Science of the Total Environment 631–632 (2018) 597–607

Contents lists available at ScienceDirect

Science of the Total Environment

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

Sediment dynamics in a large shallow lake characterized by seasonal flood pulse in Southeast Asia☆

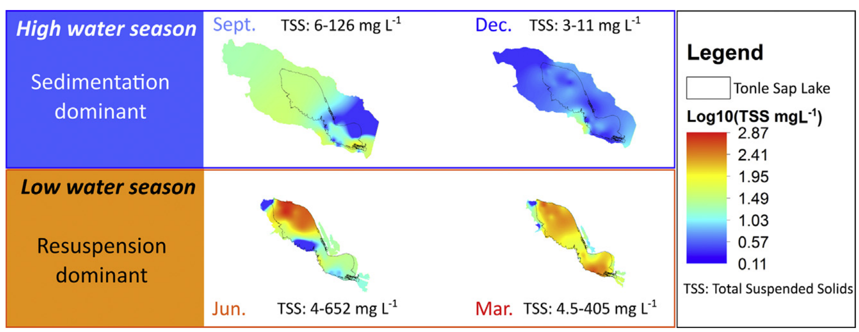
Siev Sokly [a,c,*,1], Yang Heejun [a], Sok Ty [b], Uk Sovannara [a], Song Layheang [b], Kodikara Dilini [a], Oeurng Chantha [b], Hul Seingheng [c], Yoshimura Chihiro [a]

[a] Department of Civil and Environmental Engineering, Tokyo Institute of Technology, Japan
[b] Department of Rural Engineering, Institute of Technology of Cambodia, Cambodia
[c] Department of Chemical Engineering and Food Technology, Institute of Technology of Cambodia, Cambodia

HIGHLIGHTS

- Tonle Sap Lake is a large and shallow lake influenced by a flood pulse system.
- Sediment dynamics were investigated in this lake and its floodplain vegetation.
- Floodplain vegetation showed a reduction of sediment resuspension.
- Tonle Sap Lake had two distinct characteristics: sink and source of the sediment.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 December 2017
Received in revised form 6 March 2018
Accepted 6 March 2018
Available online xxxx

Editor: Jay Gan

Keywords:
Sedimentation
Resuspension
Vegetation
Tonle sap Lake
Floodplain
Shallow lake

ABSTRACT

Most of studies on sediment dynamics in stable shallow lakes focused on the resuspension process as it is the dominant process. However, understanding of sediment dynamics in a shallow lake influenced by flood pulse is unclear. We tested a hypothesis that floodplain vegetation plays as a significant role in lessening the intensity of resuspension process in a shallow lake characterized by the flood pulse system. Therefore, this study aimed to investigate sediment dynamics in this type of shallow lake. The target was Tonle Sap Lake (TSL), which is a large shallow lake influenced by a flood pulse system of Mekong River located in Southeast Asia. An extensive and seasonal sampling survey was conducted to measure total suspended solid (TSS) concentrations, sedimentation and resuspension rates in TSL and its 4 floodplain areas. The study revealed that sedimentation process was dominant (TSS ranged: 3–126 mg L^{-1}) in the high water period (September–December) while resuspension process was dominant (TSS ranged: 4–652 mg L^{-1}) only in the low water period (March–June). In addition, floodplain vegetation reduced the resuspension of sediment (up to 26.3%) in water. The implication of the study showed that resuspension is a seasonally dominant process in shallow lake influenced by the flood pulse system at least for the case of TSL.

☆ Contributed to: *Science of the Total Environment*

* Corresponding author at: 2-12-1-M1-4, Ookayama, Meguro-ku, Tokyo 152-8552, Japan.
E-mail address: siev.s.aa@m.titech.ac.jp (S. Siev).
[1] Now at: Tokyo Institute of Technology, Tokyo, Japan.

https://doi.org/10.1016/j.scitotenv.2018.03.066

1. Introduction

Floodplains, ones of the highly productive landscapes on earth, are crucial for both flood management and conservation of the natural ecosystems (Opperman, 2014). Such landscapes are continuously enriched with nutrients derived from the nutrient-rich sediments from diverse headwaters and lateral sources (Tockner and Stanford, 2002). Sediments play an important role in shaping biological communities as well as delimiting ecosystem processes in floodplains (Tockner et al., 2010). During overbank flooding, floodwaters spread out over floodplains and, due to relatively slow water velocities on the floodplain, much of the sediment in transport is deposited. Nutrients such as phosphorus are largely absorbed by sediment particles and thus biologically consumed by the floodplain communities (Olde Venterink et al., 2006; Opperman, 2014). Therefore, floodplains frequently function as hot spots of high primary and secondary production which provide trophic support for food webs in the ecosystems (Bayley, 1995; Sparks, 1995; Tockner and Stanford, 2002; Tockner et al., 1999, 2010). At a high trophic level, floodplains also support highly productive freshwater fisheries by providing habitats for spawning and growth (Baran et al., 2001; Grosholz and Gallo, 2006).

The flow regime in a parent river may also shape the floodplain area at its basin, producing a wide array of aquatic habitats (e.g., ponds and lakes) via meandering processes (Tockner et al., 2010). Important aquatic habitats such as ponds and lakes are considerably shallow and prone to sediment resuspension. Particularly, wind-induced waves and water currents could easily disturb sediment surfaces causing resuspension of the sediment (Evans, 1994; Zhu et al., 2015). Commonly, resuspension of sediment increases the concentration of suspended solids in the water column which has a great impact on the water quality of shallow lakes and numerous biotic interactions (Horppila and Nurminen, 2001, 2003; Matisoff et al., 2017; Qin et al., 2006). Moreover, in such lakes, resuspension often significantly contributes total settling flux (Evans, 1994).

In general, shallow lakes are dominated by the resuspension process throughout the year (e.g., Taihu Lake). The intensity of sediment resuspension is influenced by many factors, including lake shape, water depth, and wind-induced wave action (Evans, 1994; Zhu et al., 2015). The dynamic ratio (DR) is defined as $\sqrt{Surface\ Area\ (km^2)}/Average\ Depth\ (m)$. This ratio has been applied to several lakes (e.g., Bachmann et al., 2000; Håkanson and Bryhn, 2007; Zhu et al., 2015). DR was found to have a positive linear relationship with the resuspension rate (Zhu et al., 2015). A DR > 0.8 indicates that a lake is prone to sediment resuspension (Bachmann et al., 2000). Throughout the year, DR is stable or varies slightly in a typical shallow lake of which water depth and water surface area do not change or slightly change, but it varies greatly in a shallow lake of a flood pulse system due to the increased surface area and depth. Moreover, the sediment load supplied into a flood-pulse-influenced-shallow lake is quite high and sedimentation may be dominant during flooding, while resuspension may be dominant during dry periods. Little attention, however, has been paid to flood-pulse-influenced-shallow lakes because investigations of sediment resuspension have typically focused on relatively stable shallow lakes (e.g., Evans, 1994; Horppila and Nurminen, 2001; Tammeorg et al., 2013; Zhu et al., 2015). Comparing to typical lakes, flood-pulse-influenced-shallow lakes may exhibit variation in parameter values and diverse benefits due to its ecosystem services, ecological functioning, and flood water storage role in the floodplain (Scheffer, 2004; Wantzen et al., 2008). Thus, additional studies are needed, not only to improve our understanding of shallow lakes, but also to contribute to the ecological and environmental management of ecosystems in such lakes driven by the flood pulse.

Tonle Sap Lake (TSL) is a large shallow lake that is influenced by a flood pulse system. Sediment in this kind of system is highly dynamic and different from that in other shallow lakes due to a large seasonal variation of water level and water surface area. The number of the sediment dynamics studies in TSL (e.g., sediment flux and sedimentation rate) is gradually increasing (Arias et al., 2014; Campbell et al., 2009; Koehnken, 2012; Kummu et al., 2008; Lu et al., 2014; Penny et al., 2005; Sarkkula et al., 2003; Tsukawaki, 1997). However, the information of resuspension of sediment in TSL was speculation and often explained by the implication of TSS observation (e.g., Campbell et al., 2009; Kummu et al., 2008; Sarkkula et al., 2003) and also sedimentation rate (e.g., Kummu et al., 2008; Penny et al., 2005; Tsukawaki, 1997) rather than the direct measurement of resuspension rate. Moreover, the investigations of the sediment dynamics in TSL are crucial for its management and could provide insight into flood-pulse-influenced-shallow lakes or similar lake systems elsewhere in the world. Therefore, this study aimed to investigate and understand sediment dynamics in TSL. We tested a hypothesis that floodplain vegetation plays as a significant role in lessening the intensity of resuspension process in a shallow lake characterized by the flood pulse system. The relevant factors considered in this study were vegetation types, locations and seasons. To achieve this, four extensive sampling campaigns were conducted to collect water and sediment samples in different water environments (rivers, lake and floodplains), water layers (surface and sub-layer) and seasons (high and low water period). In addition, sedimentation and resuspension rates were measured in the three main types of vegetation and open water on the four different floodplains of TSL.

2. Study area

Tonle Sap Lake is the largest freshwater lake in South East Asia (Bonheur, 2001; Keskinen, 2006; Kummu et al., 2006) (Fig. 1). TSL is a large shallow lake and has a relatively flat bottom, with a maximum depth of approximately 3.3 m. Connected to the Mekong River (MR) via Tonle Sap River, TSL has a unique hydrological environment that plays an important role in the active exchange between TSL and the MR through reversal flow. The hydrology of the TSL is driven by the monsoonal flood regime of MR (Kummu et al., 2014). As another important source of water, 11 principle tributaries drain directly into the lake (Fig. 1). During the dry season, the lake is about 120 km long and 35 km wide, with an area of about 2500 km^2. During the flood phases, the lake receives a large amount of water volume from MR through reversal flow and enlarges to about 250 km long and 100 km wide, with an area of about 17,500 km^2 (Campbell et al., 2009). The inflow of water discharge into the lake ranged: 104–7032 $m^3\ s^{-1}$, while the outflow of water from the lake ranged: 380–8176 $m^3\ s^{-1}$ (Lu et al., 2014). The water level of TSL varies from an average depth of <2 m in the dry season to 10 m in the flood season. The weather in the lake area is dominated by the monsoon. During the wet season in May–October, winds are predominantly from the southwest and during the dry season in November–April from the northeast (Sarkkula et al., 2003). Wind velocities are typically low, on the average 2–3 $m\ s^{-1}$, except during short storms. Average yearly precipitation varies from 1300 mm in the south to 1500 mm in the northern part of the area. Lake water temperature varies between 28 and 33 °C (Sarkkula et al., 2003). The meteorological data are limited and poorly monitored in the lake region due to lack of budget, maintenance and accessibility by the local government.

TSL receives the annual average inflows of sediment flux from MR varying from 5.1 Mt $year^{-1}$ (Kummu et al., 2008) to 6.4 Mt $year^{-1}$ (Koehnken, 2012), and releases an average outflow of sediment flux varying from 1.4 Mt $year^{-1}$ (Kummu et al., 2008) to 1.5 Mt $year^{-1}$ (Koehnken, 2012) back to MR. The concentration of TSS in the TSL ecosystem show a clear difference between the open lake and the floodplain. Typically, TSS concentration in the open lake varies from 5 to 20 mg L^{-1} in the high water period (August–December) to over 1000 mg L^{-1} during the low water period (January–July), while TSS in the floodplain is 1–10 mg L^{-1} and 100–200 mg L^{-1} during the high and low water periods, respectively (Sarkkula et al., 2003). The sedimentation rate in the lake area during the dry season is very low,