LETTER

Tributary oscillations generated by diurnal discharge regulation in Three Gorges Reservoir

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Abstract

Among the major consequences of dam construction and operation are the deterioration of water quality and the increasing frequency of occurrence of harmful algae blooms in reservoirs and their tributaries. Former studies at Three Gorges Reservoir demonstrated that the Yangtze River main stream is the main source of nutrients and pollutants to connected tributary bays. Eutrophication and other water quality problems reported for the tributaries along Three Gorges Reservoir are likely a consequence of density-driven exchange flows. Past work has focused mainly on the influence of seasonal and daily flow regulation on exchange flows, less attention has been paid to hydrodynamic processes resulting from sub-daily discharge dynamics. High-frequency measurements of flow velocity and water level in a eutrophic tributary (Xiangxi River) of Three Gorges Reservoir revealed the persistent nature of bidirectional density currents within the bay. Superimposed on this mean flow, we observed ubiquitous flow oscillations with a period of approximately 2 h. The flow variations were associated with periodic water level fluctuations with increasing amplitude for increasing distance from the river mouth (up to ±0.1 m at a distance of 27.4 km from the river mouth). They were caused by a standing wave in the tributary bay, which was generated by rapid increase or decrease in discharge following peak-shaving operation modes at Three Gorges Dam. The high-frequency wave made up the largest contribution to the temporal variance of flow velocity in the tributary bay and represents a so far overlooked hydrodynamic feature of tributaries bays in large reservoirs.

1. Introduction

Physical, chemical and biological characteristics of aquatic ecosystems are strongly affected by water level fluctuations (WLF) [1, 2]. Long-term, e.g. seasonal or multi-year WLF are the result of a variable water balance and often controlled by meteorological and hydrological processes. Short-term WLF, with periods in the order of seconds to hours can be generated by hydrodynamic processes (e.g. standing and propagating surface waves) [3]. Particularly in reservoirs, WLF are, to a large extent, subject to daily discharge regulations [4] and shiplock operation [5].

Three Gorges Reservoir (TGR) is one of the largest reservoirs in the world and is among the most controversial hydraulic engineering projects in China [6]. High environmental costs have caught the attention of researchers from the globe [7, 8]. Among the major consequences of reservoir construction and operation is the deterioration of water quality in more than 38 tributaries and the continuously increasing frequency of occurrence of harmful algae blooms in tributaries [6]. The main source of nutrients and other pollutants in tributary bays is the Yangtze River, which can flow into the bays as a density current [9]. The type of bidirectional water exchange at the river
Figure 1. Map of Three Gorges Reservoir at the Yangtze River with major tributaries. The location of Three Gorges Reservoir is marked by red box in the overview map shown in the top left corner. Gauging stations used in this study are marked by red circles. The inset map in the lower right corner shows the tributary bay of the Xiangxi River at greater detail. The sampling sites for water level fluctuations and flow velocity (ADCP—Acoustic Doppler Current Profile) are marked by red star-shaped symbols.

mouth affects nutrient and pollutant dynamics [10], algal blooms [11, 12], water quality [13, 14], phytoplankton composition [15] and sediment deposition [16] in the tributary bays. WLF of TGR can enhance the water exchange between the bays and the main reservoir and reservoir operation rules have been proposed to improve water quality in tributaries by controlling WLF by short-term (daily) discharge regulation at the dam [17, 18]. Despite the extensive number of measurements and simulations that have been conducted in TGR and its tributaries, direct observations of exchange flows at the river confluences are sparse and restricted to daily resolution. The response of the density currents to high frequency (sub-daily) WLF and the potential success of related mitigation measures remain rather speculative.

The objective of this study is to investigate the effect of short-term WLFs caused by discharge regulation of TGR on the variability of flow velocity and density-driven flows in its tributaries. For this purpose, we conducted high-frequency measurements of flow velocity and water level in the eutrophic Xiangxi Bay (XXB) in combination with the water level and discharge observations. The results will provide new perspective for understanding of hydrodynamic processes and water quality management in large reservoirs.

2. Materials and methods

2.1. Study area

Three Gorges Dam is located in the middle course of the Yangtze River (China). The Xiangxi River (XXR) is the largest tributary of TGR which is in close proximity to the dam (figure 1). The river has a watershed area of 3095 km², a length of 94 km and a mean annual discharge of 47.4 m³ s⁻¹. Xiangxi Bay (XXB) formed after the initial filling of TGR in June 2003 and extends up to 40 km from the river mouth when the reservoir is filled to its maximum water level of 175 m.a.s.l. (meter above sea level).

2.2. Data and measurements

Absolute water level measurements (in m.a.s.l.) from six gauging stations along TGR (figure 1) and discharge data were provided by China Three Gorges Corporation. The data included time series of sea-level referenced water levels with a resolution of 5 min and discharge at a resolution of 1 h for the period of January to November 2018. The relative water level and vertical profiles of flow velocity were measured in the middle and upper section of XXB (17.5 and 27.4 km upstream of the river mouth) from September 16 to 12 October 2018. Two Acoustic Doppler Current Profilers (ADCP, Teledyne RDI Sentinel 600 kHz and 1200 kHz) were deployed at the bottom of the river (~0.5 m above the riverbed). The ADCPs were configured to measure vertical profiles of flow velocity with a vertical resolution (bin size) of 0.5 m and a temporal resolution of 15 min. Hydrostatic pressure recorded by both instruments was converted to water depth (relative water level) using water density at in-situ temperature. Horizontal current velocities were measured in earth coordinates and rotated into longitudinal (along the river channel)
and transversal velocity components by rotation into the respective mean (depth and temporarily averaged) flow direction at the sampling sites. To analyze daily and sub-daily fluctuations of water level, water depth and flow velocity, the respective time series were high-pass filtered with cut-off frequencies corresponding to periods of 36 h ($7.7 \times 10^{-6}$ Hz) and 4 h ($7.7 \times 10^{-6}$ Hz). The frequency distribution of variance in water level and velocity fluctuations was analyzed in terms of power spectral density, which was calculated using Welch’s method [19].

2.3. Theoretical modes of bay oscillation
We compare basin-scale water level fluctuations in X XB with the fundamental period of standing waves in a semi-closed basin. With an open boundary at the mouth of the tributary, the fundamental period corresponds to the Helmholtz mode, with a node (minimum wave amplitude) at the mouth and an antinode (maximum wave amplitude) at the upstream end of the tributary bay. The oscillation period ($T_0$) of the Helmholtz mode depends on basin length ($L$) and water depth ($H$) as:

$$T_0 = \alpha \left[ \frac{2L}{gH} \right]^{1/2}$$

with $g$ denoting gravitational acceleration [20]. The factor $\alpha$ depends on basin geometry and is equal to two for rectangular basin of uniform depth and width. For linearly decreasing water depth from $H$ at the open mouth to zero at the upstream end of X XB, we used a value of $\alpha = 2.618$ [20].

3. Results
3.1. Water level fluctuations
The amplitude of seasonal water level variation in TGR was about 30 m, with low water level from June to September (figure 2(a)). With differences in water level smaller than 0.1 m along the up to 360 km distance between the gauging stations, the water level slope was negligible during high water levels, but increased slightly up to 0.02‰ during summer. The high-pass filtered water level time series revealed daily WLF of varying amplitude and pattern throughout most time of the year (figure 2(b)). The daily dynamics closely followed variations in discharge at Three Gorges Dam (figure S1 (available at stacks.iop.org/ERL/15/084011/mmedia)) and are the result of the seasonally varying daily pattern in hydro-power generation (examples for the different modes of daily dynamics of water level and discharge are shown in figure. S1). The rapid changes in discharge resulted in transient WLFs, i.e. depressions or elevations in front of the dam, which propagated upstream. 

Figure 2. Water level and water level fluctuations: (a) Seasonal water level at six gauging stations along Three Gorges Reservoir (TGR, see map in figure 1). The stations are located 2.3 km (Zigui) to 369.5 km (Zhongxian) upstream of Three Gorges Dam. (b) Seasonal dynamics of daily water level fluctuations (high-passed filtered water level fluctuations with periods <36 h) at Zigui. Grey background color marks the sampling period in Xiangxi Bay (XXB). (c) Daily water level fluctuations in TGR (Zigui) and in XXB (Xiakou and Pingyikou). (d) As (c), but zoom-in on period 4-5 October (grey box in panel c).
Figure 3. (a) Water level fluctuations (4 h and 36 h high-pass filtered) and (b) longitudinal flow velocity in Xiangxi Bay (XXB) at Pingyikou. Positive flow velocity corresponds to upstream flow (from TGR into XXB); negative velocity is in the direction of river flow. The red line in (b) shows water depth (the measurement range of the current profiler was limited to 24 m). Black selectrect color marks the zoomed time period of panel (c) and (d). (c) and (d) show a close-up to a 24 h period in (a) and (b), respectively.

with decreasing amplitudes. Cross-correlation analysis of WLF at the different gauging stations showed a linear increase in time lag with the increasing distance from the dam, suggesting a nearly constant speed of propagation of the daily WLFs (20 m s\(^{-1}\)) (figure S2). This speed corresponds to the phase speed \(c\) of a linear shallow-water gravity wave at a water depth \(H\) of 37 m \(c = (gH)^{1/2}\), with \(g\) denoting gravitational acceleration). The estimated depth can be considered as the equivalent water depth of a rectangular channel, while the seasonal-mean water depth at the main river channel varies strongly (21–115 m, table S1). Within the one month measurement period in XXB, the water level increased from 154 to 172 m.a.s.l., (figure S1). The water depth at the two sites where ADCPs were deployed increased from 30 to 48 m, and from 12 to 30 m, respectively. Daily WLFs with amplitudes between 0.1–0.2 m were observed throughout the entire sampling period (figure 2(c)). In XXB, daily WLFs occurred nearly synchronously and of similar amplitude as in TGR. A more detailed view (figure 2(d)), however, identified high-frequency fluctuations (with a period \(\sim 2\) h), which were superimposed on the daily WLFs in XXB, but are absent in TGR (figure 2(d)). These oscillations were nearly ubiquitously present throughout the sampling period. The amplitudes were consistently higher (up to 0.1 m) at the more upstream located sampling site (Pingyikou), compared to mid-section site (Xiakou). This observation is further evident in the power spectra of WLFs, which show a peak in spectral variance around a period of 2 h at both sampling sites in XXB (see figure S3), which is absent the spectra from TGR.

3.2. Flow velocity in Xiangxi Bay

The temporal dynamics of flow velocity in XXB was similar at both monitoring sites and is exemplified for the upper course (Pingyikou) in figure 3 (data from Xiakou are presented in figure S4). A two-layered flow structure was clearly visible at both sites, indicative of opposing density currents of river inflow along the bottom (underflow) and water flowing into XXB from TGR at mid depth and near the surface (interflow or overflow) (figure 3(b)). The river inflow occurred within a maximal 6 m (Pingyikou) to 10 m (Xiakou) thick layer along the bottom of the bay. In this bottom layer, the average longitudinal flow velocities were negative and maximal near the bottom \((-0.11 \pm 0.05 \text{ m s}^{-1}\) at Pingyikou and \(-0.12 \pm 0.06 \text{ m s}^{-1}\) at Xiakou; vertical profiles of mean flow velocities are shown in figure S5(a)). Above the inflowing water, the mean flow
Figure 4. Illustration of the generation mechanism of bay waves in Xiangxi Bay (XXB): (a) Water level fluctuations in Three Gorges Reservoir (TGR, Zigui gauging station) are shown as high-pass filtered time series with cut-off periods of 36 h to emphasize daily fluctuations (green line) and 4 h (high-frequency fluctuations, black line). Discharge at Three Gorges Dam is shown by the olive line (grey bars mark periods of discharge regulation). (b) High-pass filtered (<4 h periods) water level fluctuations at both monitoring sites in XXB (Xiakou: red line, Pingyikou: blue line). Note that the applied high-pass filter has a finite response to a step change. Therefore, it appears in (a) that the water levels start to decrease before the actual change in discharge. This is an artifact of the filter.

3.3. Nature and generation mechanism of the bay oscillation

The detailed diurnal dynamics of water level and discharge of TGR leading to the generation of the bay oscillation in XXB is illustrated in figure 4:

A rapid decrease or increase in discharge from TGR leads to a transient pile-up or depression of water level in front of the dam. These water level disturbances are only 1–2 cm in height at the dam (cf water level fluctuation in Zigui filtered at 4 h in figure 4(a)) and propagate as a surge in the upstream direction of TGR and XXB. The period (better duration, because it is not periodic) of this surge is ~2 h. During the initiation of the wave by changing discharge at the dam, the amplitudes of the high-frequency WLFs in XXB are comparable, or only slightly higher than those in TGR. However, during the following wave cycles, amplitudes are strongly amplified in XXB, while no further WLF occur in TGR. By the time the surge has propagated to the upstream end of XXB (0.35–0.37 h), the water level at the river mouth has continued to change by typically ±5 cm, which adds to the wave amplitude and results in growing wave amplitudes during the period of discharge change.

Persistent high-frequency bay oscillations of variable amplitudes are generated by both increasing as well as...
decreasing in discharge from TGR. Interfering waves generated by subsequent discharge variations lead to amplification or extinction (figure 4).

The uniform vertical distribution of wave-induced flow velocity (figure 3(d)) suggests that the 2 h oscillation in XXB represents a surface wave, rather than an internal wave. The latter would be supported by vertical density stratification and characterized by opposing flows in different layers of the water column. With a basin length \( L = 34–40 \text{ km} \) and depth \( H = 72–90 \text{ m} \), as it was observed during the year 2018 (see table S1), the fundamental period of a basin-scale surface wave (equation (1)) varies between 1.84 and 1.94 h, which is in close agreement with observed periods (1.85–1.95 h). Consistent with our observations, the amplitude of the bay wave depends on location and increases with increasing distance from the river mouth (figures 2(d) and 4(b)). For this oscillation, the theoretical ratio of wave heights at the two measurement locations had a nearly constant value of 1.19 (figure S6). The observed ratio (1.48) is higher, which can be attributed to changes of channel width and depth.

4. Discussion and conclusions

High-frequency observations of WLF and flow velocity in a large tributary bay of TGR revealed the ubiquitous presence of a bay oscillation. A standing wave of fundamental mode (Helmholtz mode) with a period of 2 h is generated by rapid discharge regulation at Three Gorges Dam. Although the wave-induced WLFs at the sampling sites were considerably smaller than daily WLFs due to discharge regulation, its projected maximum amplitude at the end of the impoundment is expected to be of comparable magnitude. Bay and harbor oscillations have been extensively studied in coastal and lake environments, where they can be generated by wind or tides [21, 22]. To our knowledge, such waves have not been observed in reservoirs in response to discharge regulation.

The observed wave period in XXB agreed well with a theoretical prediction based on basin geometry and water depth (equation (1) [20]). The oscillation amplitude can be expected to depend on the type and intensity of the initial perturbation [23]. For periodic forcing, forced oscillations are produced with amplitudes depending on friction and the proximity of the forcing frequency to the natural frequency of the system [21]. The forcing frequency in XXB is related to the duration of a transient water level change in TGR, and is only indirectly related to the periodicity of daily discharge regulation. Wave excitation can be expected to occur also for different daily patterns of discharge regulation at other seasons (figure S1) and in other tributaries. Our findings showed that the wave amplitude is mostly controlled by superposition and inference of waves generated during sequential changes in discharge. The resulting temporal dynamics of wave amplitudes is highly variable and make predictions of wave amplitudes at other seasons and in other tributaries having different resonance frequencies, rather difficult.

As an important finding, our measurements revealed that the bay oscillation had a strong effect on the temporal dynamics and vertical distribution of flow velocity in the tributary. Despite the comparably small contribution to WLFs, the 2 h bay oscillations made up the largest contribution of velocity variance in the bay. The wave caused a frequent reversal of the density current transporting water from TGR into the bay and resulted in a pulsating inflow of the river along the bed. Because vertical mixing is mainly driven by shear production of turbulent kinetic energy at the velocity gradient at the edge of the density-driven intrusion [24], the wave can be expected to provide an important control on the exchange of momentum, heat and solutes between both water masses [18]. Former studies emphasized the importance of the exchange flows for water quality in XXB by demonstrating that the Yangtze River main stream appeared to be the major contributor of dissolved and particulate water constituents [25], including heavy metals [10] and nutrients [11]. Eutrophication and other water quality problems reported for the tributaries along TGR are likely a consequence of this exchange. In fact, the upstream section of XXB, where we found the largest wave amplitudes and wave-induced velocity variations, has been identified as the hot zone where plankton blooms favorably develop [26].

Given the dominant control of the wave-induced currents on velocity and velocity shear in XXB, it appears surprising that the bay oscillations have been overlooked in the extensive research that had been conducted at this particular tributary. While field observations have been limited to discrete (daily) velocity measurements [27, 28], water level and discharge were mostly specified as daily varying boundary conditions in most numerical models [9, 26]. These studies captured the characteristics of density current in tributaries, but did not resolve the high-frequency bay oscillations. The detailed dynamics of exchange flows in a tributary of TGR in response to reservoir discharge regulation has been analyzed by Sha et al [18], using a one-dimensional hydrodynamic model. They suggested that rapid changes in discharge at Three Gorges Dam can result in a tidal-like flushing of the tributaries. High-frequency bay oscillations that are excited by rapid increase or decrease in discharge, however, were not reported in that study, indicating the importance for improving hydrodynamic models.

Numerous studies over the last decade have suggested that WLFs in TGR can be used to control the exchange flow between the main stream and the tributaries and to improve water quality in the tributaries bays [17, 29]. However, these studies are based
on simulations and observations, which resolved seasonal or daily time-scales of discharge variations. Our findings suggest that high-frequency bay oscillations need to be considered in the development of multi-objective ecological scheduling strategies for optimizing power generation, as well as upstream and downstream flows [30]. Adaptive discharge regulation, which is synchronized with the phase of previously excited bay oscillations, may provide an efficient means for controlling vertical mixing in tributaries for improving water quality and combating harmful algae blooms.

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Author contributions

A Lorke, D B Ji and D F Liu conceived the study and obtained funding; M J B extracted data and tested scaling relationships; H Q Chen and Z Y Yang provided field monitoring instruments and support; A Lorke, L H Long and L Liu contributed to data interpretation; L H Long wrote the first draft of manuscript. A Lorke and L Liu contributed to writing.

Conflict of interests

The authors declare no competing financial interests.

Data availability statement

The data that support the findings of this study are openly available at doi.org/10.5281/zenodo.3458279.

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