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Three Gorges Dam: Friend or Foe of Riverine Greenhouse Gases?

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Abstract

Dams are often regarded as greenhouse gases (GHGs) emitters. Instead, our study indicated that the world's largest dam, Three Gorges Dam (TGD), has caused significant drops in annual average emissions of CO_2, CH_4, and N_2O fluxes over 4,300 km along the Yangtze River, accompanied by remarkable reductions in annual export of CO_2 (79%), CH_4 (50%), and N_2O (9%) to the sea. Since its commencing operation in 2003, the TGD has altered carbonate equilibrium in reservoir area, enhanced methanogenesis in the upstream, restrained methanogenesis and denitrification via modifying anoxic habitats through long-distance scouring in the downstream. These findings suggested that "large-dam effects" are far beyond our previous understandings spatiotemporally, which highlights the fundamental importance of whole-system budgeting of GHGs under the profound impacts of huge dams.

Key Words: Three Gorges Dam, greenhouse gas, spatiotemporal variation, equilibrium, Yangtze River, whole system analysis

INTRODUCTION

Most rivers worldwide are supersaturated with greenhouse gases (GHGs) owing to inputs of carbon (C) and nitrogen (N) from land, and become net sources of GHGs to the atmosphere [1]. To meet the growing global demand for water and energy, more than 70,000 large dams have been constructed [2]. Such dams are regarded as a source of excessive GHGs emissions [3-5]. The estimated annual emissions are 48 Tg C as CO_2 and 3 Tg C as CH_4 from global hydropower reservoirs, and 0.03 Tg N as N_2O from all reservoirs in the world [4, 6].

Previous studies on the effects of dams on GHGs have been mostly limited to the vicinity of reservoirs [7-10]. Although these considerations hold for small dams (reservoir capacity < 10 km^3), the impacts of large dams on GHGs (reservoir capacity ≥ 10 km^3) are much greater because the original physical and biochemical equilibria are disrupted over large spatiotemporal scales. Firstly, a large dam alters the hydrodynamic conditions and material fluxes of a river: after operation commences, the peak flood discharge decreases and fluxes of nutrients and sediment exported to the sea are often reduced [11-14]. Secondly, the river regime tends to remain stable, but increasing longitudinal erosion of the riverbed after the dam causes long-term readjustment over considerable distance [15]. Thirdly, changes to water and sediment fluxes significantly affect the ecosystem functioning of microbial communities [16-18] (e.g. photosynthesis, methanogenesis, and denitrification) and GHGs emissions (Supplementary Table 1).

As the world's largest dam, the Three Gorges Dam (TGD) has been regarded as a significant source of GHG emissions [3, 4, 19]. For example, CO_2 and CH_4 emissions from the 25 km^2 core reservoir area upstream of the TGD in 2008 were estimated as

40 and 20 Gg yr^{-1} respectively, about 40- and 20-fold larger than before impoundment [20]. Similar findings [4, 21] reported that total CH_4 emission rate in the Three Gorges Reservoir (TGR) was 0.315 Gg yr^{-1}. However, the impact of TGD extends far beyond the reservoir area. The TGD has altered hydrodynamic conditions along almost the entire length of the Yangtze as physical and biochemical processes have readjusted both upstream and downstream of the dam, most notably the long-distance, long-term scouring of the riverbed downstream of the dam [15, 22, 23]. This highlights the necessity of whole river analysis in order to assess properly changes of GHGs fluxes affected by large dams.

Here we estimate changes in dissolved and emitted fluxes of GHGs in the Yangtze before and after the TGD became operational in 2003. Based on the time series of 30 water quality indices monitored over 312 months (1990~2015) and the measured GHGs (Supplementary Tables 2~4) along 4,300 km of the Yangtze River (Fig. 1), CO_2 is calculated using the well-known CO2SYS model, while CH_4 and N_2O are estimated with the artificial neural networks (ANNs) (See Methods).

RESULTS AND DISCUSSION

Temporal effect of Three Gorges Dam on CO_2 fluxes.

The mean annual pCO_2 between 1990 and 2002 was 2,526 μatm (Fig. 2). Subsequently pCO_2 declined greatly to 1,336 μatm once the TGD began operation over the whole mainstream (Fig. 2a). This declining trend is particularly significant in the middle and lower reaches, though annual pCO_2 in the upper reach remained relatively steady before and after 2003 (Fig. 2b~d). The spatially averaged annual pCO_2 of $2{,}205\,^{+2497}_{-925}$ μatm (where the numbers display the mean and range of values) in the middle reach. pCO_2 increased to 2,974 μatm during the 1990s, peaked in 1996,

and declined significantly to 1,720 μatm after TGD impoundment [24] (Fig. 2c). In the middle reach, pCO_2 decreased from 2,907 to 1,446 μatm in wet season and from 2,196 to 1,377 μatm in dry season (Supplementary Fig. 1a~d).

From 1990 to 2015, CO_2 exported to the East China Sea exhibited substantial inter-annual variations (Supplementary Fig. 2). The mean annual value increasing from about 469 Gg C yr^{-1} in 1993 until reaching a peak of 3,354 Gg C yr^{-1} during the 1998 flood and then declining back to pre-1993 levels by 2003 (Supplementary Fig. 2). Mean exported CO_2 flux from 1991 to 2015 was 1,128 Gg C yr^{-1}, corresponding to 5.6% of dissolved inorganic carbon transported by the Yangtze River (Supplementary Table 5). The annual averaged CO_2 outgassing flux and CO_2 exported to the sea over the Yangtze experienced remarkable drops of 55% and 79% since 2003, suggesting a much stronger effect due to TGD impoundment on pCO_2 than that from other influencing factors (such as the anthropogenic discharge of sulfur and nitrogen containing pollutants) reported previously [24].

Monthly and annual CO_2 emission fluxes from the upper, middle, and lower reaches were on average lower after 2003, than before, indicating that the entire mainstream progressively became a smaller emission source (Supplementary Fig. 3). The largest change occurred in the middle and lower reaches, where CO_2 emission flux dropped from 2,723 Gg C yr^{-1} before to 1,087 Gg C yr^{-1} after TGR impoundment. Annual-averaged CO_2 emission flux from the Yangtze mainstream was estimated as $2{,}420\ ^{+2590}_{-1200}$ Gg C yr^{-1} (Supplementary Table 6), which accounts for emissions from 1.3% of global rivers and 4.8% of temperate rivers [1, 25] between 25° N and 50° N. These results were convinced reliable with uncertainty analysis based on representative stations as described in Supplementary Information.

Temporal effect of Three Gorges Dam on CH_4 fluxes.

To estimate dissolved and emitted CH_4 over the Yangtze River before and after impoundment of the TGR, monthly observed data of chemical oxygen demand, dissolved oxygen, water temperature, pH and nitrogen during 1990~2015 were used for validation and verification as input variables of ANNs models (See Methods). Supplementary Fig. 4 showed spatiotemporal variations in dissolved nitrogen (NH_4^+, NO_3^-, NO_2^-) in the whole mainstream during the period 1990~2015.

After the TGR impoundment in 2003, both dissolved and emitted CH_4 concentrations increased in the upper reach, decreased in the middle reach, and hardly changed in the lower reach (Fig. 2f~h, Supplementary Fig. 5b~d). Annual averaged CH_4 concentration from 1990 to 2015 over the whole mainstream is $2.22^{+0.54}_{-0.65}$ μg L^{-1} (Fig. 2e), comparable to that for the Amazon River (Supplementary Table 7) [26]. Mean dissolved CH_4 was $3.15^{+0.62}_{-0.56}$ μg L^{-1} in the dry season and $2.57^{+0.59}_{-0.72}$ μg L^{-1} in the wet season in the Yangtze (Supplementary Fig. 1). A major change in seasonal cycles of dissolved CH_4 appears to have occurred in 2003. In the wet season, the mean dissolved CH_4 increased from 1.45 to 1.95 μg L^{-1} in the upper reach but decreased from 3.51 to 3.02 μg·L^{-1} in the middle reach. Based on the parameters derived from representative stations (Supplementary Table 8), temporal variation in CH_4 flux exported to the East China Sea decreased from 3.1 to 1.5 Gg C yr^{-1} after 2003 (Supplementary Fig. 6). Emitted CH_4 flux decreased from 3.3 to 2.7 Gg C yr^{-1} along the whole mainstream, with increasing from 0.4 to 0.5 Gg C yr^{-1} before the dam and decreasing from 2.9 to 2.2 Gg C yr^{-1} after the dam since the operation of TGD (Supplementary Fig. 7).

Temporal effect of Three Gorges Dam on N_2O fluxes.

Input variables in the ANN model for estimation of N_2O emissions included dissolved oxygen, water temperature, pH and nitrogen. Total dissolved nitrogen (NH_4^++NO_3^-+NO_2^-) increased during the period of interest, while NH_4^+ and NO_2^- had much lower concentration levels than NO_3^- (Supplementary Fig. 4). This is consistent with increasing nitrogen inputs from fertilizers to the Yangtze river basin in the past few decades, enhanced by population and economic growth in central and east China [27, 28]. After training and verification of the ANN, the modeled results showed slight reduction of dissolved and emitted N_2O owing to the dam operation since 2003. Over the Yangtze mainstream, the annual average concentration was $0.45^{+0.38}_{-0.22}$ μg·L^{-1} (Fig. 2i), demonstrated a moderate dissolved N_2O concentration compared with other large rivers (Supplementary Table 9). Dissolved N_2O experienced a maximum of 0.55 μg·L^{-1} at Xuliujing station in the river mouth (Fig. 2l), and a minimum of 0.32 μg·L^{-1} at Luzhou station in the upper reach (Fig. 2j). Impoundment of the TGR operation caused dissolved N_2O to decrease from 0.56 to 0.46 μg·L^{-1} in the middle reach after 2003 (Fig. 2k). Large amplitude variations in seasonal N_2O patterns also occurred in the middle reach (Supplementary Fig. 1k). After 2003, the average dissolved N_2O concentration declined from 0.61 to 0.51 μg·L^{-1} in the dry season and from 0.54 to 0.41μg·L^{-1} in the wet season in the middle reach. Seasonal differences of N_2O emission rates were also calculated (Supplementary Fig. 8e~h). The long-term average (1990~2015) displayed higher N_2O emission rates at Yichang and Wuhan in the wet season than in dry season, in all cases indicating the Yangtze was a net source of N_2O (Supplementary Fig. 8). Meantime, N_2O emission rates at Yichang have fallen from 39.3 to 19.2 μg·m^{-2}·h^{-1} during the wet season and from 18.4 to 11.6 μg·m^{-2}·h^{-1} during the dry season (Supplementary Fig. 8g). Based on monthly dissolved N_2O and

flow discharge, the highest values of N_2O fluxes to the estuary occurred in 1998, the year with historical floods. Mean annual dissolved N_2O fluxes to the estuary decreased from 0.46 to 0.41 Gg N yr^{-1} after TGD impoundment in 2003 (Supplementary Fig. 9), because of the disruptive effect on the physical and biochemistry equilibria of the river. The annual N_2O outgassing in the mainstream was estimated as 0.43 Gg N yr^{-1} (Supplementary Fig. 10).

Spatial effect of Three Gorges Dam on GHGs emissions.

Before 2003, pCO_2 ranged from 880 to 4,399 μatm in the mainstream channel of Yangtze River (Fig. 3a). A trend of increasing pCO_2 was evident along the mainstream, rising from 1,314 μatm in the upper reach to 4,111 μatm in the lower reach, along with the decreasing pH level of the lower reach and dilution by water entering from Poyang Lake during the period 1990~2002. After 2003, pCO_2 was almost constant upstream of the TGD, and then rose immediately downstream of the dam, being affected by flow regulation and sediment trapping [29]. It has been estimated that reservoir sedimentation caused by the presence of a dam results in an average carbon accumulation rate of 400 $g \cdot m^{-2} \cdot yr^{-1}$ globally [30]. Carbon burial therefore becomes a potential available carbon source for biological respiration and might increase pCO_2 in a reservoir, particularly in the early years after impoundment [31]. Other human activities might also increase exchanges between water and mineral, causing pCO_2 to increase [32]. The similar trends of increasing pCO_2 were observed along the mainstream in both wet and dry seasons (Fig. 3b~c). The higher values of pCO_2 in the wet season compared to the dry season, especially in middle and lower reaches, might be due to the efficient production of soil-orginated CO_2 and its transport by surface runoff [31]. Supplementary Fig. 11 shows the CO_2 emission rate profiles along the mainstream before and after operation of the TGD. These are qualitatively very

similar to the dissolved CO_2 profiles. After 2003, the mean CO_2 emission rate along the mainstream was 3.0 ± 1.7 mmol m^{-2} h^{-1}. Degassing rates were higher in middle and lower reaches than in the upper reach, being controlled by pCO_2.

CH_4 concentration was lowest in the upper reach of the Yangtze in both wet and dry season (Fig. 3d~f), primarily because of lower organic matter. After 2003, CH_4 concentration increased slightly from 1.50 to 1.83 μg L^{-1} in the upper reach, and decreased from 3.13 to 2.74 μg L^{-1} in the lower reach (Fig. 3d). The TGD impoundment influenced CH_4 emission rate in a similar trend as to its dissolved concentration (see Supplementary Fig. 5).

The TGD influenced N_2O distributions both upstream and downstream of the dam, especially in the middle reach of the Yangtze (Fig. 3g). After 2003, annual averaged N_2O concentrations decreased slightly from 0.42 to 0.38 μg L^{-1} in the wet season and from 0.55 to 0.50 μg L^{-1} in the dry season (Fig. 3h~i). The most remarkable decrease in N_2O concentration occurred at Yichang, immediately downstream of TGD (Supplementary Fig. 12a). At Yichang, monthly averaged N_2O emission rates fell both in the wet and dry season, and the amplitude of the fluctuations in N_2O emission rate also declined (Supplementary Fig. 12a) with smaller seasonal differences (Supplementary Fig. 12b) after TGD impoundment.

GHGs fluxes in response to readjustment of physical and biochemical equilibria.

Our study indicated that the TGD has caused significant drops in the overall annual GHGs fluxes emitted to atmosphere and exported to sea since 2003 (Supplementary Table 10). To interpret such changes, a whole river analysis (Fig. 4) must be made of the readjustments to hydrodynamic conditions (Fig. 4a) and biogeochemical equilibria (Fig. 4b~d) over the broader spatiotemporal scale of the

river.

Cause for CO_2 drop

Due to TGD impoundment, a backwater zone developed upstream of the dam wherein water exchanges took place between the mainstream and tributaries (Fig. 4b). Water retention time significantly increased in the reservoir in addition to the significantly decreased flow velocity (< 0.2 $m \cdot s^{-1}$) in some tributaries entering into the reservoir. Such changes replenish nutrients in the tributaries by circulation with those in the mainstream [33]. Accumulated nutrients and restricted vertical mixing in the backwater area of the tributaries favored phytoplankton growth [34, 35], further raising algae to flourish [36] (Supplementary Table 11). Algae photosynthetic removal of CO_2 and bioaccumulation of NO_3^-, $H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-} resulted in higher pH in the tributaries, promoting acceleration of eutrophication [37, 38]. The higher pH in tributary helped neutralize hydrogen ions in the mainstream, breaking the carbonate equilibrium of the river, ultimately leading to a sharp drop in CO_2 in the mainstream (Supplementary Fig. 13).

Cause for CH4 drop

Although CH_4 increased upstream, a net reduction of CH_4 emission (about 17%) happened along the whole mainstream after the TGR impoundment, due to CH_4 decrease in the downstream of TGD. The input of dissolved CH_4 to the Ocean decreased by 50%, primarily because the TGD modified the GHGs regime and disrupted the biotic equilibrium of the Yangtze (Fig. 4c). Upstream of the TGD, both dissolved and emitted CH_4 increased after the reservoir impoundment, owing to the effects of flow regulation and sediment trapping. Such carbon burial promotes heterotrophic methanogenesis, thus increasing the dissolved CH_4 content of the

reservoir [29]. Anoxic conditions due to increased water depth in front of the dam would also be beneficial to methanogens locally [11]. However, both dissolved and emitted CH_4 declined downstream of the dam, mainly because of riverbed scouring which damaged the habitat of anaerobic *Archaea* responsible for heterotrophic methanogenesis [39, 40]. In addition, the pre-impoundment clearance also reduced decomposition of OC and inhibited the significant increase of CH_4 emission in the TGR. During reservoir flushing, degassing would occur because of rapid depressurization and strong aeration, resulting in increasing emission of dissolved CH_4, lowering CH_4 concentration downstream [6, 41]. Overall, the TGD acted to regulate the CH_4 emission regime of the Yangtze, making dissolved CH_4 increase in the upper reach and decrease in the lower reach.

Cause for N_2O drop

N_2O flux emission over the mainstream decreased from 0.44 to 0.41 Gg N yr^{-1}, and N_2O export to sea fell from 0.46 to 0.41 Gg N yr^{-1} after TGD operation commenced. Land-use changes and water quality protection measures resulted in low nitrogen loading to the TGR. Formation of hypoxia or even anoxia in the reservoir was generally restricted (Fig. 4d). The promoted denitrification whereby N_2O was transformed directly to N_2, causing N_2O to decrease slightly upstream of the dam [42-44]. On the other hand, riverbed scouring downstream of the TGD altered the habitat of heterotrophic denitrifiers, slowing down denitrification. This is consistent with our findings of high NO_3^- concentration but low NO_2^- concentration in the river [45] (Supplementary Fig. 4; Supplementary Fig. 14a~b). Again, reservoir flushing would have raised degassing of N_2O and N_2. Discharge of cooler, high pressure, bottom water, supersaturated with gases, from the 175 m deep reservoir to the warmer, low pressure downstream river would enhance N_2O emission [14]. Riverine microbial

communities require phosphorus as a nutrient, and pH to regulate nitrification and denitrification processes. The estimated annual mass of reactive P retained by dams along the Yangtze was 0.5 Gmol yr^{-1} in 2010 rising to 2.9 Gmol yr^{-1} by 2030; this would have altered denitrification causing N_2O production to fall[2]. Hence, the influence of phosphorus is likely to be significantly less than riverbed scouring on the nitrogen cycle downstream of TGD. Field observations also exhibited an increase in pH downstream of TGD since 2003; this encouraged nitrification as evidenced by very low levels of ammonium recorded (Supplementary Fig. 14).

Lastly, the key concern becomes how the enlargement of CO_2 (1.8×10^2 ~ 3.4×10^2 Gg C yr^{-1}), CH_4 (0.18 ~ 0.37 Gg C yr^{-1}), and N_2O (0.0072 ~ 0.01 Gg N yr^{-1}) emissions caused by the reservoir itself would be finally offset by the reduction of GHGs emissions resulted from downstream habitat modification. According to pre-impoundment estimates of GHG fluxes from the reservoir and post-impoundment measurements on possible GHG pathways, such a balance-out would be expected at 766 ~ 819 km (for CO_2), 124 ~ 180 km (for CH_4), 18 ~ 53 km (for N_2O) downstream the TGD, respectively (Fig. 5). Under the practical scenarios for TGD operation [46] (Supplementary Table 12), the overall net reduction in GHGs emissions would be still significant (38.43 ~ 44.60 % for CO_2, 14.51 ~ 19.70% for CH_4, and 0.21 ~ 2.50% for N_2O) in the entire Yangtze. In the reservoir area, the river-valley geomorphology restricted rise of littoral shallow area (<10 m), resulting in less CH_4 and CO_2 emissions from ebullition (<8% in the gross GHG emissions estimates of the TGR, see Supplementary Table 13). Sensitivity analysis confirmed the availability of the study results under uncertainties from the models and those induced by the TGR (Supplementary Fig.15~16). In the balance, the net change of GHG emissions directly caused by the TGR could alter neither the dominant GHG emission pathways from

reservoir nor the general GHG reduction trend from the perspective of the full scope of the 4300 km along the mainstream of the Yangtze River (Details see Section 9 in Supplementary Information).

CONCLUSIONS

In contrast to the general claims that dams would increase emissions of GHGs from rivers, we found that the TGD, the world's largest dam, had caused significant reduction in annual average emissions of CO_2, CH_4, and N_2O over 4,300 km along the Yangtze River. Meanwhile, remarkable drop occurred in annual export of CO_2 (79%), CH_4 (50%), and N_2O (9%) to the sea from the river. These findings suggested that much more profound impacts of the "large dams" should be encountered than those expected from the "small dam" effects limited to the vicinity of reservoirs either spatially or temporally. The impoundment of large reservoir not only altered environments in the reservoir area, but also resulted in significant variations of riverine habitats downstream. Especially, longterm and long-distance riverbed erosion downstream of the large dam would essentially change the processes of photosynthesis, methanogenesis and denitrification, commencing the reestablishment of the biogeochemical equilibrium over the whole river system. This highlights the primary importance of the whole system analysis in understanding the complex effects of large dams on readjustments of physical, chemical and biological equilibria in large rivers globally.

METHODS

Water quality was monitored monthly at 43 hydrological stations (blue open circles, Fig. 1). Simultaneous sampling of hydrological, environmental, and all GHG constituents was undertaken in Spring and Autumn 2014 along the continuum of 4300

km (i.e., the actual sinuous channel length, equivalent to 2.05 times the straight line distance of 2102 km from start to the end sampling sites. red circles, Fig. 1). Further monthly sampling took place from November 2014 to September 2015 at six stations (purple solid circles, Fig. 1). Given the limited data available for model establishment (Supplementary Table 2~3), we also included data from previous studies conducted at certain sites along the Yangtze River. Details of model verification are given in Supplementary Table 14 & 15. All samples were collected in triplicate. Dissolved CO_2, CH_4, and N_2O were determined using the headspace equilibration technique [47]. CO_2, CH_4, and N_2O emission rates were measured using the static floating chamber technique [47-48]. CO_2, CH_4, and N_2O concentrations were obtained using a gas chromatograph.

Water chemistry monitoring was conducted by the Changjiang Water Resources Commission on a monthly basis from 1990 to 2015. pH, total alkalinity, HCO_3^-, water temperature (T), pCO_2, and dissolved CO_2 concentrations were determined at 18 stations (Supplementary Table 16). As described in Supplementary Fig.17 and Supplementary Fig.18, artificial neural networks based on backward propagation were used to calculate dissolved CH_4 (with inputs of chemical oxygen demand, dissolved oxygen, water temperature, pH, NO_3^-, and NH_4^+) and N_2O (with inputs of NH_4^+, NO_2^-, NO_3^-, dissolved oxygen, water temperature, and pH). The model validation of dissolved CH_4 and N_2O concentrations (including data from previous studies conducted at certain sites along the Yangtze River) was shown in Supplementary Fig. 19 and Fig. 20. Sensitivity analysis was performed by changing input variables (Supplementary Fig. 15 and Fig. 16). For comparison, calculated dissolved N_2O concentrations from previous regression models were listed in Supplementary Table 17. The greenhouse gas (GHG) emission rate across the air-water interface was

calculated using a two-layer diffusive gas exchange model [49]. Herein, k_{600} is an important parameter for calculating gas emission rate from dissolved gas concentration. Based on the reexamination of existing empirical formulas for k_{600} (Supplementary Table 18), k_{600} was determined for monitoring sites at different reaches of Yangtze River (Supplementary Table 19). Wind speed data near the hydrological stations were extracted from the China Meteorological Data Sharing Service System (http://data.cma.gov.cn). Atmospheric CH_4 concentration was assumed equivalent to the monthly averaged global background concentration at six monitoring stations across the world (NOAA/CMDL/CCGG air sampling network, http:// www.cmdl.noaa.gov/). Model validation and parameter (e.g. k_{600}) determination were detailed in Supplementary Information.

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AUTHOR CONTRIBUTIONS

J.R.N. designed the research. J.R.N., H.Z.W., T.M. and R.H. performed the research. H.Z.W., T.M., R.H., Z.L. and J.F.C. analyzed the data; P.C., A.G.L.B., Y.Y., B.L., Y.C.W., M.S.Z. and T.W. contributed new ideas and information; J.R.N., H.Z.W., Z.L.,

and Y.Y. wrote the paper with help of A.G.L.B. and P.C. All authors read, commented on and approved the final version of this article.

Conflict of Interest. The authors declare no competing financial interests.

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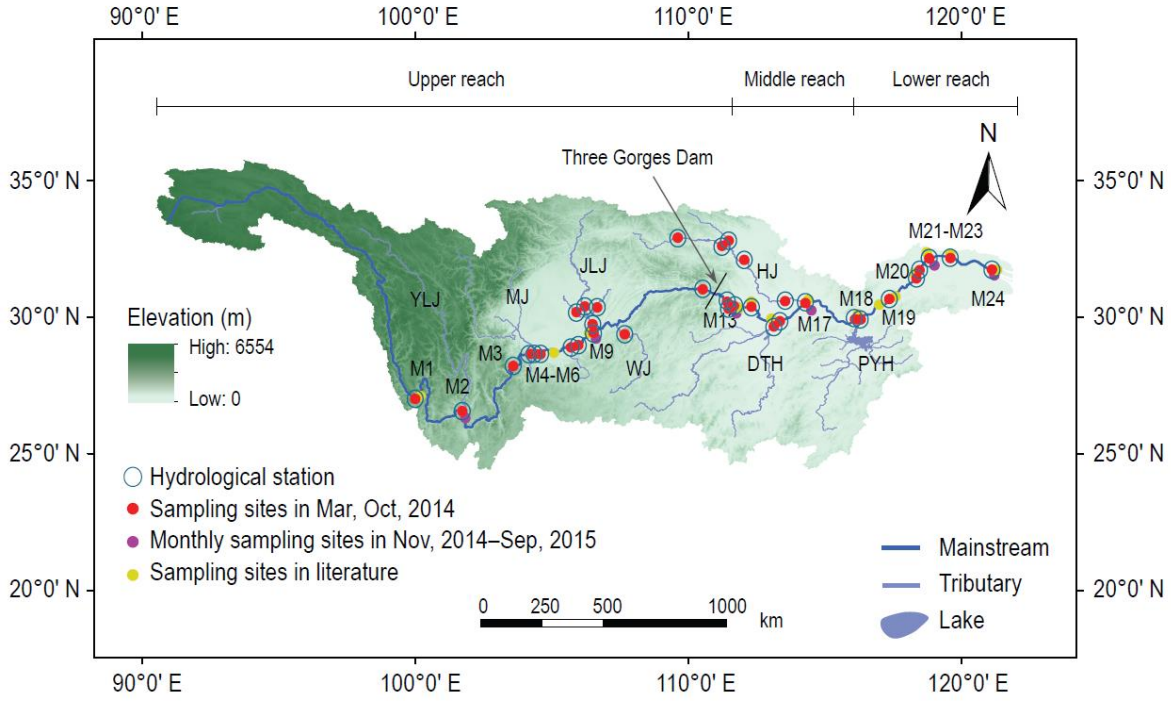

Fig. 1. The Yangtze River Basin and sampling sites. Lines indicate the mainstream river and its tributaries, the former having a continuum of 4,300 km (i.e., the actual sinuous channel length, equivalent to 2.05 times the straight-line distance of 2,102 km from start to the end sampling sites). Yellow solid circles show locations of previous sampling sites (see Supplementary Table 2~3); red solid circles show the locations of our recent simultaneous sampling sites in March and October 2014 (details see Supplementary Table 4); purple solid circles show the locations of our monthly sampling sites from October 2014 to September 2015; blue open circles show locations of the hydrological stations. The upper reach is from Shigu (M1) to Yichang (M13), the middle reach from Yichang to Hukou (M18), and the lower reach from Hukou to Xuliujing (M24). The major tributaries include Yalongjiang (YLJ), Minjiang (MJ), Jialingjiang (JLJ), Wujiang (WJ), and Hanjiang (HJ); two river-regulated lakes are Dongting (DTH) and Poyang (PYH) Lakes.

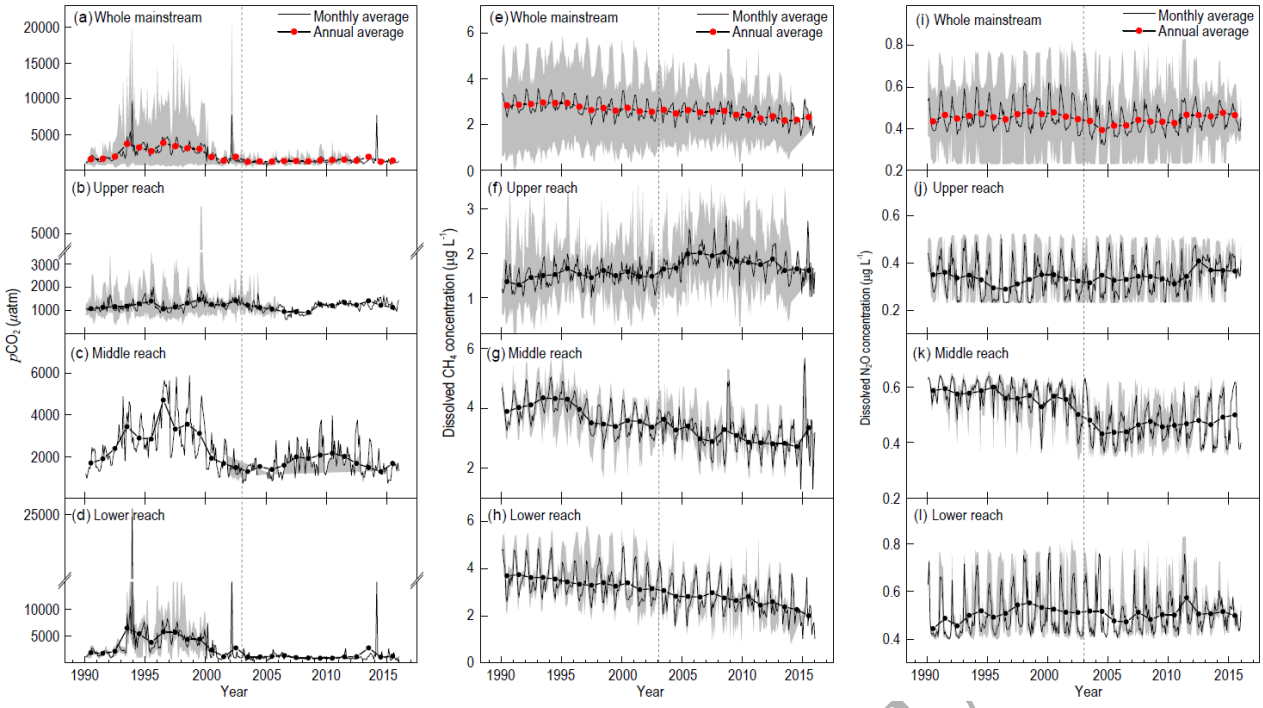

Fig. 2. Temporal variations in monthly and annual averaged dissolved GHGs concentrations from 1990 to 2015. Monthly and annual averaged pCO_2 along the whole reach (**a**), the upper reach (**b**), the middle reach (**c**), the lower reach (**d**); monthly and annual averaged dissolved CH_4 along the whole reach (**e**), the upper reach (**f**), the middle reach (**g**), the lower reach (**h**); monthly and annual averaged dissolved N_2O along the whole reach (**i**), the upper reach (**j**), the middle reach (**k**), the lower reach (**l**). The shadow areas represent the range of dissolved GHGs concentrations at different monitoring stations in the corresponding reaches. Vertical dashed lines denote 2003, when TGD commenced operation.

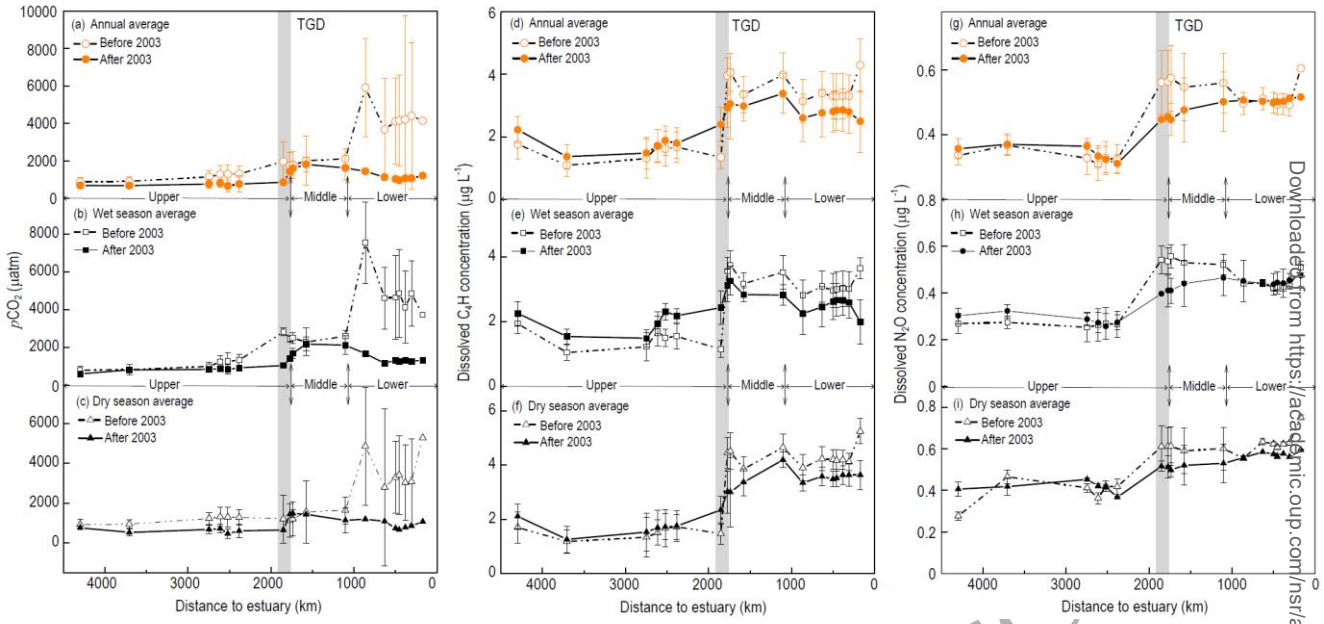

Fig. 3. Spatial variations in annual and seasonal dissolved GHGs concentrations in the 4300 km continuum of the Yangtze River. Annual (**a**), wet season (**b**) and dry season (**c**) averaged dissolved CO_2 concentration profiles along the Yangtze mainstream before and after TGD impoundment in 2003; annual (**d**), wet season (**e**) and dry season (**f**) averaged dissolved CH_4 concentration profiles before and after TGD impoundment, and annual (**g**), wet season (**h**) and dry season (**i**) averaged dissolved N_2O concentration profiles before and after TGD impoundment. The error bars are the standard deviations in different time at monitoring stations. The shaded area indicates where the TGD reservoir is located.

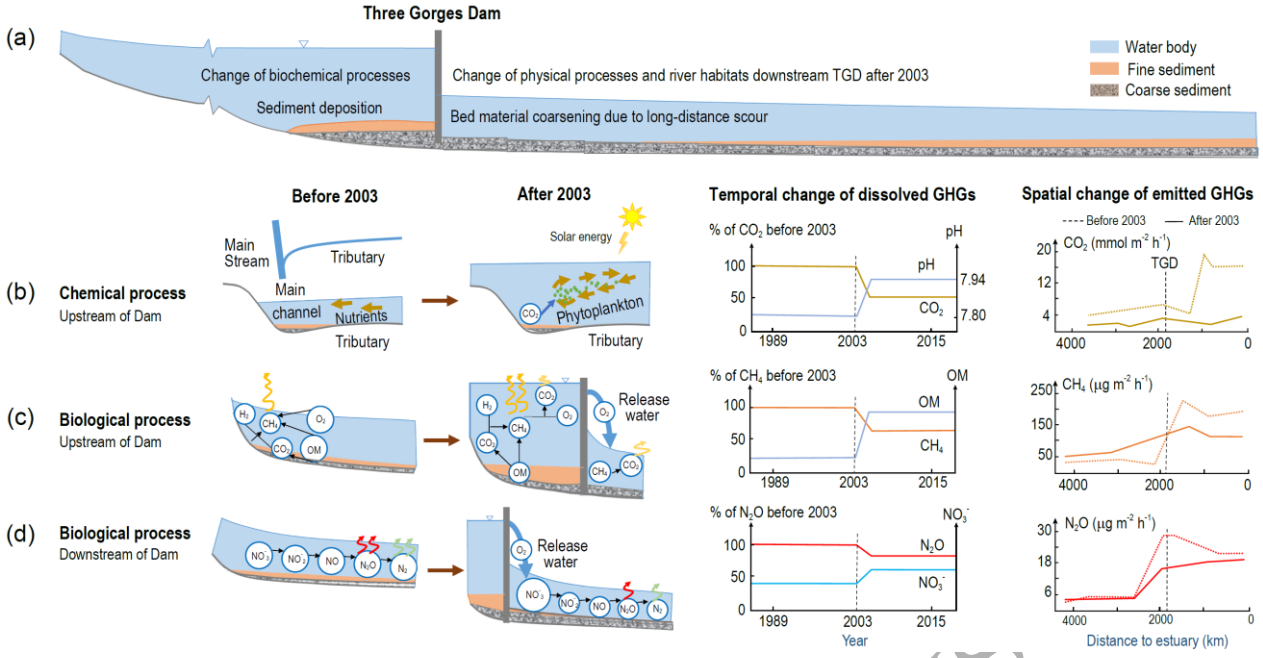

Fig. 4. Whole system analysis concerning readjustment of physical and biogeochemical equilibria involved in regulation effects of Three Gorges Dam on GHGs emissions from the Yangtze River.

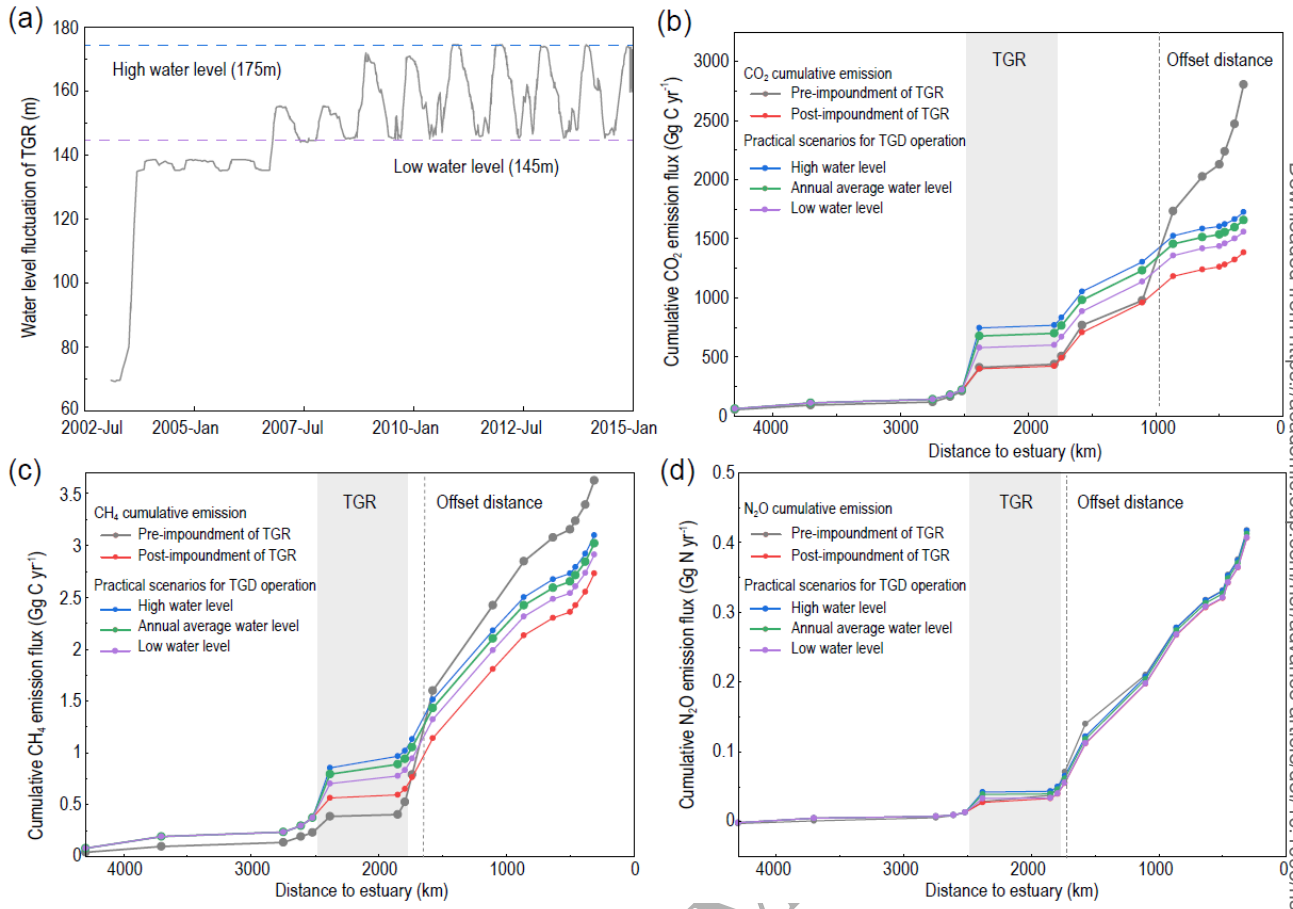

Fig. 5. The balance of GHGs emission fluxes enlarged by the reservoir itself and those reduced by habitat modification downstream the dam under practical TGD operation. According to different scenarios for annual variation of TGD operating water level (**a**), the balance-out distance was 766 ~ 819 km for CO_2 (**b**), 124 ~ 180 km for CH_4 (**c**), and 18 ~ 53 km for N_2O (**d**) downstream the dam, respectively. Under the averaged operating water level, the vertical dotted lines indicate the locations where the changed GHGs emission fluxes due to the reservoir was offset by the decreased in the downstream of the dam.