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Water Temperature and Ice Conditions in Fengman Reservoir, Winter of 2012-2013

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A comprehensive prototype observation in the Fengman Reservoir was carried out to investigate the temporal and spatial variations of water temperature and ice conditions during the winter of 2012-13. The observed data show: 1) surface water temperature in the reservoir presents a longitudinal increase of 7.0℃ in autumn, which results in the variation of freeze-up date along the reservoir; 2) a vertical inversion water temperature distribution existed beneath the ice cover, and the temperature drops in the front of the dam due to the heat discharge of power station during the ice season; 3) the outflow water temperature decreases at a steady rate of 0.16℃/day before freeze-up in the reservoir, but maintains a 2.1℃ temperature during the ice season, with a 60km open channel in the downstream part of the reservoir; 4) both freeze-up and break-up developed from upstream to downstream, and the ice thickness was non-uniform; 5) the temperature distribution in the ice cover is linear, and the estimated heat exchange beneath the ice cover is 8.5W/m^2.

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1. Introduction

Ice is an important hydrological phenomenon in reservoirs and lakes in cold regions. Ice processes including formation, growth, and decay are affected by hydraulic and thermal conditions. Donchenko (1987) summarized important findings on the variation of ice conditions in reservoirs based on the observed data from more than 30 reservoirs between 1950 and 1980 in the former U.S.S.R. To date, many reservoir ice problems, for instance the relationship between water temperature and ice conditions, ice dynamics, and ice jam in the tail of reservoir, are still not well understood. This paper reports findings from initial field observations in the Fengman Reservoir.

Fengman hydropower station is located on the main stream of the Second Songhua River in Jilin City, China, as shown in Figure 1. The height of dam is 91.7m and the backwater length is about 153km. Baishan and Hongshi hydropower stations are located upper stream. In winters, ice covers the whole area of Fengman Reservoir, and its maximum thickness can reach 1.0m. The prototype field observation was initiated during the winter of 2012-2013 to gain a better understanding on the characteristics of water temperature and ice conditions.

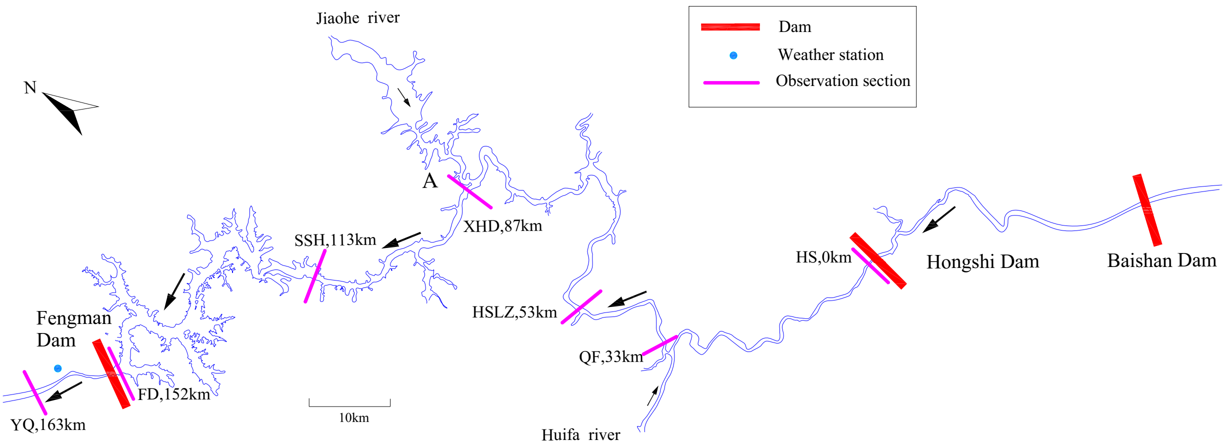

Figure 1. Fengman Reservoir and observation sections

2. Observation details

The cross sections of field survey on water temperature and ice conditions in Fengman Reservoir are shown in Figure 1. Vertical water temperature profiles in reservoir were measured by the YSI6600 multiparameter water quality Probe on October 9, 2012, January 1, and April 8, 2013. The vertical distance between two measuring points on water temperature profile was 1 to 3m. A thermistor chain was used to record the ice cover temperature at the FD cross section near the dam from January 1 to April 14, 2013. Two mechanical thermographs (http://www. lgoume. com, ZDR.) were installed at the inflow section (HS section) and 10 km downstream of the Fengman Dam (YQ section), to obtain hourly inflow and outflow water temperature data from October 12, 2012 to April 11, 2013. Ice survey consisted of recording the date of the freeze up and breakup, and measuring the thickness of ice and snow covers. Thickness measurement was carried out 2 times every week at HSLZ, XHD, SSH, and FD from January 1 to April 12, 2013. Air temperature and reservoir operation data were collected from the meteorological station and Fengman power station, respectively.

3. Variation of Thermal Conditions

3.1 Water temperature variation before freeze up

Figure 2 shows the 2D water temperature distribution in Fengman Reservoir. In autumn, the decrease of air temperature leads to the fall of water temperature that result in the vertical density convection in the surface layer and the formation of a certain thickness of the isothermal layer. Due to the limitation of meteorological conditions and the large depth of the water, the thickness of stratosphere reached 40m in depth, and a thermocline with difference of vertical temperature about 7.5℃ existed beneath the stratosphere at the FD cross section. Meanwhile, there was an increase of surface water temperature of about 7.0℃ from the tail to the front of the reservoir. Fengman Reservoir is divided into three different zones, the shallow-depth zone (0-53km from the tail area of the reservoir), the middle-depth zone (53-113km), and the deep water zone (113-153km). The replacement rate may be expressed as：

$$b_j = V_{in} / V_j \qquad [1]$$

in which b_j = the replacement rate of store water in reservoir during a month; V_{in} = the inflow runoff; V_j = store water volume in different waters of reservoir. For an average monthly flow rate of 250m^3/s and the water level 254m in winter, the value b_j in the shallow-depth zone, the middle-depth zone, and the deep water zone are 5.3, 0.7, and 0.3, respectively. This indicates that the time for replacing deep waters needs 3.3 months, resulting in a remarkable heating effect on the reservoir in winter. In addition, the longitudinal difference of temperature in these zones also affected the freeze up date in the reservoir (See Table 1).

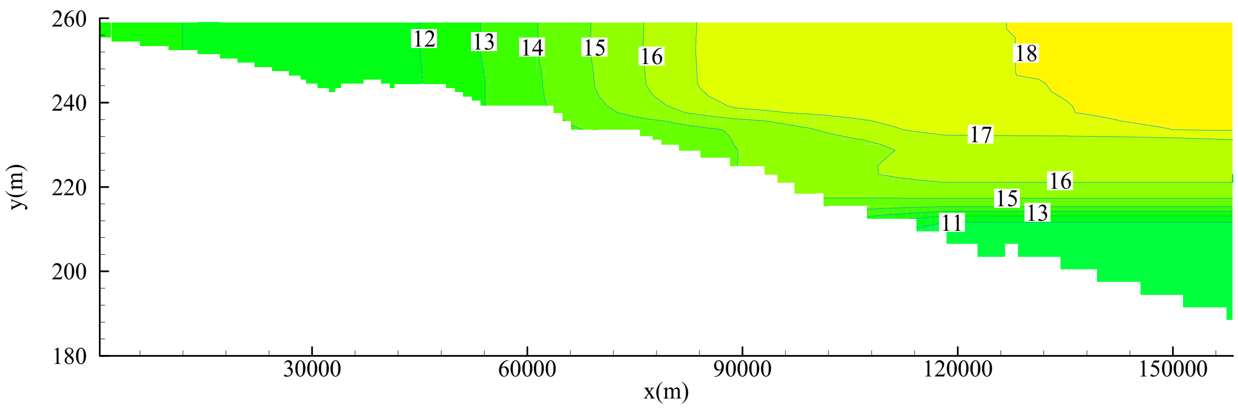

Figure 2. 2D distribution of water temperature on October 9, 2012

3.2 Water temperature variation in the ice season

As show in Figure 3, water temperature presented a vertical inversion distribution in the ice season, and the temperature profile of XHD and FD had an obvious difference about 3.0℃ in deep waters, while that of HSLZ was uniform at vertical direction, influenced by the inflow and the storage of heat in reservoir. The surface water temperature was 0.5℃~1.3℃ at a depth of 1.0m, and it remains relatively stable until April in FD section, on account of the small heat flux at ice-water interface (about 8.5 w/m^2). From January 1 to April 8 in FD cross section, the vertical water temperature was falling, under the influence of the discharge of Fengman Power

Station. The difference of temperature at the depth of 10 m between these two dates was about 2.0℃.

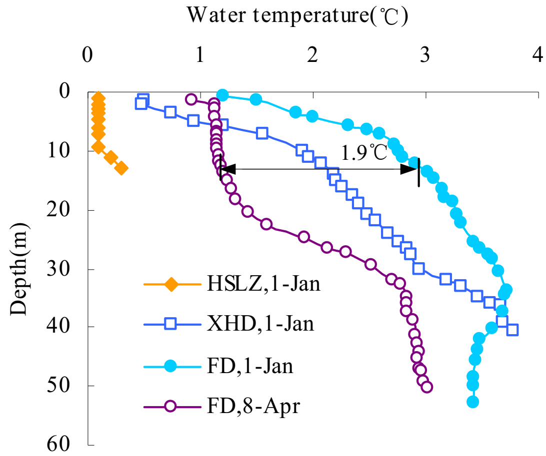

Figure 3. The vertical temperature distribution in the reservoir on January 1 and April 8, 2013

3.3 Water temperature of the inflow and outflow in winter

Figure 4 shows the variations of outflow and inflow temperature in Fengman Reservoir from October 12, 2012 to April 11, 2013. Water temperature of the outflow gradually dropped at a steady rate of about 0.16℃/day before the freeze up in reservoir, while the maximum value of air temperature variation was 33℃. However, the temperature of outflow water changed 9.9℃ from Nov.1 (12.1℃) to Dec.31 (2.2℃), 2012, which was averagely 6.7℃ higher than that of the natural river (about 0.0℃) before the Fengman Dam construction. When ice covered the reservoir, it hindered the heat loss from the water surface and the outflow temperature remained at a stable value of about 2.1℃. When the heat flux of the flow from YQ cross section was 3.4×10^9J/s, and an open channel about 60 km was maintained downstream, despite that the air temperature was -16.4℃ from January 14 to 19, 2013.

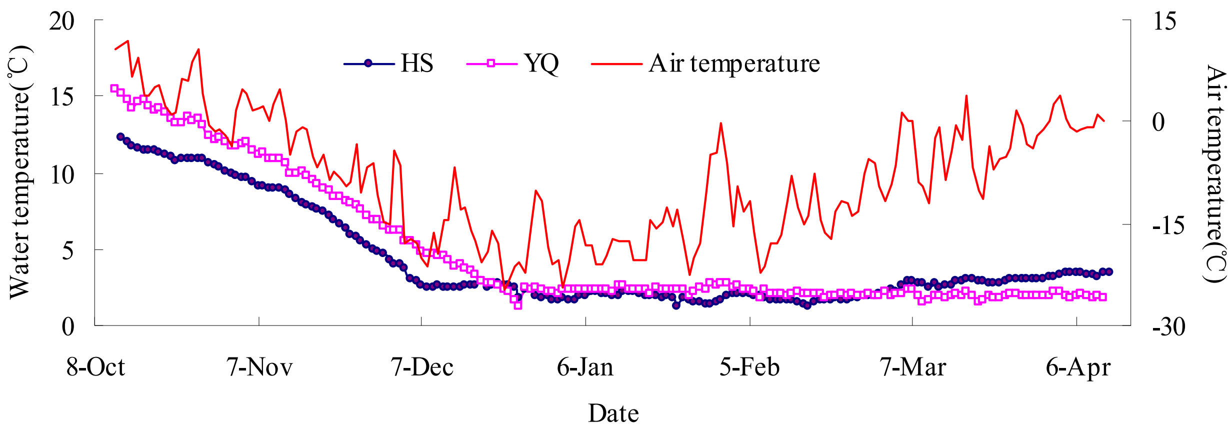

Figure 4. Observed temperature of inflow and outflow in Fengman Reservoir

The variation trend of inflow in Fengman Reservoir was basically the same as that of outflow, because it was influenced by Baishan Reservoir whose regulation was similar to Fengman Reservoir. When the inflow temperature reached about 2.0℃, it could also form about 40.0 km open channel in the tail of Fengman Reservoir.

4. Ice Regime in Fengman Reservoir

4.1 Characteristics of ice conditions

According to the observation data (shown in Table 1), the order of freeze-up and break-up were both developed from upstream to downstream river, but the freeze-up of the whole reservoir completed in one month while the break-up lasted longer. This regular phenomenon had a close relationship with water depth and air temperature. Affected by the cold climate, the ice season in reservoir lasted more than 100 days, which led to inhibiting the energy between water and air for a long time.

The ice thickness showed obvious temporal and spatial variations in Fengman reservoir (See Figure 5). The maximum rate of change of the cover thickness occurred on the first 30 days after the freeze-up, mainly due to the large heat flux from the initial thin ice cover, and the cold air temperature. During the middle period, ice thickness remained relatively stable and reached at its peak value, resulting from the thicker snow and thermal equilibrium between ice and water. After mid-March, the ice cover began to melt, and the maximum rate of ice melting occurred in the last 20 days, caused by solar radiation and positive air temperature. Ice thickness in different area of reservoir was quite different at the same time. The thickest ice cover occurred in the middle of reservoir, and then less thick in the front of the dam, the last in the tail of reservoir, which were contributed by the freeze up date and thermal conditions beneath the ice cover. In the middle of January, February, March, the maximum discrepancy could reach 8cm, 45cm, and 12cm, respectively.

Snow cover influences the growth of ice cover thickness (Donchenko, 1987). The snow cover provides insulation between air and ice cover, snow cover resulted in small variations of ice thickness in mid and late ice season. A sudden large increase of ice thickness at the FD cross section occurred in mid-March due to the snow ice formation (See Figure 5).

Table 1. Ice characteristics in the Fengman Reservoir

Cross section	Freeze-up date	Break-up date	Ice cover duration (day)	Maximum ice thickness (cm)	Maximum snow thickness (cm)
HSLZ	2012-12-2	2013-3-16	105	40	10
XHD	2012-12-10	2013-4-27	139	51	49
SSH	2012-12-19	2013-4-29	132	44	43
FD	2012-12-26	2013-5-2	128	63	35

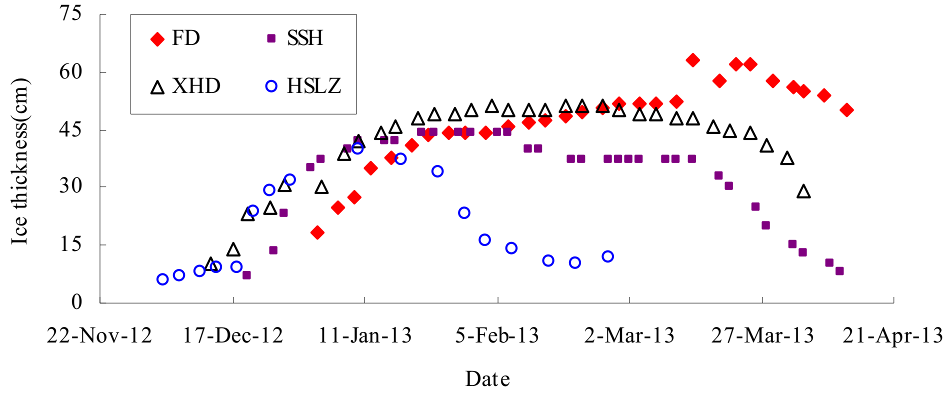

Figure 5. The changing process of ice thickness with time in Fengman Reservoir

4.2 Temperature variation in ice cover in front of the dam

The variation of ice surface temperature in front of Fengman dam and air temperature from January 1 to April 11, 2013, are shown in Figure 6. The proportional coefficient between ice surface temperature and air temperature can be used to describe their relationship. The average ratio of ice temperature and air temperature was 0.29 in the main period of ice growth from January 1 to March 15, 2013, while the minimum was 0.09 (February 1), the maximum was up to 0.48 (January 11). Compared with the ratio of 0.55 in Hongqipao Reservoir (Xiao, et al. 2004), the difference may arise from the difference in the snow thickness. Furthermore, the ice surface temperature reached 0.0℃ though air temperature was below zero, resulting from snow thickness and other factors such as rainfall, solar radiation.

A linear distribution of temperature in ice cover was assumed and proved valid (Shen and Chiang 1984; Hao, et al. 2009). The ice temperature distributions over the thickness on January 16, 31, and February 14, 2013, are shown in Figure 7. They vary linearly with correlation coefficients of 0.99, 0.99, and 0.97, respectively. The observation herein confirms that the linear temperature profile assumption is valid in the calculation of ice cover temperature in reservoirs.

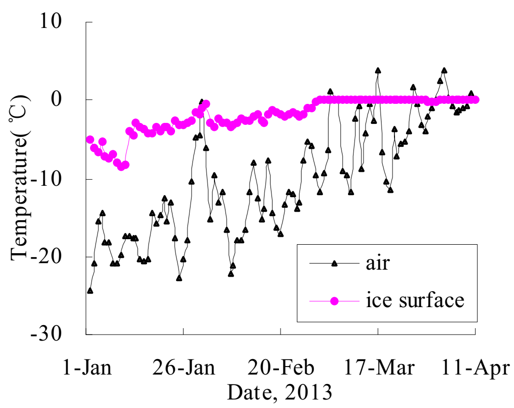

Figure 6. The changing process of the ice thickness with time in FD cross section

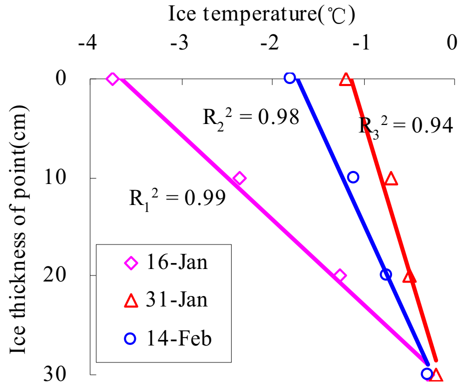

Figure 7. The linear correlation of the ice temperature in FD cross section

4.3 Energy balance at ice-water interface

After the initial ice cover formed in the reservoir, a heat balance equation at the bottom of the ice cover can be established (Shen and Chiang 1984):

$$k_i \frac{\partial T_i}{\partial z} - q_{wi} = \rho_i L_i \frac{dh}{dt} \quad [2]$$

where k_i, ρ_i, T_i = conductivity, density and temperature of the ice; q_{wi} = heat flux from water to ice; L_i = the latent heat of ice melting; and dh/dt = the rate of the ice thickness variation.

Some typical formulas (Ji, et al. 2002; Oveisy, et al. 2012) were given for the calculation of heat exchange at ice-water in large water body:

$$q_{wi} = \rho_w C_p C_h u_{wi} (T_w \text{-} T_m) \quad [3]$$

$$q_{wi} = -k_w \frac{dT_w}{dz} \quad [4]$$

where k_w, ρ_w, T_w , C_p = conductivity, density, temperature and specific heat of the water; T_m= freezing point of the water, 0.0℃; u_{wi} = velocity of water beneath the ice; C_h =. heat transfer coefficient between ice and water.

But these calculation methods of heat exchange at ice-water display obvious difference, and it is difficult to choose a reasonable one to evaluate heat exchange at ice-water in reservoir. Therefore, Equation 2 and some observed data shown in Figure 5 and Figure 6 are used to calculate directly the mean value of heat flux from water to ice during January 3 and February 28, 2013. The value of q_{wi} herein is 8.5W/m^2,and it is about one-third of heat flux in ice cover (29W/m^2), while the loss heat flux from water to air estimated by using the empirical formulas (Shen and Chiang 1984) may be up to 315W/m^2 without the ice cover. However, The value of q_{wi} is 2.5 W/m^2 using equation 3 and 0.6 W/m^2 from equation 4 with C_h = 0.3×10^{-3}, u_{wi} = 0.002m/s, T_w = 0.9℃ (at a depth of 1.0m). The underestimated heat exchange at ice-water may result in the excessive increase of ice thickness and water temperature beneath the ice.

5. Conclusions

A prototype observation was made to investigate ice conditions and water temperature of Fengman Reservoir during the winter of 2012-13. These observed data indicated that the heat distribution in reservoir caused obvious temporal and spatial variations of ice formation, growth, and decay. Ice cover hindered the heat transfer between air and water, resulting in the slow decline of water temperature over the depth in front of the Fengman Dam and the stability of the outflow water temperature in reservoir. Furthermore, a linear distribution of temperature in ice cover was observed, and the estimated heat flux from water to ice was about $8.5W/m^2$. The field observation of a large reservoir in the present paper is relatively comprehensive. However, some factors such as topography, wind dynamic are not involved. Therefore, in order to further understand the ice process in the reservoir, these aspects and the relationship between branches and the main reservoir should be considered in the future study.

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