

The sink of sediments suspended by waves in Lake Pyhäjärvi

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Abstract:

A field survey was conducted in Lake Pyhäjärvi, South-West Finland. Measured wave lengths were not long enough to cause active suspension of sediment at the bottom but surface seiches as ultra-long waves due to the same wind certainly could touch the bottom only around the nodal lines. However it was confirmed after reading the water level records. There were probably simultaneous currents induced by the wind which generated waves and excited seiches. These combined processes would disturb the bottom and produce turbidity. Suspended sediment should have arrived from sources taking time to travel over half width of 4 km. The CTD profiles around the deepest point of the lake were taken and compared with the nearest cast in the talweg. A thermally unstable intermediate layer was consistently found from an array of temperature loggers in the valley, and the anomaly was just below the average depth of 5 m in temperature profiles. Thermal inversion in the intrusive layer was about 0.1°C at 15°C, which was to be compensated by a density difference equivalent to 14 mgL⁻¹ silt concentration. The lowest temperatures were found at the bottom of the profile. It is similar to dense bottom currents due to lower temperature with higher turbidity. Water level loggings were started to detect the surface seiching periods at two stations and lasted for two weeks. The results demonstrate intermittent stirring of bottom sediments and those were absorbed in the deepest part as a sink of sediment.

1. Introduction

Lake Pyhäjärvi is a shallow, temperate lake in the southwestern Finland. The surface area is 155 km², NW-oriented and the average depth is 5 m. It is not very deep however the floor is inclined to the deeper western side with the depression of 26 m. The bottom topography

causes gyres due to longitudinal winds and flow patterns of horizontal circulation are affected by the river discharge going to north and wind direction, fair or against the withdrawal.

In early 1990's, sediment traps, water samplers and a current meter were used in the survey and the sediment laden flow was simulated (Huttula [1], 1994). The results show that there is a variation in time and space for rates of sedimentation. In the deepest part of the lake, the measured sedimentation corresponds to annual accumulation rates reported in the past. It was calculated that the critical depth of erosion for inorganic particles is 3 m however the organic material is resuspended more easily and typical currents of 5 cm s^{-1} erode it even at the depth of 10 m. The model calculated the suspended solids concentration quite well at shallow sites but at deep sites the values were too low.

The situation is similar to the South Basin, Lake Biwa: a shallow, tropical and NNE-oriented lake in Japan, with the area of 53 km^2 and the averaged depth is 4 m, the western half is deeper, and the topographic gyre by southerly wind and deflected convection by north wind. The direction of outflow is the difference. There forms light diurnal stratifications as polymictic during daytime and mixed up at night. The difference from Lake Pyhäjärvi is the minimum temperature over 4°C and the Coriolis parameter is less than two thirds of the Finnish lake.

It is discussed here the suspension process due to alternate and periodic currents of wind waves and surface seiches. Thermally induced currents similar to dense bottom currents are observed only in transition area connecting to the deeper half of Lake Biwa (Okubo [2], 1995). However it is possible here within the lake according to the high contrast in depth.

2. Methods

An ADCP (Sentinel, RDI) was employed to record the offshore wave properties in deep water (Sta.Es). Two level gauges (U20-001, HOBO, Onset) were started at Säkylä harbor (Sta.E) and the Northernmost point (Sta.N) at the pier in Pyhäjärvi Institute. An array of nine temperature loggers (U22-001, HOBO, Onset) was set in the vertical close to the deepest point Sta.W. The meteorological data were provided from the lake float of SYKE (Sta.S), Finnish Environmental Institute. The onshore wave measurement using a current meter (AEM, JFE Alec) was conducted at a stony beach (Sta.En) west to Iso-Vimma on Sep 14 and Sep 15, both on early hours in the afternoon. A CTD profiler (Infinity, JFE Alec) was repeatedly casted during setting the loggers (Sta.W and Sta.Ws).

A mild wind of $U=4 \text{ ms}^{-1}$ blew on Sep 14 PM and it

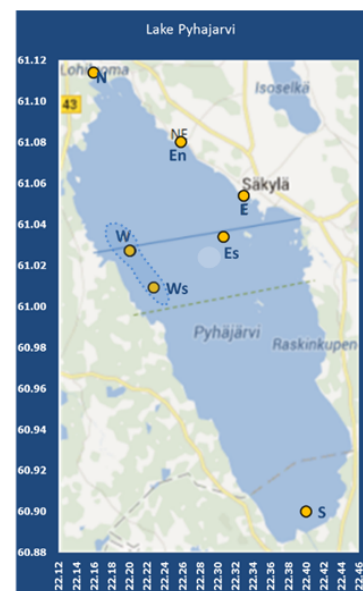


Fig. 1 Location of measurement: N, E: water level; En, Es: on- and offshore wave; W: Thermal Array; Ws, W: CTD; S: Weather station

was up to $U=6 \text{ ms}^{-1}$ on Sep 15 PM. Under moderate winds, typical wave period $T_{1/3}$ on the lake was not more than 2 seconds for the two days. The maximum Fetch is $F=25,000 \text{ m}$ and realistic values are assumed. The Wilson Formula [3],

$$\begin{aligned} gH_{1/3}/U^2 &= 0.30\{1-[1+0.004 (gF/U^2)^{1/2}]^{-2}\} \\ gT_{1/3}/2\pi U &= 1.37\{1-[1+0.008 (gF/U^2)^{1/3}]^{-5}\} \end{aligned} \quad (1)$$

Deep wave condition was kept during the measurement as shown in Table 1.

Table 1 Property of deep water wave

$T_w(s)$	$c_o(\text{ms}^{-1})$	$L_o(\text{m})$	$h_o(\text{m})$	$t_{\min}(\text{hr})$	Date
1.8	2.8	5.0	2.5	4.9	Sep 14, 2013
2.0	3.1	6.2	3.1	4.5	
2.3	3.6	8.3	4.1	3.9	Sep 15, 2013
3.0	4.7	14.0	7.0	3.0	
4.0	6.2	25.0	12.5	2.2	

In the notation, the suffix “o” denotes the value of deep water as the initial condition at $h/L=1/2$, $c_o=1.56T_w$ and $L_o=c_oT_w$, in which h is the local depth, L the wave length, c : celerity, and T_w : wave period. When T_w is over 2.5 sec, L becomes double the averaged depth h .

The ADCP performed on measurement days: longer period and small amplitude of $H=0.15 \text{ m}$ corresponds to the calm condition on Sep 14 PM and $T_w=2 \text{ sec}$ and the wave height $H=0.25 \text{ m}$ is recorded on Sep 15 PM.

Furthermore 20% and 12% of the surface area of the lake is shallower than 4 m and 3 m, respectively. Those mostly cover the northeastern part of the lake. So marginally shallow water waves were certainly developed especially due to the southerly winds and in a shallow northern part of the lake otherwise such turbidities should not appear. The situation might be the starting time of cooling and thermal destratification was going on. The evidence is a sign that the lake bed was exposed to the shear stress and resuspension. The velocity potential leads the magnitude of 3 to 9 cms^{-1} which is enough to provide the lift for the particles

For the condition, $F=8,000\text{m}$, $U=5 \text{ ms}^{-1}$,

$$\frac{gF}{U^2} = 3,140 \rightarrow H_{1/3} = 0.254\text{m},$$

$$T = 1.87\text{s}, \quad c = \sqrt{\frac{g}{k} \tanh kh} = 2.02$$

$$L = cT = 3.77\text{m}$$

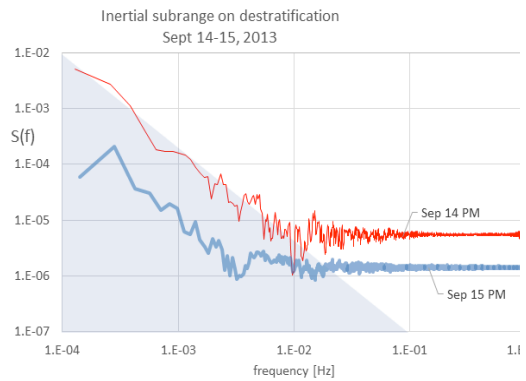


Fig. 2 Frequency spectra from temperature fluctuation of current meter for the wave measurement: showing inertial sub-range to the -5/3 power law

The fact shows seiche as the longest wave of the basin size works as a stirrer near the bottom. The process begins when wind blows and after the wind gets weak or ceases, the particle settling starts above the sloping bottom, then northwestern deep sink receives sediment. If particles are attached to the bottom on the way those will wait for the next wind. Both the temperature fluctuation and the power of spectrum reduced on the second day while the waves were rather excited. This is no doubt the sign of destratification and the $-5/3$ power law in the inertial sub-range is seen in typical destratification processes (Okubo [4], 1993). There are several humps on the sloping spectrum curves between 0.00016 Hz and 0.0016 Hz (100 min and 10 min) in Fig. 2. It is the frequency range of the seiches discussed later. Horizontal velocity in the orbital motion in waves at $z = -0.3h$

$$u = \frac{H\sigma}{2} \frac{\cosh k(h+z)}{\sinh kh} = 1.34H \frac{1.27}{0.875} = 1.94H, \quad (2)$$

where $k = \frac{2\pi}{L} = 1.57$; $\sigma = \frac{2\pi}{T_{1/3}} = 2.68$

Using $u=0.3$ m/s and $u=0.6$ m/s corresponding wave height $H=0.15$ m to $H=0.31$ m is found.

3. Results

The temperature array stood at Sta.W in the lake since Sep 14 14:00 then water temperatures were just going up as in Fig. 3 and turned to go down from Sep 15 21:00. It was the destratification and also the start of cooling phase. Two loggers at 5.25 m and 20.32 m in the profile show lowest temperatures. For the former, a possibility of systematic error of 0.1°C, it was simply checked by comparing records in the air before and after the measurement in vain.

Unstable thermal profile between 5.25 m and 6.10 m is not to be surprised, adjacent upper and lower loggers show intermediate temperatures, which is because of negative buoyancy of silt concentration into adjacent layers. A possible answer for the former is a clear water intrusion. The latter is about the bottom. No more than 20 m depth was observed in the CTD profiles around there, the closest cast showed that depth is only 16 m. The record shows an intermittent descends, which looks similar to dense bottom currents in Lake Biwa [2].

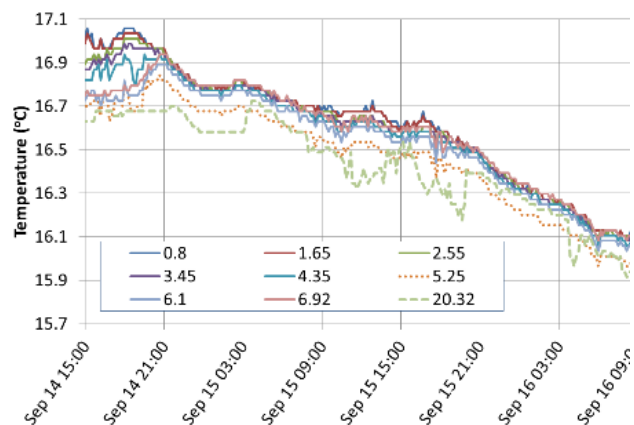


Fig. 3 temperature record measured by the array: low temperature at 5.25 m depth is due to turbid intrusion and those at 10.32 m are maintained by the bottom current

The CTD was used in a drifting boat and Sta.W is in a deep valley, so it was actually drifted away from the site. Turbidity unit FTU could be converted into the weight concentration using the formula to estimate and compare with the buoyancy flux due to temperature difference. Table 2 shows the routine and procedures where settling velocity is subject to the Stokes formula. By using the corresponding friction velocity causing sediment suspension, the concentration of maximum possible transport by Celik & Rodi [5],

$$C_b = 0.034 \frac{u_*^2}{\sigma g h w_s} U, w_s = \frac{\sigma g D^2}{18\nu}, \beta = 1 + 1.56 \left(\frac{w_s}{u_*} \right)^2 \quad (3)$$

It is necessary to justify the particle size D and settling velocity. According to Huttula [1], the median grain size in the outlet water of the lake had a range of D=19.2 to 55.7 μm .

Table 2 Properties of suspended sediments

C(mgL ⁻¹)	D (μm)	w _s (ms ⁻¹)	U (ms ⁻¹)	u* (ms ⁻¹)	β	ζ
2.65	20	3.6 · 10 ⁻⁴	0.04	0.0046	1.010	0.194
13.3	25	5.6 · 10 ⁻⁴	0.06	0.0105	1.004	0.132
26.5	30	4.0 · 10 ⁻⁴	0.08	0.0077	1.004	0.129

Friction velocities in the first two rows are estimated by using the submerged specific weight, $\sigma=1.65$ for usual sediment in lakes. Considering the case for light material, the half value, $\sigma=0.825$ was used for the last row in Table 3. When the friction velocity was overestimated, the reason could be explained by assumed concentration itself. Volumetric concentration of 10 ppm ($C_b=10^{-5}$) is on the border. Organic material is said more easily resuspended. The FTU is the optical-based unit and weight conversion should be based on the field calibration.

Both temperature and turbidity profiles change from Sta.Ws (Sep14 15:43) to the deeper Sta.W (Sep14 15:19) shown in Fig.3, where the inverse layer seems not to be detected by the rapidly sinking CTD. It is observed along the dense bottom current flow receiving the particle flux with the warmer water. The downward heat and settling mass fluxes are negative and positive buoyancy flux in the water column.

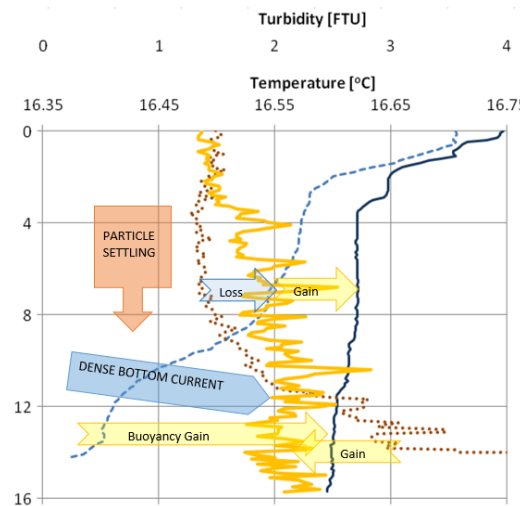


Fig.4 Temperature (blue) and turbidity (brown) profiles temperature increases and turbidity increases at 3 m to 12 m and decrease 12 m to 14 m from Sta.Ws (broken/dotted) to Sta.W (solid)

The buoyancy flux is observed between the stations (Ws and W) in an incremental time to flow the distance. The turbid water after mixing comes up to the sediment sink by two paths. Highly suspended loads ($\zeta < 0.1$) intrude directly above the floor at the depth 3 m, and faintly suspended ($\zeta > 1$) or bed loads are advected by bottom currents at 10 m or deeper. The former is seen at Sta.W and the turbidity profile deeper than 5 m looks spiky and frequent appearance of local maximum and minimum values. The latter is found at Sta.Ws, typical profiles at the upstream of the bottom current.

Looking downstream of dense bottom current from Sta.Ws to Sta.W, the lower temperature at Sta.Ws got warm toward Sta.E receiving the run down heat flux due to particle sinking. It was done by settling particles losing turbidity or concentration. It is apparent gain of buoyancy as the total density is reduced. This is an integration to convert temperature and turbidity into density using the formula [6], where T is water temperature, C: volume concentration in ppm, $\sigma = 1.65$: the submerged specific weight of inorganic mineral particles, n: relative submerged weight of particles including conversion factor from turbidity (FTU) into volumetric concentration (ppm). Dense bottom currents are driven by the density difference, mostly temperature difference in the bottom layer. It was only 0.2°C in Fig.4 for the distance of 2,460 m and the difference was solved during the advection. The process is a spatial change but it is first treated as a temporal change. Temperature array profiles contain inversions of 0.1°C consistently. It was equivalent to the turbidity excess of 14 mgL^{-1} .

Two cross sections are shown in Fig.5. The deeper is drawn in solid line and the shallower in dashed line. The corresponding lengths are shown in Fig. 1 in the same way. When the wind parallel to the section blows induced convective circulation pattern in winter is the upper sketch and the lower shows in stratified seasons.

The wave measurement was done on the very final stage of destratification of the year and situation was similar to the transition between them. Turbid water on the measurement was mainly in the northeastern part of the lake and it reached to the deepest area along sloping bottom. The current may receive the particle precipitation and the settling flux induces down slope flux of negative buoyancy, which is due to cold temperature, suspended solids and dissolved matters. The

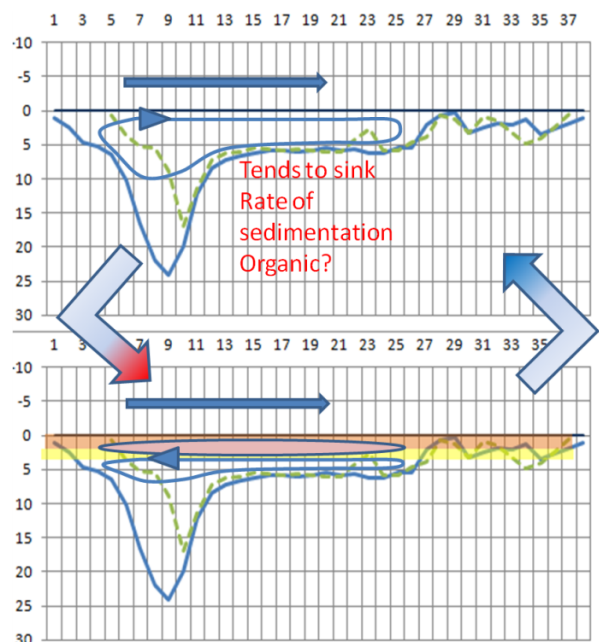


Fig. 5 Circulations in winter (upper) and the summer (lower) situations of vertical circulation

flux ratio is the same as the salt finger in the Oceans. Okubo *et al.* [7] described on the laboratory experiment of the finger regime in Turner [8].

The bottom current gets silt flux and run down heating which causes deceleration of the bottom current and the depths of detachment and the turbid intrusion are different from others depending from the temperature gradient and settling velocity of the particulate matters. A common fact is that the fine sediment would be drifted to the deepest part and settled down at the sink and removed by the action of waves and currents. It will be discussed on the seiching characteristics.

4. Discussion

Two water level gauges were started at the two locations, Sta.N and Sta.E. The monitoring is worth to observe and continued every minutes for two weeks. One minute interval spectral analysis covers the range from 2 minutes to 1 day for two days duration. Middle part of the lake would be closer to the nodes and higher velocities of seiches are observed. The four peaks are noticed in Table 3. The simple estimation on the mode shows the period of 49.0 min is just the average of two observed periods (58 min and 41 min). As pressure data includes atmospheric pressure and the difference in hydrostatic pressures is free from the surface pressure. The difference (N-En) in water level (kPa) is equivalent to 3 cm to 9 cm

Table 3 Surface seiches in Lake Pyhäjärvi

period (min)	mode	length (km)	nodes	celerity (ms ⁻¹)	talweg (m)
97.5	Long	48	Uni-	8.21	6.87
58.0	Long	24	Bi-	6.89	4.85
40.5	Long	16	Tri-	6.58	4.42
31.5	Lateral	12	Uni-	6.35	4.11

The velocity amplitude of uni-nodal seiche at the bottom is

$$U = H\sigma \frac{1}{\sinh kh} = \frac{2\pi\Lambda/97.5/60}{\sinh(5 \cdot 2\pi/48,000)} = \frac{3.22 \cdot 10^{-5}}{6.54 \cdot 10^{-4}} = 0.049 \quad (4)$$

where the typical amplitude at the anti-node $\Lambda=0.03$ m, and that it would be 0.1 ms^{-1} , if it is double. A gap in the water level is noticed on Sep 21, around 6 cm. A displacement of the logger could mark on the record in this way however there is a possibility of the outflow discharge, within the range up to $10 \text{ m}^3/\text{s}$ could be controlled on the day. It was local water surface profile and the Sta. N is very close to the outgoing river.

When discharge increased the depth at Sta. N decreased and the record shows this tendency. It is also nearly diurnal temperature variation is seen on the successive days. The record is not long enough to discuss total thermal processes on the lake.

5. Conclusions

It was found as follows on the waves, seiches and their roles in the redistribution of bottom materials in Lake Pyhäjärvi, Finland:

1) Sediment resuspension due to wave action becomes significant when the wave period gets longer than 2.5 seconds. Waves become those in shallow water in areas of the average depth of 5 m. In most littoral area where the condition met the finer sands have been already disappeared.

2) Water levels at two stations were monitored half a month and four surface modes with the periods 95.7 min, 58.0 min, 40.5 min, and 31.5 min were extracted by means of spectral analyses. Alternative currents due to seiching near the nodal lines are responsible for suspension. Resultant turbidity causes the bottom current or turbid intrusion observed.

3) Existence of turbid intrusion suggests that thermal stratification does act on the density field however higher turbidity was found in CTD profiles on the slope connected to the deepest point and double-diffusive convective process seems to be relevant.

4) Both waves and seiching would suspend sediments rather frequently. The increase in turbidity gives a rise to bottom current as the first path to arrive the perimeter of the deepest zone. It is followed by two options: intrusion at the depth of 5 m or the current on sloping bottom. These are considered as the final sedimentation.

5) There forms a thermal inversion of 0.1°C around the layer of the local settling, which is equivalent to the weight concentration of 15 mgL⁻¹ in a water temperature zone around 15°C. There is little information on the bottom currents on the deeper slope.

6) A bottom current is driven by wind mixing/cooling. Sediment laden cold water goes down the slope into the sink area leaving a cloud of finer particles in the intrusion at the average depth. The underlying current is decelerated receiving warm precipitation from the cloud and loses negative buoyancy.

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