Impact of Wind on the Spatio-Temporal Variation in Concentration of Suspended Solids in Tonle Sap Lake, Cambodia

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Shear stress analysis

Sediment resuspension occurs when total shear stress exceeds critical shear stress in the lake. For lakes, computing reliable values for the shear stress is more complicated, given the spatial and temporal variation of the shear stresses. Wave and currents may induce shear stresses in different directions. Hence, the magnitude of bottom shear stress due to currents and waves should be compared, and checked if the condition for resuspension.

Resuspension was assessed by calculating and comparing the shear stress of wind-induced currents and waves, and critical shear stress. It is to be noted again that sediment resuspension occurs when total shear stress exceeds critical shear stress in the lake. In addition, resuspension was also compared with other environmental parameters (wind speed, TSS, settling velocity, water depth, sediment grain size, etc.) to understand the sediment resuspension in detail.

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The magnitude of bottom shear stresses the currents (τ_{curr}), and wind-induced shear stress at the surface of the lake (τ_0) are estimated using a quadratic drag law, as given in eq 3.1.

$$|\tau_{curr}| = 0.1\tau_0 = 0.1C_D\rho_a W^2 \quad (3.1)$$

where ρ_a denotes the density of air and the C_D denotes drag coefficient

$$C_D = 0.001(0.75 + 0.067W) \quad (3.2)$$

Shear stress due to currents in large shallow lakes such as TSL is much smaller than shear stress due to waves satisfactory (Chung et al., 2009; James et al., 2004). Critical shear stress can be calculated from eq. 3.3,

$$\tau_{cr} = \tau_c^* \rho R g D_{s50} \quad (3.3)$$

where $R = \rho_s - \rho/\rho$ (the submerged specific gravity), ρ_s is the sediment density, D_{s50} denotes the sediment grain size, and g is the acceleration of gravity. The critical (non-dimensional) Shield's parameter, τ_c^* can be obtained by curve fittings to experimental data set for incipient motion developed by (Parker et al., 2003),

$$\tau_c^* = 0.5 \times \left[0.22Re_p^{-0.6} + 0.06 \times 10^{\left(-7.7Re_p^{-0.6}\right)}\right] \quad (3.4)$$

where $Re_p = \sqrt{gRD_{s50}}D_{s50}/\eta_0$, with η_0 denoting the kinematic viscosity of water.

In addition, TSS was also compared with loss on ignition (LOI) (at 550 ^{O}C) of sediments. LOI is one of the indicators of sediment organic matters. Sediments with high LOI are expected to have low specific gravity, and high water content (Otsubo and Muraoka, 1987).

Assessment of resuspension rate

Resuspension rate was calculated by following eq 3.5,

$$\frac{dS}{dt} = \frac{1}{D}(-\beta S + E) \tag{3.5}$$

where S is the suspended sediment concentration (mgm^{-3}), D is the depth of water column (m), β is the settling velocity (ms^{-1}) and E is the erosion rate $(mgm^{-3}s^{-1})$

The erosion rate is usually parameterized as a function of bottom stress produced by waves and currents. Luettich (1990) showed that wave-induced stress dominates compared to current stress by a factor 4-10 depending on the value of bottom roughness. Wave-induced bottom orbital velocities usually are much smaller than mean current velocities but can also generate the bottom shear stress of the same magnitude. Assuming the existence of threshold value of shear stress and taking only wave-induced shear stress into account the erosion term E can be written as follows:

$$E = 0 \; (H < H_c) \tag{3.6}$$

$$E = K\left[\frac{H - H_c}{H_{ref}}\right]^n \; (H > H_c) \tag{3.7}$$

where H is a wave height (m), H_c is the critical value of wave height, $H_{ref} = 0.01m$ is the reference wave height, K is the empirical factor, n is the power exponent. The concept of critical shear stress $\tau_c > 0$ and respectively $H_c > 0$ was criticized by (Lavelle et al., 1984) who showed that experimental results can also be interpreted with $\tau_c = 0$ ($H_c = 0$) due to random nature of bottom stresses and particle movement. Since the wave height depends mainly on quadrature of wind speed the eq. 3.5 can be modified in the following way:

$$\frac{dS}{dt} = \frac{1}{D}(-\beta S + \alpha W^p) \tag{3.8}$$

where W is the wind speed (ms^{-1}), α is the empirical wind factor and p is the power exponent.

An analytical solution of Eq. (5.8) can be found in a form of the convolution integral:

$$S = \frac{\alpha}{H} e^{-(\beta t/D)} \int_0^t W^p(\tau) e^{(\beta t/D)} d\tau + S(0) e^{-(\beta t/D)} \tag{3.9}$$

where $S(0)$ is the initial SS concentration at $t = 0$. In the case of constant wind speed the solution can be obtained in the closed-form:

$$S = S(0)e^{-(\beta t/D)} + \frac{\alpha W^p}{\beta}\left(1 - e^{-(\beta t/D)}\right)$$

$$= \frac{\alpha W^p}{\beta} + \left(S(0) - \frac{\alpha W^p}{\beta}\right) e^{-(\beta t/D)} \tag{3.10}$$

Since, $\frac{\alpha W^p}{\beta}$ is constant, and under steady state condition, influence of initial conditions decreases to zero with time, whereas erosion increases with time. The SS concentration converges exponentially to the constant value $\frac{\alpha W^p}{\beta}$, which represents the balance between erosion and gravitational settling processes.

Under unsteady state condition, when set on a surface, small particles are held by various forces which are combination of physical attractions, shear stresses, and mechanical stresses. The SS concentration can be find with kinetic model of entrainment by a turbulent fluid drag force and the expression at the constant condition as shown in eq 3.11,

$$\frac{dS}{dt} = f_0 exp\left(-\frac{U}{PE}\right) \tag{3.11}$$

where f_0 is a typical frequency of vibration, U the height of the potential well, and PE the average potential energy of a particle.

For the assessment of resuspension, it is required to integrate the wind effect to the parameters of eq. 3.11. The PE of a particle of sediment in the water column is given as in eq. 3.12,

$$\frac{4}{3}\pi\rho_s r^3 \dot{\beta} = \frac{4}{3}\pi r^3(\rho_s - \rho_0)g - 6\pi\eta r\beta \tag{3.12}$$

where ρ_s, ρ_0 are the density of sediment and water, *r* is the radius of sediment, η is the fluid viscosity and *v* is the settling velocity from Stocks Law.

Integrating eq. 5.12, average potential energy of particle is calculated as eq. 3.13,

$$\begin{aligned} PE &= \frac{4}{3}\pi r^3(\rho_s - \rho_0)g \times \frac{D}{2} \\ &= \frac{2}{3}\pi r^3(\rho_s - \rho_0)gD \end{aligned} \tag{3.13}$$

Substitution of $\frac{H}{2}$ to the transition of potential energy is due to PE is the parameter of average potential energy.

On the other hand, Q the height of the potential well must be applied wind effect as the relational expression in the form of wind-induced wave energy. The potential energy of the water column per unit bottom area is

$$dE_{p_1} = \int_{-D}^{\gamma} \rho g z dz = \frac{1}{2}\rho g(\gamma^2 - D^2) \tag{3.14}$$

Assuming dE_{p_2} as the potential energy at the time of still water without waves,

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$$dE_{p_2} = \int_{-D}^{0} \rho g z dz = -\frac{1}{2}\rho g D^2 \tag{3.15}$$

wind-induced wave potential energy is obtained by subtracting the potential energy at still water from the potential energy of the water column as in eq 3.16,

$$dE_p = dE_{p_1} - dE_{p_2} = \frac{1}{2}\rho g \gamma^2 \tag{3.16}$$

Water level change of regular wave $\gamma = (H/2)\cos(kx - \omega t)$ is substituted and integrated to obtain the average wavelength as below.

$$U = E_p \times L = \frac{1}{2}\rho g \int_{x}^{x+L} \frac{H^2}{4} cos^2(kx - \omega t) dx = \frac{1}{16}\rho g H^2 \times L_w \tag{3.17}$$

Substituting eq. 3.14 and 3.17 in eq. 3.11, resuspension rate is obtained as one more definition as given in eq 3.18,

$$\frac{dS}{dt} = f_0 exp\left(-\frac{3}{8\pi}\frac{\rho_0}{\rho_s - \rho_0}\frac{H^2}{D} \times L_w\right) \tag{3.18}$$

or

$$\frac{dS}{dt} = f_0 exp\left(K\frac{H^a}{D} \times W^b\right) \tag{3.19}$$

where *K* is the given constant value, *a* and *b* are the power exponents.

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Table A3.1. Total and critical shear stresses across various cross section in TSL, Cambodia

Point	Total Shear Stress (Pa)		Total Shear Stress (Pa)	Critical Shear Stress (Pa)
	Wind-induced waves	Wind-induced currents		
Dec 2016				
CS1-1	2.0	0.0005	2.0	3.2
CS1-2	0.2	0.0005	0.2	3.2
CS1-3	1.5	0.0005	1.5	2.5
CS2-1	0.6	0.0011	0.6	3.3
CS2-2	0.1	0.0011	0.1	2.4
CS2-3	0.6	0.0011	0.6	2.7
CS2-4	0.6	0.0011	0.6	2.8
CS2-5	0.8	0.0011	0.8	3.9
CS3-1	1.5	0.0011	1.5	3.4
CS3-2	1.5	0.0011	1.5	2.7
CS3-3	0.3	0.001	0.3	2.8
CS3-4	1.0	0.001	1.0	1.7
CS3-5	0.1	0.001	0.1	5.4
CS3-6	0.4	0.001	0.4	4.6
CS3-7	0.8	0.0011	0.8	2.2
CS4-1	0.0	0.0005	0.0	1.2
CS4-2	0.4	0.0005	0.4	3.1
CS4-3	0.3	0.0005	0.3	1.1
CS4-4	0.0	0.0005	0.0	1.3
CS4-5	0.2	0.0005	0.2	1.5
CS4-6	1.2	0.0005	1.2	3.2

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Point	**Total Shear Stress (Pa)**		**Total Shear Stress (Pa)**	**Critical Shear Stress (Pa)**
	Wind-induced waves	**Wind-induced currents**		
CS4-7	0.1	0.0006	0.1	2.9
CS4-8	0.5	0.0006	0.5	1.3
CS5-1	1.6	0.0003	1.6	2.9
CS5-2	0.7	0.0003	0.7	2.4
CS5-3	0.5	0.0003	0.5	3.9
CS5-4	0.8	0.0004	0.8	0.8
CS5-5	0.7	0.0004	0.7	1.0
CS6-1	1.2	0.0004	1.2	3.6
CS6-2	0.7	0.0004	0.7	2.1
CS6-3	0.2	0.0004	0.2	1.1
CS6-4	1.2	0.0004	1.2	1.9
CS6-5	0.2	0.0004	0.2	1.5
CS7-1	3.0	0.0004	3.0	3.9
CS7-2	0.9	0.0004	0.9	1.7
CS7-3	1.3	0.0004	1.3	5.1
CS7-4	2.9	0.0004	**2.9**	1.6
March 2017				
CS1-1	1.0	0.0004	1.0	3.2
CS1-2	0.5	0.0004	0.5	3.2
CS1-3	0.4	0.0004	0.4	2.5

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Point	Total Shear Stress (Pa)		Total Shear Stress (Pa)	Critical Shear Stress (Pa)
	Wind-induced waves	Wind-induced currents		
CS2-1	1.6	0.0004	1.6	3.3
CS2-2	1.1	0.0004	1.1	2.4
CS2-3	0.8	0.0004	0.8	2.7
CS2-4	0.2	0.0004	0.2	2.8
CS2-5	0.9	0.0004	0.9	3.9
CS3-1	0.2	0.0005	0.2	3.4
CS3-2	1.2	0.0005	1.2	2.7
CS3-3	0.9	0.0005	0.9	2.8
CS3-4	0.7	0.0005	0.7	1.7
CS3-5	4.6	0.0005	4.6	5.4
CS3-6	0.6	0.0005	0.6	4.6
CS3-7	0.3	0.0005	0.3	2.2
CS4-1	0.6	0.0004	0.6	1.2
CS4-2	0.7	0.0004	0.7	3.1
CS4-3	0.3	0.0004	0.3	1.1
CS4-4	0.3	0.0004	0.3	1.3
CS4-5	0.1	0.0004	0.1	1.5
CS4-6	1.2	0.0004	1.2	3.2
CS4-7	0.8	0.0004	0.8	2.9
CS4-8	0.0	0.0004	0.0	1.3
CS5-1	0.2	0.0007	0.2	2.9
CS5-2	1.7	0.001	1.7	2.4

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Point	Total Shear Stress (Pa)		Total Shear Stress (Pa)	Critical Shear Stress (Pa)
	Wind-induced waves	Wind-induced currents		
CS5-2	5.9	0.0005	**5.9**	2.4
CS5-3	3.3	0.0008	3.3	3.9
CS5-4	2.5	0.001	**2.5**	0.8
CS5-5	1.8	0.0009	**1.8**	1.0
CS6-1	1.0	0.0006	1.0	3.6
CS6-2	3.1	0.0008	**3.1**	2.1
CS6-3	0.5	0.0008	0.5	1.1
CS6-4	0.7	0.0008	0.7	1.9
CS6-5	1.8	0.0008	**1.8**	1.5
CS7-1	5.8	0.0008	**5.8**	3.9
CS7-2	0.2	0.0008	0.2	1.7
CS7-3	2.0	0.0008	2.0	5.1
CS7-4	3.3	0.0009	**3.3**	1.6
June 2017				
CS1-1	0.5	0.0009	0.5	3.2
CS1-2	0.4	0.0009	0.4	3.2
CS1-3	0.0	0.0008	0.0	2.5
CS2-1	0.6	0.0005	0.6	3.3
CS2-2	0.1	0.0005	0.1	2.4
CS2-3	0.7	0.0005	0.7	2.7
CS2-4	0.5	0.0005	0.5	2.8

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	Wind-induced waves	Wind-induced currents		
CS2-5	0.9	0.0005	0.9	3.9
CS3-1	0.7	0.0008	0.7	3.4
CS3-2	1.4	0.0008	1.4	2.7
CS3-3	1.2	0.0008	1.2	2.8
CS3-4	0.9	0.0008	0.9	1.7
CS3-5	2.1	0.0008	2.1	5.4
CS3-6	3.4	0.0008	3.4	4.6
CS3-7	0.9	0.0008	0.9	2.2
CS4-1	0.0	0.0008	0.0	1.2
CS4-2	0.0	0.0007	0.0	3.1
CS4-3	0.3	0.0007	0.3	1.1
CS4-4	0.4	0.0007	0.4	1.3
CS4-5	0.0	0.0007	0.0	1.5
CS4-6	0.6	0.0007	0.6	3.2
CS4-7	0.3	0.0007	0.3	2.9
CS4-8	0.0	0.0007	0.0	1.3
CS5-1	0.7	0.0006	0.5	3.2
CS5-2	1.0	0.0006	0.4	3.2
CS5-3	1.9	0.0006	0.0	2.5
CS5-4	0.7	0.0006	0.6	3.3
CS5-5	0.7	0.0006	0.1	2.4

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	Wind-induced waves	Wind-induced currents		
CS6-1	1.3	0.0007	0.7	2.7
CS6-2	0.6	0.0007	0.5	2.8
CS6-3	0.5	0.0007	0.9	3.9
CS6-4	0.3	0.0006	0.7	3.4
CS6-5	1.0	0.0006	1.4	2.7
CS7-1	2.9	0.0007	1.2	2.8
CS7-2	0.6	0.0007	0.9	1.7
CS7-3	1.1	0.0007	2.1	5.4
CS7-4	0.5	0.0007	3.4	4.6