Impact of Spring Freshet Flooding and Summer Rainfall Flooding on the Water Quality of an Alpine Barrier Lake

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Abstract

Background: Among the many types of lakes, the barrier lake attracts special attention. China's Lake Jingpo is one of the world's rare such alpine lakes. Spring freshet flooding and summer rainfall flooding are factors that significantly increase barrier lake instability while also impacting water quality.

Results: This study constructed a hydrodynamic water-quality model to simulate the impacts of spring freshet flooding, summer rainfall flooding, and 30-year frequency rainfall flooding on the flow-field and water quality at Lake Jingpo. Results showed that the lake-area flow field was generally weak (mostly lower than 0.015 m/s), but spring freshet flooding in April and summer rainfall flooding in August-September increase flow velocities to 0.045 m/s and above, much higher than in other months. Mudanjiang is the largest river that enters Lake Jingpo. Its flow reaches $4.81 \times 10^8 \text{ m}^3$, $29.77 \times 10^8 \text{ m}^3$, and $58.4 \times 10^8 \text{ m}^3$ during the spring freshet flooding, summer rainfall flooding and 30-year frequency rainfall flooding period, respectively. The longest diffusion distances were measured from the lake mouth to the point of impact; these were 16.3 km, 33.1 km, and 43.6 km for the above periods, respectively. Our research revealed that precipitation played an important role in seasonal water quality at Lake Jingpo, and larger amounts of precipitation, longer diffusion distances, and increased pollutant concentrations.

Conclusions: Compared to the effects of the spring freshet flooding period, the summer rainfall flooding and 30-year frequency rainfall flooding period more significantly affected water quality at Lake Jingpo. There was more overall precipitation, longer diffusion distances, and increased pollutant concentrations in the lake area. Alpine barrier lake environments are very fragile, which need greater care efforts and more stringent measures to control pollution sources throughout entire catchment area.

Background

Barrier lakes are formed by volcanic lava flows or landslides caused by earthquakes or other such phenomena. These events may obstruct flow and collect water in valleys or riverbeds. Some barrier lakes have been anthropogenically created on large rivers to generate hydroelectric power. An example is the Kananaskis barrier lake in Alberta, Canada. Based on topography and/or the formation process, barrier lakes can be further divided into alpine barrier, lava barrier, and moraine barrier lakes. Among the many types of lakes, barrier lakes attract special attention due to the unique formation process and beautiful scenery. However, some barrier lakes are unstable and prone to collapse (Sun et al., 2014). The most famous is Lake Geneva in Switzerland, which is an alpine moraine barrier lake (Jacquet et al., 2014). With an area of 582 km^2 , it is also the largest alpine barrier lake (Gallina et al., 2017). Lake Jingpo is another of the world's rare alpine lakes. It was created after several volcanic eruptions produced lava that blocked local river water to form a mountain barrier lake. However, scientific research on Lake Jingpo is very scarce compared to other barrier lakes (Wang et al., 2015).

Both the frequency and intensity of summer rainfall flooding are increasing (Groisman et al., 2005; Walsh et al., 2014; Cooney et al., 2019). In this context, spring freshet flooding and summer rainfall flooding

increase barrier lake instability while also impacting water quality. Spring freshet entail rapid flooding due to late spring melts, while summer rainfall flooding often occur in summer and autumn (Smith et al., 2011). Owing to their special structures, barrier lakes continually interact with their original bodies of water, which are usually large rivers. Alpine barrier lakes are also surrounded by mountains. As such, snow melts or rainfall runoffs that move through inflowing rivers and mountains play important roles in the natural processes associated with barrier lakes (Chao and Seo, 2007; Dorum et al., 2010).

The Lake Jingpo catchment is located in northeast China; heavy precipitation thresholds have been trending upward in this area during spring, summer, and winter months. With the increasing frequency of these heavy precipitation events (Li et al., 2015), the impacts of spring flooding and summer rainfall flooding have made more obvious impacts on water quality at Lake Jingpo. This attracted significant attention from both the local government and Ministry of Ecology and Environment, China.

There is no real-time monitoring of either rainfall or inflowing river and lake water in many such situations that now arise. There are also few preliminary studies on the rainfall impact period. It is thus difficult to use real-time monitoring data to explain the impacts of spring freshet flooding and summer rainfall flooding on lake water quality. Thus, model simulation techniques are now being applied increasingly to simulate the impacts of these events on both water quantity and quality at many lakes (Moore, 2007; Chen et al., 2015; Zhang et al., 2017). Among these simulation tools is the commonly used MIKE 21 software. MIKE 21 is a comprehensive modeling system used to simulate hydraulics and hydraulic-related phenomena in different bodies of water. The system contains a wide range of engineering and environmental applications that can be used to examine coastal hydraulics, oceanography, wave dynamics, harbors, rivers, environmental hydraulics, and sediment processes (Warren and Bach, 1992). After more than 25 years of continuous development and improvement, MIKE 21 now combines the experiences of thousands of worldwide users. It also includes many different modules. For example, it includes the Advection Dispersion Module (AD), which can simulate the transport process of dissolved matter in water due to convection and diffusion, and the Hydrodynamics (HD) module, which can simulate changes in water level and flow caused by various forces. MIKE 21 contains an extensive range of hydraulic phenomena and can be used to simulate any two-dimensional free-surface flow that ignores stratification. An increasing number of engineers and scientists around the world now rely on MIKE 21 as a key simulation tool.

The aims of his study are (1) to simulate annual variations in the flow-field of a typical large alpine barrier lake, (2) to simulate the impacts of spring freshet flooding, summer rainfall flooding, and 30-year frequency rainfall flooding on water quality at an alpine barrier lake to determine the impact, scope, and impact period, and (3) to provide scientific support for the subsequent control of lake pollution.

Study Area

Lake Jingpo is a typical alpine barrier lake. Further, it is world's second largest such lake. It is located in northeast China (N 43°46′-44°18′, E 128 °30′-129°30′); the lake area is in Heilongjiang province, but most

of the catchment area is in Jilin Province (Fig. 1). The total area of the Lake Jingpo catchment measures 11,664.67 km², of which 79.8% is in Jilin Province (9,312.39 km²), while the remaining 20.2% is in Heilongjiang Province (2,352.28 km²). Lake Jingpo is in a deep mountain valley with an elevation range of 339.17-1,260.7 m. Some of this area is covered by extinct volcanos. The lake itself was formed by several volcanic eruptions that intercepted the Mudanjiang River, which is both the outflowing and largest inflowing river.

Lake Jingpo catchment is located in a temperate continental monsoon climate zone. It is characterized by windy and rainless weather in spring, concentrated rainfall in summer, a cool climate, short autumn, and cold winter. There is a large temperature difference between daytime and nighttime. The annual average temperature is 3.5 °C, while the highest is 38 °C, and the lowest is - 40.1 °C. Annual average precipitation measures 549 mm, which is normal for a temperate humid climate. The distribution of precipitation varies significantly during the year. For instance, summer precipitation (June-August) accounts for approximately 61% of the annual total. There are only short durations of sunshine, while the wind direction is stable, the three-dimensional climate characteristics are remarkable, and temperatures vary with altitude. The snowfall period lasts from October to March of the following year; the average snowfall period is 172 days. It usually begins to freeze during mid-to-late October and gradually begins to melt in March of the following year.

The literal meaning of Lake Jingpo translates as “lake as clear as a mirror.” This reflects that its water quality was once very good. Lake Jingpo is still a tourist attraction and a shining pearl in northeast China. As recently as 2012, it was designated as a “good water quality lake” by the Ministry of Ecology and Environment, China. However, the recent expansion of local farmlands, economic growth of the upstream area, and vigorous development of tourism have caused nutrient concentrations in the lake’s water to rise. This is especially evident during the summer rainfall flooding period (July to September), when the concentrations of both total nitrogen (TN) and total phosphorus (TP) can exceed 2 mg/L and 0.2 mg/L, respectively. Similar, TN and TP concentrations also begin to peak during the spring freshet period. However, they do not reach the same levels seen during the summer rainfall flooding period. The deteriorating water quality at Lake Jingpo has caused concern among various environmental protection departments. As such, significant efforts will be made to protect Lake Jingpo over the next few years.

Lake Jingpo has a water area of 91.5 km² and a water storage capacity of 11.8×10^8 m³. The water exchange period totals 116.7 days (3.13 times per year). The annual variation characteristics of Lake Jingpo’s water level are as follows: The highest water level mainly occurs during the main rainfall period (from August to September), while the lowest water level mainly occurs from March to April, the annual average water level is 347.95 m, the highest water level is 354.43 m, and the lowest water level is 339.17 m. A total of 11 main inflowing rivers enter Lake Jingpo. The upper reaches of the Mudanjiang River are its main source of water inflow. The surface of Mudanjiang River measures about 50–150 m wide, while its normal water depth is 1.0–2.0 m, and the maximum and minimum velocities have been rated at 2.75 m/s and 0.09 m/s, respectively. Lake water is mainly recharged by surface runoff; the Mudanjiang River inflows an average of 2.53 billion m³/a each year. Indeed, it accounts for 68.6% of the

total river inflow into the lake, which is 2.18 times the total inflow of all other rivers. The outflowing water from Lake Jingpo is mainly used to generate hydraulic power. After discharging from the power plant, water enters the outflowing Mudanjiang River through an underground passage. Further, part of the water body flows into the Mudanjiang River through the Diaojiaolou Fall at the northern end of the lake. A map of the water system is available in Fig. 2.

Figure 3 shows land use in the Lake Jingpo catchment. Here, forestlands account for 70.7%, arable lands account for 23%, grasslands account for 3.4%, the water system accounts for 1.7%, gardens accounts for 0.3%, town, village, industrial, and mining lands account for 0.2%, traffic lands account for 0.3%, and other lands account for 0.4%. The total population of the Lake Jingpo catchment is approximately 466,500. Most people are concentrated in Dunhua City of Jilin Province and Ningan City of Heilongjiang Province.

Methods

Data collection

All meteorological data were derived from China surface climate readings (<http://www.cma.gov.cn/>) taken by the China Meteorological Science Data Sharing Service Network. Rainwater pollutant concentrations in the Lake Jingpo catchment were provided by the Heilongjiang Academy of Environment Sciences; morning rainwater pollution conditions for 2017–2018 were as follows: A total nitrogen concentration (TN) of 3.89 mg/L, total phosphorous concentration (TP) of 0.015 mg/L, ammonia nitrogen concentration ($\text{NH}_4\text{-N}$) of 1.52 mg/L, and COD_{Mn} of 11.67 mg/L. Hydrological data from a total of 11 inflow points and one outflow point (a power plant) were also collected by our research group. River-water inflow rates were obtained from the local hydrological monitoring station (Dashanzuizi Station), while outflow information was taken from the water consumption records at the power plant or our own monitoring methods over a one-year period (using the Acoustic Doppler Velocimeter; Link Quest ADCP, Flow Quest 2000-AFA-BC, USA). Other inflowing or outflowing hydrological information collection points are shown in Fig. 4.

The amounts of water flowing into and out of Lake Jingpo were the main driving forces of waterflow in the lake area; the Dashanzuizi estuary was the main entrance to the lake area and the most important “source power.” Measured discharge data taken by Dashanzuizi Flow Station in 2018 (see Fig. 5) indicate that April is the spring freshet season, while July–September is the summer rainfall flooding season. Larger flow volumes enter Lake Jingpo during these times, especially during the summer rainfall flooding season.

Lakebottom elevation is shown in Fig. 6 (Yellow Sea Height datum).

Establishing and calibrating the flow model

The MIKE 21 HD hydrodynamic model was used to build the water flow model. This was done to analyze water balance, study water-level characteristics, and determine velocity variation in the lake area while gathering necessary hydrodynamic field elements for subsequent pollutant calculations. As such, a total of 13,500 grids were established across the lake's surface area; the model's mesh size was 250 m, while the time step was 60 s. The eddy viscosity coefficient was calculated using the Smagorinsky subgrid scale formula (Smagorinsky coefficient of 0.5) and manning roughness factor of $32 \text{ m}^{1/3}/\text{s}$.

The MIKE 21 HD hydrodynamic model was calibrated using automatic monitoring station data concerning water quantity and velocity information for all of 2018. The relative hydrologic information source is described in Sect. 3.1, while calibration results are shown in Fig. 7. Lake Jingpo's actual measured water level was nearly unchanged from January to February, but trended downward from February to March. The spring freshet season then caused an increase and subsequent decrease from April to June, followed by higher water levels from July to September due to summer rainfalls (the highest level was reached at the end of August). The water level gradually decreased from October to December. Compared with the measured water level, the maximum error of the simulated water level at Lake Jingpo was less than 0.3 m. As such, the two-dimensional hydrodynamic model used in this study accurately reflected the hydrodynamic characteristics of Lake Jingpo and was suitable for research.

Establishing and calibrating the water quality model

We constructed a water quality model using the MIKE 21 AD convection and diffusion module. This model was used to simulate the concentration distributions of COD, $\text{NH}_4\text{-N}$, TN, and TP in the lake area during the year 2018. We calculated the pollution loads entering Lake Jingpo by combining data accumulated by the Dashanzuizi Flow Station in 2018 and our measured data. As such, the total pollution loads and proportions entering from the Mudanjiang River (in parentheses) were determined at TN 2446.61 t/year (64.62%), TP 232.39 t/year (81.63%), ammonia nitrogen 913.75 t/year (73.35%), and COD_{MN} 14633.59 t/year (59.65%). The total pollution loads and proportions (in parentheses) entering from other rivers flowing into Lake Jingpo were as follows: TN 1339.61 t/year (35.38%), TP 52.3 t/year (18.37%), ammonia nitrogen 331.93 t/year (26.65%), and COD_{Mn} 9900.42 t/year (40.35%).

Model correction was realized by adjusting the attenuation coefficient, diffusion coefficient, and non-point source load into the lake. Figure 8 shows a comparison of the measured water-quality values with those simulated by the model. Here, the model's predictions were generally very similar to the actual measured values. While there were some differences, all errors were in the acceptable range. The measured and simulated concentration values were similar for TN in the range of 0–25 km; the variation trend differed a little in rest range, but the concentration difference was only about 0.2 mg/L. The measured and simulated concentration values for TP were very close. While the concentration change trends differed in the range of 15–20 km, the difference between concentration values was small. Further, the concentration value changes were in the range of 0.10–0.14 mg/L in the range of 20–40 km and the trends were essentially the same between the two group values. There were some differences between the simulated and measured COD concentration values. However, the concentration difference was very small. The two curves showed very similar trends and maximum concentrations were also in similar positions. The concentration differences for $\text{NH}_4\text{-N}$ were large in the range of 0–20 km when compared

with the simulated concentration curve. However, the variation trends were similar in the range of 20–40 km; the variation ranges and trends for $\text{NH}_4\text{-N}$ were also very similar.

Results

Annual variations in the flow field at Lake Jingpo

The icebound season at Lake Jingpo lasts from October to February of the following year. As such, we were only able to analyze changes in the flow field from March to September, 2018 (Fig. 9). Results indicated that the lake-area flow field was generally weak (mostly lower than 0.015 m/s). However, flow velocity significantly increased during the spring freshet season (April) and summer rainfall flooding period (August–September). The most significant changes were seen in August, when flow velocities were measured at 0.045 m/s and above. This was much higher than in other months, thus indicating that spring freshet flooding and summer rainfall flooding have important effects on flow velocity at Lake Jingpo.

Impact of the spring freshet season on water quality at Lake Jingpo

Spring freshet flooding typically occur in April for the Lake Jingpo catchment area. This is when the temperature rises above 5 °C and there is sufficient sunshine to melt the surrounding snow and ice. Along with water, these events carry pollution into the lake. Figure 10 shows the diffusions of TN, TP, COD_{Mn} , and ammonia nitrogen over the 24 days of the spring freshet period. These four pollutants diffuse with very similar trends; on the first day that spring freshet flooding enter the lake, concentrations in the mouth area rise rapidly (4–10 times the initial value). These pollutants will have spread to infiltrate approximately 25% of the lake body by the ninth day; by the 24th day, this will have increased to cover nearly 50%. However, the relatively small inflow of spring freshet flooding means that these pollutants are unlikely to spread to the northern part of the lake, even after 24 days.

TN concentrations in Lake Jingpo range from 0.7 mg/L to 1.2 mg/L before spring freshet flooding enter. When this occurs, TN concentrations at the entrance exceed 1.7 mg/L. Pollutants gradually diffuse downstream in the direction of flow as more spring freshet flooding enter the lake. As such, TN concentrations in the affected area increase to more than 1.7 mg/L. However, TN concentrations do not significantly increase in the northern lake area due to the limited reach of the spring freshet flooding (as of day 24).

TP concentrations range from 0.08 mg/L to 0.12 mg/L before spring freshet flooding enters Lake Jingpo. After this occurs, however, TP concentrations exceed 0.28 mg/L. The affected area is limited during the early stages. At this time, the downstream lake remains almost totally unaffected. Concentrations will gradually increase in the downstream area with the further diffusion of spring freshet flooding. They will ultimately exceed 0.28 mg/L in approximately half the lake area by the end of the impact period.

COD_{Mn} concentrations are less than 6.0 mg/L before spring freshet flooding enter the lake area. Concentrations at the lake mouth will rise to 8.4 mg/L when this first occurs. The continuous transportation of these waters increase COD_{Mn} concentrations to 8.4 mg/L and above in the upstream area, but the downstream area remains nearly unchanged.

NH₄-N concentrations in Lake Jingpo are in the 0.06–0.30 mg/L range before spring freshet flooding enter. However, they exceed 0.84 mg/L when this does occur. The downstream lake area is nearly unaffected during the early influx stage. The continuous diffusion of spring freshet flooding will eventually raise NH₄-N concentrations to 0.72 mg/L and above in the upstream area, but the downstream area will remain unaffected.

Impact of the summer rainfall flooding on water quality at Lake Jingpo

Summer rainfall flooding often hits the Lake Jingpo catchment area in July-September each year. A large amount of precipitation washes the ground and brings in many pollutants during those times. This sharply increases lake pollutant loads for a short time and thus impacts water quality. A simulation of the pollutant transportation process is shown in Fig. 11. As seen, it generally only takes eight days of summer rainfall flooding for pollutants to diffuse to around 25% of the total lake area, and takes approximately 16 days for pollutants to diffuse to the hydraulic powerplant. Compared to the spring freshet period, this is a faster transfer with a larger impact range.

TN concentrations in most of the lake are between 0.2–0.8 mg/L before summer rainfall flooding period. However, concentrations at the lake mouth increase to 2.8 mg/L when this occurs (approximately 14 times higher than before flooding). The entire lake is affected by day 16, when TN concentrations increase to varying degrees throughout.

TP concentrations are below 0.2 mg/L before summer rainfall flooding. However, they subsequently increase sharply. By day 16, TP concentrations exceed 0.42 mg/L in most of the lake area from Dashanzuizi to the powerplant.

COD_{Mn} concentrations are lower than 8.8 mg/L before the flooding. However, these subsequently increase to more than 11.2 mg/L. The continuous influx of floodwaters enable surface scouring that far exceeds that of the spring freshet period, thereby causing COD_{Mn} concentrations in most of the lake to exceed 11.2 mg/L.

NH₄-N concentrations are approximately 0.3–0.4 mg/L before the flooding enters the lake area. However, those at the lake mouth increase to 1.5 mg/L when this begins. Continuous rainfall flooding thereafter raises NH₄-N concentrations to exceed 1.5 mg/L throughout most of the lake. The maximum NH₄-N concentrations during these times are around double those of the spring freshet flooding period. Moreover, the polluted lake area is much larger than during the spring freshet flooding period.

Impact of 30-year frequency flooding on water quality at Lake Jingpo

We examined the impact of summer rainfall flooding on water quality at Lake Jingpo by simulating 30-year frequency rainfall. Figure 12 shows the transport and diffusion processes of TN, TP, COD_{Mn}, and NH₄-N, respectively. The diffusion trends of these four pollutants are very similar throughout Lake Jingpo. Entrance to the lake on the first day will typically cause rapid concentration rises; by day 11, this problem will affect nearly 50% of the lake surface. Concentrations will peak by day 21, at which time they will gradually weaken. For example, the concentrations of TN and TP increased rapidly (from about 1 mg/L and 0.06 mg/L to more than 3 mg/L and 0.42 mg/L, respectively). These reached peak impact by day 11. Finally, a weakening trend appeared on day 21. Further, COD_{Mn} concentrations in Lake Jingpo were less than 9 mg/L before the 30-year frequency rainfall flooding. However, floodwaters caused these concentrations to increase rapidly, reaching more than 12 mg/L. The concentrations of ammonia nitrogen also increased rapidly, moving from 0.6 mg/L to more than 1.5 mg/L.

Discussion

Effects of precipitation on water quality at Lake Jingpo

A comparison of the effects of spring freshet flooding, summer rainfall flooding, and 30-year frequency rainfall flooding periods on water quality at Lake Jingpo revealed larger amounts of precipitation, longer diffusion distances, and increased pollutant concentrations (Table 1). Mudanjiang is the largest river that enters Lake Jingpo. Its flow reaches $4.81 \times 10^8 \text{ m}^3$, $29.77 \times 10^8 \text{ m}^3$, and $58.4 \times 10^8 \text{ m}^3$ during the spring freshet, rainfall flooding, and 30-year frequency rainfall flooding periods, respectively. The longest diffusion distances were measured from the lake mouth to the point of impact; these were 16.3 km, 33.1 km, and 43.6 km for the above periods, respectively. Increased pollutant concentrations refer to the maximum concentration differences from before and after rainfall floodwaters entered the lake. A correlation analysis showed that, although $P > 0.05$ (0.1093–0.2823), the longest detected diffusion distances and increased values of all four tested pollutant concentrations were positively correlated with water flow from the Mudanjiang River (correlation coefficient between 0.895 and 0.994). That is, our analysis showed a positive relationship between the Mudanjiang River and overall precipitation, which is similar to the previous studies by Zheng et al (2006). As such, precipitation plays an important role in seasonal water quality at Lake Jingpo. Water from the Mudanjiang River flows with the tremendous velocity in the upper reaches, thus caused soil wastage that greatly damages standing crops, plantations, settlements, and roads in the catchment area (Liu, 2013).

Table 1 Comparison of water quality at Lake Jingpo for different rainfall periods

Table 1
Comparison of water quality at Lake Jingpo for different rainfall periods

	Inflow from Mudanjiang to lake (m ³)	Longest diffusion distance (km)	Increased value of pollutant concentration (mg/L)			
			TN	TP	COD _{Mn}	NH ₄ - N
Spring freshet	4.81 × 10 ⁸	16.3	1.00	0.16	2.4	0.64
Rainfall flood	29.77 × 10 ⁸	33.1	2.6	0.36	4.2	1.1
30-year frequency rainfall flood	58.4 × 10 ⁸	43.6	2.8	0.39	5.6	1.2

Similar findings were reported by Hill (1978) in southern Ontario, where the lowest total dissolved solid content was found in February (due to lower runoff), while the highest was found in May (due to much larger runoff from watersheds). Many previous studies have revealed that major pollutant compositions in surface waters can be controlled by the interactions between precipitation and both surface-geological and biological materials (Correll et al., 1999; Garg et al., 2006; Salim et al., 2015). The temporal concentrations of TN, TP, COD_{Mn}, and NH₄-N in streams and lakes are primarily governed by discharge; these increase with flow (Lesack, 1993). This study investigated the upper reaches of Jingpo Lake Basin pass, which is a densely populated and industrialized area (Dunhua city). Some part of lake is surrounded by arable lands. Rainstorm floodwaters will thus carry many contaminants into the lake, thereby causing a rapid increase in pollutant concentrations.

Alpine barrier lakes require stricter environmental protection measures

Barrier lakes are formed when large rivers (usually the main sources of flow) are blocked. As such, both the water quality and quantity of these rivers greatly influence these elements in barrier lakes. With spring freshets and summer rainfall flooding periods, confluent rainwater runoff from lake catchment areas will soon enter the lake along the main river course, thus causing a rapid decline in water quality over a short period of time (e.g., between two weeks and one month). On the other hand, alpine barrier lakes are characterized by high altitudes and cold winters. As such, there is usually an ice-sealing period. Because pollutants do not degrade well in icebound lakes, concentrations in water columns under icebound areas are usually higher (Jin, 1995). The icebound season at Lake Jingpo lasts approximately 18 weeks, while there are four weeks of spring freshets, and 16 weeks of summer rainfall flooding. As such, there are only 10 weeks of good seasonal conditions without inclement climate impacts. The above analysis indicates that alpine barrier lake environments are generally very fragile. As such, these areas need increased levels of care. For instance, pollution control should be more stringent throughout catchment areas when compared to efforts at other types of lakes.

Conclusions

Our conclusions can be divided into the three main following points:

First, spring freshets and rainfall periods have important effects on flow velocity at Lake Jingpo. Due to its icebound season, waters only flow from March to September. The flow field is usually weaker than 0.015 m/s under normal conditions. However, spring freshets in April and summer rainfall flooding in July-September increase flow velocities to 0.045 m/s and above, much higher than in other months.

Second, compared to the effects of the spring freshet period, the summer rainfall flooding and 30-year frequency rainfall flooding period more significantly affected water quality at Lake Jingpo. There was more overall precipitation, longer diffusion distances, and increased pollutant concentrations in the lake area.

Third, alpine barrier lake environments are very fragile. As such, greater care efforts and more stringent measures are needed to control pollution sources throughout entire catchment area.

Abbreviations

AD

Advection Dispersion

HD

Hydrodynamics

TN

total nitrogen

TP

total phosphorous

COD_{Mn}

chemical oxygen demand by permanganate index method

NH₄-N

ammonia nitrogen

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

Not applicable.

Authors' contributions

CHL and CY designed the whole research and edit the manuscript. JXL and WWW designed the modelling approach. YZ and HW assisted with collection of field data helped develop and test early drafts of the model, performed the literature review, prepared and edited the manuscript. MK and CY secured funding for the project, assisted with the interpretation of subsequent data. All authors read and approved the final manuscript.

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References

1. Chen, Z.Y., Ma, L.Q., Shu, Y., et al., 2015. Back Analysis of the Draining Process of the Tangjiashan Barrier Lake. *Journal of Hydraulic Engineering*, 141(4), 05014011.
2. Cho, J.H., Seo, H.J., 2007. Lake water quality modelling considering rainfall-runoff pollution loads. *Journal of Environmental Impact Assessment*, 16(5), 341-350.
3. Cooney, E.M., McKinney, P., Sterner, R., et al., 2019. Tale of Two Storms: Impact of Extreme Rain Events on the Biogeochemistry of Lake Superior. *Journal of Geophysical Research: Biogeosciences*, 123(5), 1719-1731.

4. Correll, D.L., Jordan, T.E., Weller, D.E., 1999. Transport of nitrogen and phosphorus from Rhode River watersheds during storm events, *Water Resources Research*, 35, 2513-2521.
5. Donat, M.G., Lowry, A.L., Alexander, L.V., O’Gorman, P.A., Maher, M., 2016. More extreme precipitation in the world’s dry and wet regions. *Nature Climate Change*, 6, 508–513.
6. Dorum, A., Yazar, A., Sevimli, M.F., et al., 2010. Modelling the rainfall-runoff data of susurluk basin. *Expert Systems with Applications*, 37 (2010), 6587-6593.
7. Gallina, N., Beniston, M., Jacquet, S., 2017. Estimating future cyanobacterial occurrence and importance in lakes: a case study with *Planktothrix rubescens* in Lake Geneva. *Aquatic Sciences*, 79, 249-263.
8. Garg, R.K., Saksena, D.N., Rao, R.J., 2006. Assessment of physico-chemical water quality of Harsi Reservoir, District Gwalior, Madhya Pradesh. *Journal of Ecophysiology and Occupational Health*, 6(1), 33-40.
9. Groisman, P.Y., Knight, R.W., Easterling, D.R., Karl, T.R., Hegerl, G.C., Razuvaev, V. N., 2005. Trends in intense precipitation in the climate record. *Journal of Climate*, 18(9), 1326–1350.
10. Hill, A.R., 1978. Factors affecting the export of nitrate nitrogen from drainage basins in southern Ontario. *Water Research*, 12:1045-1057.
11. Jacquet, S., Domaizon, I., Anneville, O., 2014. The need for ecological monitoring of freshwaters in a changing world: A case study of Lakes Annecy, Bourget and Geneva. *Environmental Monitoring and Assessment*, 186, 3455-3476.
12. Jin, X.C., 1995. Chinese Lake Environment (III), China Ocean Press, Beijing, China, pp. 80-92. (in Chinese)
13. Lesack, L.F.W., 1993. Export of nutrients and major ionic solutes from a rainforest watershed in the central Amazon basin. *Water Resources Research*, 29, 743-758.
14. Li, Y., Wang, Y.H., Lv, X.M., Ye, Y.C., Ji, Y.H., 2015. Spatial distribution and temporal change in extreme weather events in three provinces in Northeast China, *Resources Science*, 37(120), 2501-2513. (in Chinese)
15. Liu, W., 2013. Analysis of hydrological characteristics of Mudanjiang urban section in the middle reaches of Mudanjiang River basin. *Heilongjiang Science and Technology of Water Conservancy*, 41(8). (in Chinese)
16. Moore, R.J. 2007. The PDM rainfall-runoff model. *Hydrology and Earth System Sciences*, 11(1), 483-499.
17. Salim, A.B., Gowhar, M., Ashok, K., 2015. Pandit Assessing the influence of stream flow and precipitation regimes on water quality of the major inflow stream of Wular Lake in Kashmir Himalaya. *Arabian Journal of Geosciences*. DOI 10.1007/s12517-015-2083-1.
18. Smith, J.A., Villarini, G., Baeck, M.L., 2011. Mixture Distributions and the Hydroclimatology of Extreme Rainfall and Flooding in the Eastern United States. *Journal of Hydrometeorology*, 294-309.

19. Sun, T., Liang, J., Chai, F.X., et al., 2014. Studies on Risk Level Assessment of Barrier Lake Based on BPANN. *Applied Mechanics and Materials*, 644, 5676-5680.
20. Wang, X., Liu, L.S., Li, L., et al., 2015. Correlation analysis of algae composition and environmental factors in Lake Jingpo. *China Environmental Science*, 35(11), 3403-3413. (in Chinese)
21. Warren, I.R., Bach, H.K., 1992. MIKE 21: a modelling system for estuaries, coastal waters and seas. *Environmental Software*, 7, 229-240.
22. Yu, J.H., Gong, Y.F., Mao, W.H., 2019. Comparative Analysis on Two Extreme Severe Precipitation Events in Yongji County, Jilin Province in July 2017. *Journal of Chengdu University of Information Technology*, 34(3), 287-296. (in Chinese)
23. Zhang, W., Villarini, G., Vecchi, G.A. 2017. Impacts of the Pacific Meridional Mode on June–August precipitation in the Amazon River Basin. *Quarterly Journal of the Royal Meteorological Society*, 143(705), 1936–1945
24. Zheng, D.C., Cui, G., Jin, Z., et al., 2006. Hydrological characteristics of the upstream of Mudanjiang River. *Water Resources & Hydropower of Northeast China*, 12,37-37. (in Chinese)

Figures

Figure 1

Location of Lake Jingpo catchment. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research

Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Water system map of Lake Jingpo catchment. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Land use at the Lake Jingpo catchment. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Sites of the hydrological information collection points. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

Daily average flow (m³/s) at Dashanzuizi Station in 2018

Figure 6

Lake bottom elevation map. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 7

Flow model calibration results for Lake Jingpo

Figure 8

Figure 9

Flow field distribution of Lake Jingbo from March to September. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 11

Impact of summer rainfall flooding on water quality of Lake Jingpo. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 12

Impact of 30-year frequency flooding on water quality at Lake Jingpo. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.