Journal of Hydrology 539 (2016) 254–264

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

# *In-situ* erosion of cohesive sediment in a large shallow lake experiencing long-term decline in wind speed

Tingfeng Wu [a], Huttula Timo [b], Boqiang Qin [a,*], Guangwei Zhu [a], Ropponen Janne [b], Wenming Yan [c]

[a] State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, PR China
[b] Finnish Environment Institute SYKE, Jyvaskyla, Finland
[c] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, Jiangsu 210098, PR China

ARTICLE INFO

*Article history:*
Received 12 September 2015
Received in revised form 1 May 2016
Accepted 6 May 2016
Available online 26 May 2016
This manuscript was handled by Tim R. McVicar, Editor-in-Chief, with the assistance of Dawen Yang, Associate Editor

*Keywords:*
Lake Taihu
Lacustrine cohesive sediment erosion
Wind waves
Ratio of wavelength to water depth (*L*/*D*)
Decline in wind speed
Sverdrup–Munk–Bretschneider (SMB) model

SUMMARY

In order to address the major factors affecting cohesive sediment erosion using high-frequency *in-situ* observations in Lake Taihu, and the response of this erosion to long-term decline in wind speed, high-frequency meteorological, hydrological and turbidity sensors were deployed to record continuous field wind-induced wave, current and sediment erosion processes; Statistical analyses and mathematic modeling spanning 44 years were also conducted. The results revealed that the unconsolidated surficial cohesive sediment frequently experiences the processes of erosion, suspension and deposition. Wind waves, generated by the absorption of wind energy, are the principal force driving this cycle. When the wavelength-to-water depth ratio (*L*/*D*) is 2–3, wave propagation is affected by lakebed friction and surface erosion occurs. When *L*/*D* > 3, the interaction between wave and lakebed increases to induce massive erosion. However, influenced by rapid urbanization in the Lake Taihu basin, wind speed has significantly decreased, by an average rate of $-0.022$ m $s^{-1}$ $a^{-1}$, from 1970 to 2013. This has reduced the erodible area, represented by simulated *L*/*D*, at a rate of $-16.9$ $km^2$ $a^{-1}$ in the autumn and winter, and $-8.1$ $km^2$ $a^{-1}$ in the spring and summer. This significant decrease in surface erosion area, and the near disappearance of areas experiencing massive erosion, imply that Lake Taihu has become calmer, which can be expected to have adverse effects on the lake ecosystem by increasing eutrophication and nuisance cyanobacteria blooms.



## 1. Introduction

In the littoral zone, sediment erosion is a fundamental process, not only for shore protection engineering, but also for aquatic ecosystems. Hydrodynamically induced sediment erosion can affect lake shoreline morphology and underwater topography (Allan and Kirk, 2000), sediment suspension (Luettich et al., 1990), internal nutrient release (Qin et al., 2004; Stone, 2011), the underwater light field (Liu et al., 2013), primary productivity (Schallenberg and Burns, 2004), the formation of buoyant cyanobacterial blooms (Wu et al., 2013), and the distribution of macrophytes (Havens, 2003), zoobenthos (Cai et al., 2012) and fish (Hofmann et al., 2008).

Although much attention has been paid to developing models of lacustrine sediment erosion (Hamilton and Mitchell, 1996; Luettich et al., 1990; Sheng and Lick, 1979), the lack of *in-situ* studies has limited our understanding of these processes, which will be enhanced in large shallow lakes. Generally, sediment erosion will occur when hydrodynamically induced shear stress exceeds the critical shear stress (Evans, 1994; Sheng and Lick, 1979). Li and Amos (2001) noted that the basis for predicting the critical shear stress of cohesive sediment is currently unknown, and therefore measurements must be made for specific sites and mud types, as the value depends upon mineralogy, the degree of consolidation and any benthic biological activities. However, despite the risk of increasing model error, many sediment model developers still prefer to determine critical shear strength from information in the literature and model calibration (Altunkaynak and Wang, 2010; Bailey and Hamilton, 1997; Chen et al., 2002). The main reason for this is that obtaining the required field measurements is an almost impossible task due to significant spatial differences in the sediments of natural waterbodies. So the challenge remains to find an alternative way of representing the erosion under differing shear stresses. Further *in-situ* studies are clearly required to address this issue.

In addition to the variable nature of the sediment, the short timescale of a single sediment erosion event is also a barrier for

* Corresponding author. Tel.: +86 25 86882192.
*E-mail addresses:* tfwu@niglas.ac.cn (T. Wu), qinbq@niglas.ac.cn (B. Qin).

http://dx.doi.org/10.1016/j.jhydrol.2016.05.021
0022-1694/

*in-situ* studies of sediment erosion. In many shallow lakes, hydrodynamically induced sediment erosion is mainly controlled by the wind field (Hamilton and Mitchell, 1996; Jin and Ji, 2001; Wu et al., 2013). However, compared with the winds that blow over oceans, winds across most lakes generally have variable directions, low speeds and a short effective fetch because of the limited exposure to water surface and the complexity of watershed land use and topography (Allan and Kirk, 2000; Bachmann et al., 2000; Hofmann et al., 2008). A single stable wind event usually lasts for less than one day and is hard to forecast (Wu et al., 2015). Therefore, accurate wind forecasts and high-frequency sampling are required to conduct effective *in-situ* studies of wind-induced sediment erosion. Recent technological advances have made wireless sensors available for such high-resolution temporal studies of sediment erosion in natural waterbodies (Liu and Huang, 2009; Porter et al., 2005; Wu et al., 2013).

Given the importance of the influence of wind field on sediment erosion, the influence of the globally observed near-surface wind decline must also be taken into account. Climate change and anthropogenic influence have significant effects on the aquatic ecological system (Yu et al., 2013). Reviewing changes in global near-surface terrestrially observed wind speed, McVicar et al. (2010, 2012a) concluded that speeds have been declining globally, including in most of China. They proposed that this decline will alter mixing regimes and associated biogeochemical processes in freshwater (McVicar et al., 2012b). Long-term wind changes are expected to influence lake hydrodynamics (Galiatsatou et al., 2016), and further sediment erosion. The corresponding sediment suspension in shallow lake is closely related to lake eutrophication processes through changes in the concentration of internal nutrients, underwater light and the vertical distribution of algae (Stone, 2011; Wu et al., 2015; Zhu et al., 2014). Therefore, an analysis of long-term variations in sediment erosion in highly productive lakes will assist in testing the hypothesis that wind decline will affect biogeochemical processes in freshwater ecosystems (McVicar et al., 2012b).

Given the importance of sediment erosion in shallow lakes and its potential linkage to long-term wind speed variation, a study was conducted in Lake Taihu, China using *in-situ* high-frequency observation, statistical analysis of long-term meteorological data and mathematic model simulation, to achieve two primary objectives: to clarify the main force driving lacustrine sediment erosion; and to investigate the influence of the observed decline in near-surface wind speed on that erosion.

## 2. Materials and methods

### 2.1. Study site

Lake Taihu (30°55′40″–31°32′58″N, 119°52′32″–120°36′10″E) is a large shallow eutrophic lake located in the subtropical monsoon climatic region of China (Fig. 1). The lake is very eutrophic, and cyanobacterial blooms have drawn worldwide attention (Guo, 2007; Qin et al., 2007; Stone, 2011). With a multi-year mean water surface elevation of 3 m, the lake covers an area of 2338.1 km$^2$ with average water depth 1.9 m, maximum depth <3 m, and hydraulic retention time 300 d. The lake has a flat underwater terrain with average slope only 19.7″. The majority of the shoreline is exposed to a long fetch. These physical characteristics mean that wind waves frequently influence the lake and its ecosystem (Qin et al., 2007). The hydrology is very complex, owing to the 51 important rivers that are connected to the lake (Fig. 1). During wet season, spanning the spring, from March to May, and the summer, from June to August, flooding runoff enters through the western or southwestern parts of the basin, traverses the lake, and exits to the east, before flowing into the East China Sea. There is little precipitation in dry season, during the autumn, from September to November, and winter, from December to February.

### 2.2. Investigation of sediment physiochemical features

To determine the sediment physiochemical characteristics in Lake Taihu, sediment core samples were collected from 49 sites (Fig. 1). A glass tube (diameter 0.06 m) of length 0.5 m was used to collect the cores. Each core was cut horizontally in 0.01-m intervals from top to bottom. Each core was cut horizontally into 0.01-m segments from top to bottom using a self-made stainless steel cutting ring (diameter 0.018 m, length 0.009 m). Sediment in the cutting ring was used to determine bulk density. Water content was determined by oven drying at 105–110 °C. Loss on ignition (LOI) was measured by 4-h ignition of the dried sediment at 550 °C. Additional sediment core samples were collected to determine the grain size distribution using a Mastersizer 2000 (Malvern Instruments Ltd., Malvern, UK).

### 2.3. Wind, wave, flow and sediment erosion observation

In order to investigate the hydrodynamically induced sediment erosion in this large shallow lake, high-frequency *in-situ* observations of wind direction (*UD*), wind speed (*U*), turbidity, lake currents and wind waves were made at the lake center between 00:00 August 5, 2014 and 12:00 on August 26, 2014 (Fig. 1). The mean water depth at the observation site was 2.9 m. The observation site comprised a large platform on which a portable weather station (model WXT520; Vaisala Inc., Helsinki, Finland) was mounted. The WXT520 can automatically record wind speed and direction every 30 min, at a height of 10 m above the water surface. Additionally, a YSI multi-parameter sonde (YSI Inc., Yellow Springs, OH, USA) was suspended from the platform to automatically record turbidity 1.5 m above the sediment–water interface, also every 30 min. Turbidity can represent the changes in suspended sediment (*SS*) content of the water column (Ding et al., 2012; Zhang et al., 2007). The sonde was cleaned and calibrated in advance to guarantee accuracy and stability.

A wave recorder produced by the English Valeport Company (MIDAS DWR; Valeport Ltd., Totnes, UK) was installed on the lake bottom at the observation site to record PUV data via a pressure sensor, and flow velocity using an electromagnetic current sensor. The resolutions of pressure and flow velocity recorded by the MIDAS DWR were 0.005 m and 0.001 m s$^{-1}$, respectively; its sampling rate was 8 Hz and its wave burst interval was 30 min. In total, 4096 samples were collected during each wave burst period.

To expand the wind speed record, the daily mean *U* (10 min mean speeds) and *UD* (direction corresponding to the maximum wind speed) spanning from 1956 to 2013 from Dongshan Meteorological Station were collected. These wind speed data have been adjusted from their measured height of 24.5 m to 10 m above the lake surface, using the elevation-adjusted equation provided by CERC (1984). Although wind data from a single locality is unable to capture the spatial heterogeneity of the wind field over the entire lake, Dongshan is the only station within the lake area with long-term wind data.

### 2.4. Calculation of wave- and current-induced shear stresses

Wave-induced shear stress ($\tau_w$) and current-induced shear stress ($\tau_c$) were calculated using following equations (Hamilton and Mitchell, 1996; Luettich et al., 1990):

$$\tau_w = \frac{\rho H_S \nu^{0.5} \omega^{1.5}}{2\sinh(kD)} \qquad (1)$$