordance with the variation of the grain-size distribution in the sediments. For the Yangtze River sites S1 to S4, each pair of values was within the range of analytical variability (about 15%). It indicated that there was no significant nitrogen absorption by the sediment, which was in agreement with the monitoring data that more than 90% of nitrogen in the Yangtze River existed in dissolved form, as compared to more than 50% organic carbon transported in particulate form[30].

The total carbon (TC) contents in the sediments sampled from the Yangtze River showed little differences between different sampling sites, with the average value of 2.69% ± 0.15%. However, the carbonate contents in those sediments showed a declining tendency along the Yangtze River from the Xiluodu Dam (S1) to the middle of TGR (S5), whereas the percentage of loss-on-ignition obviously increased. The results showed that the carbon forms in the Yangtze River sediments transformed with less inorganic carbon and more organic carbon due to sediment absorption of the DOM from the water of the polluted tributaries.

In summary, the results showed that the sediment from the upper Yangtze River may act as adsorbents for organic matter further downstream. This research provides direct field evidence for the importance of organic uptake by suspended sediment to the water quality improvement when the tributaries associated with more organic contamination flow into the Yangtze River. The results suggest that the sediment flowing through the Xiluodu Dam could continuously absorb the organic pollution from the tributaries flowing through the Sichuan Basin, which may result in the decrease of DOM entering the TGR. Similar results were found within the TGR downstream from the
Chongqing Urban Section of the Yangtze River[31-32].

3.2. Partitioning behaviour of Organic Matter between sediment and water
In Table 3, the partition coefficient $K_p$ of Organic Matter for sediment-water systems, which is the ratio of the content of POM in sediment and the concentration of DOM in water, showed an obvious increase along the Yangtze River from the Xiluodu Dam (S1) to the middle of TGR (S6). The highest $K_p$ of $2.99 \times 10^3$ in the middle of TGR (S5) was nearly twice times compared to the lowest $K_p$ downstream from the Xiluodu Dam (S1), whilst the relatively higher $K_p$ ($2.46 \times 10^3$) appeared at the head of TGR (S4). The results showed that the Yangtze River sediments can be highly enriched with organic matter compared to the water, and the sharp increase of POM in the Yangtze River sediment samples also indicated that the sediment from the upper Yangtze River continuously accumulate the organic matter along the Yangtze River. The average of $K_p$ in the Yangtze River was $(2.26 \pm 0.55) \times 10^3$, which is slightly lower than that in its tributaries, i.e. the Min River and the Tuo River. The results showed that the content of POM on the studied sediments was really much higher than the concentration of DOM at each sampling cross-section. The partition coefficient $K_p$ in the studied area is positively correlated with the DOM levels at each of the sampling sites, which indicated that the increasing content of POM in the Yangtze River downstream from the Xiluodu Dam may be attributed to the higher level of DOM in the tributaries delivered from Sichuan Basin.

Table 3. Partition coefficient ($K_p$) of Organic Matter for sediment-water systems and contribution ratio $(R_{DOM}, R_{SOM})$ of annual load of DOM and POM

| River | Sites | $K_p$ (times) | $A_{DOM}$ (million t/a) | $A_{POM}$ (million t/a) | $R_{DOM}$ (%) | $R_{POM}$ (%) |
|-------|-------|-------------|----------------|----------------|----------------|----------------|
| Yangtze | S1 | $1.68 \times 10^3$ | 0.78 | 2.35 | 25.0 | 75.0 |
|       | S2 | $1.74 \times 10^3$ | 1.30 | 3.00 | 30.3 | 69.7 |
|       | S3 | $2.42 \times 10^3$ | 1.49 | 4.73 | 23.9 | 76.1 |
|       | S4 | $2.46 \times 10^3$ | 1.59 | 4.61 | 25.6 | 74.4 |
|       | S5 | $2.99 \times 10^3$ | 3.18 | 7.13 | 30.8 | 69.2 |
| Min   | S6 | $2.61 \times 10^3$ | 0.65 | 0.95 | 40.6 | 59.4 |
| Tuo   | S7 | $2.59 \times 10^3$ | 0.14 | 0.29 | 32.8 | 67.2 |

The sum of annual load of DOM in both of the Min River and the Tuo River is 0.79 million t/a, which is slightly higher than that of the sampling site S1 from the upper Yangtze River (i.e. the Jinsha River). Compared to that, the total annual load of POM in both of the Min River (0.95t/a) and the Tuo River (0.29t/a) is 1.24 million t/a, which is only half of that of the upper Yangtze River (S1). The results indicated that the polluted tributaries flowing through the Sichuan Basin contributed considerable DOM load to the TGR rather than POM. The annual amount of DOM at the Zhutuo station at the head of the TGR was 1.59 million tons. The annual amount of DOM double increased to 3.18 million tons in the middle of TGR when the Yangtze River flowing through the urban city of Chongqing, which is 1.4 times higher than that in the Min River and 10 times higher than that in the Tuo River. The results showed that the central industry city of Chongqing contributes much higher DOM load to the TGR compared to the upper tributaries. Totally, the results indicated that the external load of DOM from the tributaries and the industry city contributed most of DOM to the TGR water.

In the studied area, the average percentage of annual amount DOM transported by the waters was $29.8 \pm 5.8\%$ and the average percentage of annual amount POM delivered by the sediments was $70.1 \pm 5.8\%$, which indicated that the sediment was the main carrier for transporting the organic matter. Between the Pingshan Station where the Xiluodu Dam located (S1) and the Zhongxian Station in the middle of TGR (S5), the percentage of annual amount DOM increased from 25.0% to 30.8%. Compared to the Yangtze River, the percentage of annual amount DOM was relatively higher in both the Min River and the Tuo River. The percentage of annual amount DOM was positively correlated
with the DOM level in the corresponding waters. Although the content of POM continuously increased on the sediments sampled from S1 to S5, the percentage of annual amount POM decreased from 75.0% to 69.2%. The percentage of annual amount POM in the sediment sampled from the Min River and the Tuo River was also lowered to 59.4% and 67.2%, respectively. It is noticeable that the percentage of annual amount POM was negatively correlated with the DOM level in the waters, which means the sediments with relatively high content of POM in the studied area did not contribute organic matter to the water column. The results indicated that the preferential partitioning of organic matter in the sediment would be helpful to decrease the DOM level in the water column.

3.3. Estimates of variation in DOM load due to sediment trapping by the Xiluodu Dam
The Jinsha River transfers 255 million tons of suspended sediment load from its Pingshan Station to the TGR, which contributes 76% of the total suspended sediment load (334 million tons) entering Zhutuo Station in the Yangtze River. The tributaries of the Min River and the Tuo River contribute only 17% of suspended sediment load to the TGR (Table 1). Hence, the Jinsha River contributes most of the suspended sediment load to the TGR. It should be reasonable that the suspended sediment from the Jinsha River plays the key role in decreasing the DOM transported from the polluted tributaries due to sediment absorption.

| Year | $D_i$ (%) | $R_i$ (%) | Year | $D_i$ (%) | $R_i$ (%) | Year | $D_i$ (%) | $R_i$ (%) |
|------|-----------|-----------|------|-----------|-----------|------|-----------|-----------|
| 10   | 58.0      | 22.3      | 40   | 55.8      | 21.4      | 70   | 48.7      | 18.7      |
| 20   | 57.6      | 22.2      | 50   | 54.3      | 20.9      | 80   | 43.9      | 16.9      |
| 30   | 56.9      | 21.9      | 60   | 52.3      | 20.1      | 90   | 39.8      | 15.3      |

Using the formula 7, the difference of POM (2.40 mg/g) was taken as the absorption content by the sediment from the upper Yangtze River. That absorption content multiplied with the annual sediment load of 255 million tons at the Pingshan Station, the annual amount of DOM absorbed by the sediment in the Jinsha River was estimated to be 612 million tons, which accounted for 38.6% of the annual DOM amount at the Zhutuo Station entering the TGR.

The reduction ratio of the sediment load at the Pingshan station has been predicted since the Xiluodu Dam being impounded in 2015 and listed in Table 4 (Zhu and Chen, 2005). According to the formula (8) mentioned above, the DOM load entering the TGR would increase 22.3% ten years since the first impoundment of Xiluodu Dam. However, the impact of sediment trapping by the Xiluodu Dam on the TGR’s DOM load was predicted to be lowered with the increasing sediment outflow through the dam. The DOM load entering the TGR would only increase 15.3% in the next ninety years. Hence, the potential value for the annual DOM load entering the TGR would increase in the range of 15% -- 23%, which indicates the sediment from the upper Yangtze River is of potential importance in relation to environmental management and organic mitigation operations. Release of trapped sediment from the Xiluodu Dam could be considered to be an effective method for mitigating DOM load in the TGR.

Given that the adsorption behaviour of a chemical depends on the physiochemical properties of that chemical on its own and the absorbents, that estimated value in this paper could not be conclusive because the DOM includes a lot of complicated organic compounds with greatly variable physiochemical properties and the sediment regarded as absorbents have highly episodic nature.

Acknowledgment
This study was financially supported by both of the National Natural Foundation of China (Grant No.41301290&41977075) and the laboratory and equipment management at Sichuan University. The laboratory work associated with the highly precise equipments was conducted at the University of
Exeter in the United Kingdom. The authors would thank Professor Quine T. A. and Professor D. L. Higgitt for constructive suggestions, which is helpful in improving this manuscript.

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