Analysis of Water Balance Changes and Influencing Factors of Issyk-Kul Lake over the Past 60 Years: Postprint

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Abstract

Based on satellite remote sensing data, information on the area and water level changes of Issyk-Kul Lake over the past 60 years was extracted, and the time series of water volume changes in Issyk-Kul Lake was retrieved. Combined with CRU meteorological data from 1960–2020, temperature and precipitation observation data from the Cholpon-Ata meteorological station from 1960–2000, and inflow water volume observation data, a lake water balance model was established to analyze the variation characteristics of each water balance component and explore its influencing factors. The results show that: (1) Since 1960, the water volume change of Issyk-Kul Lake has experienced a process of continuous decrease followed by fluctuating increase, with 1998 being the inflection point of this change. From the 1960s to the mid-1980s, the inflow water volume was mainly affected by irrigation water diversion and continued to decrease; after 1986, it turned into an upward trend with the reduction of irrigation water and the increase of precipitation and glacier meltwater. Precipitation in the lake area increased at a rate of 9.1 mm $\cdot$ $(10a)^{-1}$, and evaporation showed a significant increasing trend overall with the warming of the lake area and the increase of lake area. (2) Before the mid-1980s, the lake water volume of Issyk-Kul Lake showed a negative balance in most years, with groundwater continuously replenishing the lake. Since 1986, the water budget deficit of the lake gradually decreased, and since 1998, it has been dominated by positive balance. (3) The interactive relationship among water balance components such as inflow runoff, precipitation, and evaporation determines the change in lake water volume, while climate change in the runoff generation area and irrigation water diversion in the irrigation area indirectly drive the change in lake water volume by altering the inflow runoff. From 1960–1986, human activities dominated by irrigation water diversion were the dominant factor driving the water volume change of Issyk-Kul Lake, with a contribution rate of 71.6%. Since 1987, the cumulative contribution of climate change factors to lake water volume change has exceeded 80%.

Full Text

Analysis of Water Balance Change and Influencing Factors in Issyk-Kul Lake in Recent 60 Years

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Abstract

Based on satellite remote sensing data, this study extracted information on the area and water level variations of Issyk-Kul Lake, reconstructed the time series of water volume changes, and established a lake water balance model by integrating meteorological data, temperature and precipitation observations from the Cholpon-Ata meteorological station from 1960–2000, and inflow water volume observations. The study analyzed the changing characteristics of each water balance component and explored their influencing factors. The results indicate that: (1) Since 1960, the water volume of Issyk-Kul Lake has undergone a process of continuous decrease followed by fluctuating increase, with 1998 serving as the inflection point of this change. From the 1960s to the mid-1980s, inflow volume was primarily affected by irrigation water diversion and continued to decrease, then turned to an increasing trend after 1986 with reduced irrigation water consumption and increased precipitation and glacial meltwater. Precipitation in the lake area increased at a rate of 9.1 $\mathrm{mm} \cdot (10\mathrm{a})^{-1}$, while evaporation showed a significant increasing trend with rising temperatures and expanding lake area. (2) Before the mid-1980s, Issyk-Kul Lake exhibited a negative water balance in most years, with groundwater continuously recharging the lake. Since 1986, the water balance deficit gradually decreased, and since 1998, positive balance has dominated. (3) The interactive relationship among water balance components such as inflow runoff, precipitation, and evaporation determines lake water volume changes, while climate change in runoff-producing areas and irrigation water diversion in cultivated areas indirectly drive lake water volume changes by altering inflow runoff. From 1960–1986, human activities dominated by irrigation diversion were the primary factor driving Issyk-Kul Lake water volume changes, with a contribution rate of 71.6%. Since 1987, the cumulative contribution of climate change factors to lake water volume changes has exceeded

80%.

Keywords: Issyk-Kul Lake; water balance; inflow runoff; climate change

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1. Introduction

The arid region of Central Asia is one of the areas with the densest distribution of inland lakes globally, including numerous large lakes exceeding 2 km^2. Under the background of global warming, climate change and its hydrological response in Central Asia have attracted widespread attention from the scientific community. Inland lakes in the arid regions of Central Asia serve not only as indicators of regional climate change but also as important components of the water cycle. Investigating the water budget changes of inland lakes and their response to changing environments is crucial for understanding climate-hydrology patterns in arid regions.

In recent decades, inland lakes in the Central Asian arid zone have undergone dramatic changes with significant spatial differences. The reasons affecting these inland lakes are complex, involving both climate fluctuations and human activities, as well as lake size, morphology, elevation, underlying surface characteristics, and hydrological cycles. Generally, high-mountain closed lakes located in low-lying basins are partially supplied by stable glacial meltwater, less disturbed by human activities, and sensitive to regional climate change, such as Sayram Lake, Ayakekum Lake, and Aqikkol Lake. In contrast, in plain areas, agricultural irrigation water diversion and reservoir construction have altered the spatiotemporal distribution of water resources, causing water that originally flowed into downstream terminal lakes to be consumed in oasis areas. This leads to dramatic changes in the water balance of terminal lakes in arid regions. When human interference exceeds climate factors, lakes exhibit area shrinkage, water level decline, and volume reduction, as seen in the Aral Sea, Bosten Lake, and Alakol Lake.

Issyk-Kul Lake is the largest high-mountain closed lake in Central Asia. Multiple rivers originating from the Kungey Alataw and Terskey mountains flow into Issyk-Kul Lake. Since the late 19th century, with water diversion for reclamation, many rivers have been used for irrigation before reaching the lake. The changes in Issyk-Kul Lake reflect the combined impacts of climate change and human activity interference, showing distinct phased characteristics. Previous studies have shown that since modern times, the water level of Issyk-Kul Lake has generally declined, with the change process divisible into fluctuating decline and slow fluctuating rise stages. Lake area changes have strong synchrony with water level changes, showing a trend of first decreasing then increasing. Before the 1980s, water diversion for irrigation caused continuous water level decline in Issyk-Kul Lake. Since 1987, climate change in Central Asia, characterized by significant increases in precipitation, glacial meltwater, and river runoff, has indirectly promoted lake water level rise. However, most previous studies analyzed single hydrological elements such as area or water level and their driving factors, with data mainly concentrated before 2010, lacking research on recent changes in Issyk-Kul Lake, particularly regarding water balance component variations, budget status changes, and the quantitative contributions of each water balance component to lake water volume changes.

Therefore, this study selected Issyk-Kul Lake as the research area. Based on Landsat TM/ETM+/OLI remote sensing imagery, we extracted lake area and water level information, combined with historical Jason1/2/3 altimetry satellite data to reconstruct long-term area and water level change sequences, and inverted lake water volume changes. Using long-term meteorological data, hydrological observation data, and land use data, we established a lake water balance model to quantitatively analyze the changes and interactive relationships among multiple elements including precipitation, evaporation, inflow runoff, and lake water volume. We also analyzed the contributions of key climate change and human activity factors to Issyk-Kul Lake water volume changes. The research results can provide data support for water resource regulation and ecological protection in the Issyk-Kul Lake basin.

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2. Materials and Methods

2.1 Data Collection

Remote Sensing Data: Landsat TM/ETM+/OLI images were used to extract the area change time series of Issyk-Kul Lake from 1991-2020, with image dates concentrated in August-October. Water level data were obtained from two sources: early-stage data came from Romanovsky' s research, while later-stage water level information was extracted from TOPEX/Poseidon (T/P) and Jason1/2/3 altimetry satellite data products.

Meteorological Data: The Cholpon-Ata station, located on the north side of Issyk-Kul Lake, was selected as the representative station. Meteorological station data were obtained from the National Cryosphere Desert Data Center (http://www.ncdc.ac.cn), including monthly average temperature and monthly precipitation parameters. Monthly average temperature and precipitation data from 1960-2000 were provided by Yilinuer Alifujiang et al. Due to geographical constraints and policy reasons, relevant data were severely missing and required supplementation with meteorological reanalysis data. The Climatic Research Unit (CRU) TS 4.05 dataset from the University of East Anglia (http://data.ceda.ac.uk/badc/cru/data/cru_{ts}/) was used, with a spatial resolution of 0.5°$×$0.5° and parameters including monthly average temperature and precipitation from 1960-2020.

Land Cover Data: Land cover data from the European Space Agency Climate Change Initiative (https://www.esa-landcover-cci.org) with a spatial resolution of 300 m × 300 m were used to extract the temporal series of cultivated land area changes in the Issyk-Kul Lake basin.

Hydrological Data: Lake inflow observation data were provided by Wang Guoya et al. Annual runoff data from 1960-2017 came from watershed hydrological simulation results. Lake evaporation observation data were obtained from CAwater (http://www.cawater-info.net/index_e.htm). Glacier area data came from the "Earth Big Data Science Engineering Data Sharing Service System" provided by the Chinese Academy of Sciences (http://data.casearth.cn/). Annual irrigation water consumption data for the Issyk-Kul Lake basin were provided by Wang Guoya et al., covering the period 1960-2015.

2.2 Lake Water Volume Calculation

Using Landsat TM/ETM+/OLI images, lake area information was extracted using a "global-local" adaptive iterative threshold segmentation method with manual revision to obtain a multi-period lake area change sequence from 1991-2020. Due to the strong synchrony between Issyk-Kul Lake area and water level changes, the area change time series from 1991-2020 was used to estimate water level changes. Based on the remote sensing-extracted water level and area time series, the water volume of Issyk-Kul Lake was estimated.

2.3 Lake Evaporation Calculation

Lake evaporation was calculated using measured data (temperature, sunshine hours, etc.) from the Cholpon-Ata station on the north side of Issyk-Kul Lake. The Penman-Monteith formula performs well in both humid and arid regions but requires numerous parameters including maximum temperature, minimum temperature, wind speed, sunshine hours, and relative humidity, limiting its application. The Hargreaves formula can calculate evapotranspiration based solely on temperature and geographic location. This study used the Hargreaves formula to calculate lake evaporation. The required parameters include daily average maximum temperature, daily average minimum temperature, and extraterrestrial radiation. Daily average maximum and minimum temperature data were provided by the meteorological station, while extraterrestrial radiation data could be obtained from relevant literature based on latitude.

The formula is as follows:

$$ET_{0H} = 0.0023 \times (T_{max} - T_{min})^{0.5} \times (T_{mean} + 17.8) \times R_a$$

Where: ET_{0H} is the reference evapotranspiration calculated by the Hargreaves formula ($\mathrm{mm \cdot d^{-1}}$); T_{max} is the daily average maximum temperature (°C); T_{min} is the daily average minimum temperature (°C); T_{mean} is the daily average temperature (°C); R_a is the water equivalent to extraterrestrial radiation ($\mathrm{mm \cdot d^{-1}}$).

The total lake evaporation is calculated as:

$$W = A \times ET_{0H}$$

Where: W is the total lake evaporation; A is the lake area.

2.4 Temperature and Precipitation Time Series Reconstruction

While station-measured data have high accuracy, they have limitations in reflecting the spatial-temporal characteristics of temperature and precipitation. CRU gridded data can reflect the spatial-temporal distribution characteristics of precipitation and temperature but contain systematic errors. Therefore, it is necessary to correct the gridded temperature and precipitation data to compensate for missing station data. Using 1960–1990 as the calibration period and 1991–2000 as the validation period, the monthly scaling method was employed to correct the CRU data.

The precipitation series correction formula is:

$$P_{cor,i} = a_i \times p_i$$

$$a_i = \frac{\bar{O}_i}{\bar{P}_i}$$

Where: i is the month (1-12); a_i is the ratio of measured to simulated monthly precipitation; $\bar{P}_i$ is the average monthly precipitation during the calibration period; $\bar{O}_i$ is the average monthly precipitation at the meteorological station during the calibration period; p_i is the uncorrected precipitation; and $P_{cor,i}$ is the corrected monthly precipitation.

The temperature series reconstruction used linear scaling:

$$T_{cor} = T_{obs} + (T_{sim} - T_{obs})$$

Where: T_{cor} is the corrected temperature; T_{obs} is the station-measured temperature; and T_{sim} is the simulated temperature.

To evaluate the applicability of the corrected reanalysis data in the study area, relative error (ARE) and correlation coefficient (R^2) were used as criteria. The relative error formula is:

$$ARE = \frac{sim - obs}{obs} \times 100\%$$

Where: sim is the simulated value; obs is the observed value; and N is the number of samples.

Comparison of station data with corrected CRU data from 1960–1990 shows that the correlation between corrected CRU precipitation data and station data improved, with R^2 increasing from 0.78 to 0.91 and relative error decreasing from 30.91% to 12.51%. The error between corrected temperature data and measured annual average temperature was within 0.5°C. These results indicate that the corrected CRU precipitation and temperature sequences meet accuracy requirements, and the reconstruction method is applicable in the study area.

Table 1 Accuracy evaluation of temperature and precipitation time series reconstruction results

Parameter	Period	R^2	ARE (%)
Temperature	1960–1990	0.96	3.2
Precipitation	1960–1990	0.91	12.51

2.5 Water Balance Model

The relationship between lake storage change and water increase/decrease during a period can be expressed by the water balance equation:

$$\Delta V = A(h) \times \Delta h = (P + Q_{in} - E - Q_{out}) \times \Delta t$$

Where: ΔV is the lake storage change (10^8 m^3); Δt is the calculation period (year); A is the lake surface area (km^2), which is a function of water level h; Δh is the water level change (m); P is the precipitation in the study area (10^8 m^3); Q_{in} is the inflow water volume (10^8 m^3); E is the total evaporation in the study area (10^8 m^3); and Q_{out} is the outflow water volume (10^8 m^3).

According to the actual situation of the Issyk-Kul Lake basin, the water balance equation is expressed as:

$$\Delta V = P + Q_{river,in} + Q_{groundwater,in} - Q_{groundwater,out} - E$$

Where: $Q_{river,in}$ is the river inflow volume (10^8 m^3); $Q_{groundwater,in}$ and $Q_{groundwater,out}$ are groundwater inflow and outflow volumes (10^8 m^3), respectively. Since Issyk-Kul is a closed lake without outflow rivers, the residual term can be expressed as:

$$Q_{residual} = Q_{groundwater,in} - Q_{groundwater,out}$$

3. Results

3.1 Changes in Lake Area, Water Level, and Volume

The synchrony between Issyk-Kul Lake area and water level changes is strong, showing an overall trend of first decreasing then increasing (Fig. 2). From 1960–1986, the lake area decreased rapidly. From 1986–1998, the decreasing trend slowed, but due to the lowest basin precipitation in nearly 60 years (148.1 mm) in 1986, the water level dropped to 1606.17 m and the area decreased to

6236 km^{2}. After 1998, with increased precipitation, lake water level and area began to rise, reaching 1607.84 m and 702 km^{2} by 2017, basically restoring to the level around 1960. From 2017-2020, lake area and water level fluctuated and decreased slightly, maintaining around 6210.09 km^{2} and 1607.63 m.

Issyk-Kul is a high-mountain inland lake formed by crustal subsidence. The wedge-shaped lake basin determines that lake water volume changes will not be too dramatic. Since 1960, the maximum water volume change is 86\$×10^{8}\$ m^{3}, which is very small compared to the total water volume of over 16000\$×10^{8}\$ m^{3}. The water volume change trend is consistent with water level and area changes: continuously decreasing during 1960-1986 at a rate of 2.1\$×10^{8}\$ m$^{3}\cdot(10a)^{-1}$; slowly rising during 1986-1998; slightly decreasing during 1998-2005; and fluctuating slightly after 2005 at a rate of -0.084\$×10^{8}\$ m$^{3}\cdot(10a)^{-1}$. By 2020, the water volume was 16143.6\$×10^{8}\$ m^{3}, higher than the multi-year average of 16105.7\$×10^{8}\$ m^{3}.

Figure 2 [Figure 2: see original paper] Changes in water level, area and volume of Issyk-Kul Lake from 1960 to 2020

3.2 Changes in Water Balance Components

3.2.1 Precipitation Changes The multi-year average precipitation in the Issyk-Kul Lake area is 334.26 mm. Precipitation showed a decreasing trend from 1960-1986, dropping from 420.2 mm to 279.8 mm, with 1986 being the lowest precipitation year. From 1986-1998, precipitation increased continuously at a rate of 3.7 mm$\cdot a^{-1}$. Since 1998, precipitation has shown a fluctuating increasing trend, reaching 321.8 mm in 2017, which is 96% of the multi-year average precipitation. The overall increasing trend is significant (significance level α=0.01), with an increase rate of 9.1 mm$\cdot(10a)^{-1}$.

Figure 3 [Figure 3: see original paper] Precipitation change in Issyk-Kul Lake from 1960 to 2020

3.2.2 Lake Evaporation Changes Lake evaporation shows strong synchrony with temperature changes in the lake area. The average annual evaporation is about 927.6 mm according to CAwater observations. The overall evaporation trend is significantly increasing (significance level α=0.01), with an increase rate of 15.7 mm$\cdot(10a)^{-1}$. Before 1998, lake surface evaporation remained relatively stable, with an average of 911.7 mm. After 1998, with rising temperatures in the lake area, evaporation fluctuated and increased. Evaporation fluctuated greatly during 2005-2010. Due to reduced precipitation in 2017, inflow decreased by 12.8\$×10^{8}\$ m^{3}, and influenced by glacier ablation, inflow runoff increased rapidly. By 2020, the average annual evaporation reached 972.5 mm.

Figure 4 [Figure 4: see original paper] Changes in evaporation from Issyk-Kul Lake, 1960-2017

3.2.3 Inflow Runoff As shown in Fig. 5, the inflow to Issyk-Kul Lake shows an overall increasing trend, with interannual variation ranging from 30.23$\times10^{8}$ m^3 to 49.62$\times10^{8}$ m^3 and a multi-year average of 39.41$\times10^{8}$ m^3. A mutation from decreasing to increasing inflow occurred in 1986, which is basically consistent with the mutation time of Central Asian climate shifting from "warm-dry" to "warm-wet". From 1960-1986, basin precipitation was generally at a low level, and inflow was mainly affected by agricultural irrigation diversion and continued to decrease. Agricultural irrigation water consumption accounted for the largest proportion of water consumption in the Issyk-Kul basin, disrupting the natural balance of groundwater and surface water. Since 1986, basin precipitation has increased rapidly, with an average increase of 29.34 mm compared to the previous period, plus increased glacier meltwater supply due to warming, which is the main reason for the shift from continuous decrease to increasing trend in inflow. From 1998-2017, basin precipitation remained at a high level in most years; irrigation water consumption decreased, with agricultural, industrial, and urban water consumption decreasing by 53.49% and 15.7% respectively in 2015 compared to 1986. The dual effects of increased runoff supply and decreased irrigation diversion maintained a gradually rising trend in inflow, reaching 49.07$\times10^{8}$ m^3 in 2017. Due to the impact of precipitation recovery and glacier ablation, inflow runoff increased rapidly, reaching 44.61$\times10^{8}$ m^3 in 2020, which is 5.2$\times10^{8}$ m^3 higher than the multi-year average inflow.

Figure 5 [Figure 5: see original paper] Change of the inflow to Issyk-Kul Lake from 1960 to 2017

3.2.4 Residual Term According to the water balance formula, the residual term can be approximated as the change in groundwater, reflecting the interaction between Issyk-Kul Lake and groundwater. The interannual and decadal changes in the water balance residual of Issyk-Kul Lake are shown in Fig. 6. Before the 1980s, the lake water volume was basically in a negative balance state, with groundwater continuously recharging the lake. During 1960-1986, the water balance residual was negative in most years, indicating negative lake balance, with groundwater continuously recharging the lake. The 1970s had more groundwater recharge, averaging 4.76$\times10^{8}$ m^3. From 1986-1998, the water balance deficit gradually decreased. Since 1998, the water balance residual has been positive in most years, with lake water budget in surplus, indicating that surface runoff and precipitation recharge can maintain lake water balance. From 2010-2017, the residual fluctuated between -12.7$\times10^{8}$ m^3 and 13.2$\times10^{8}$ m^3.

Figure 6 [Figure 6: see original paper] Inter-annual (a) and chronological (b) change of water balance in Issyk-Kul Lake, 1960-2017

Figure 7 [Figure 7: see original paper] Chronological distance of each component of the water balance of Issyk-Kul from 1960

4. Discussion

Issyk-Kul Lake is a closed inland lake located in a high-mountain basin. Its water sources include inflow from rivers of various sizes, precipitation, and groundwater recharge (water income), while lake surface evaporation is the main pathway of water dissipation (water expenditure). At the watershed scale, climate change in runoff-producing areas and human activities dominated by irrigation water diversion in oasis areas around the lake indirectly drive lake water volume changes by affecting inflow runoff.

Studies by Shen Yongping et al. indicate that the North Atlantic Oscillation is positively correlated with westerly circulation over northern Eurasia. The North Atlantic Oscillation index was in positive and negative fluctuation periods before 1980, while 1980–1995 was a continuous positive phase period and 1995–2010 was a continuous negative phase period. Increased water vapor may be the main reason for precipitation increase in Central Asia. Meanwhile, since the early 1980s, temperature changes in Central Asia have fluctuated dramatically, with the warming rate after 1997 significantly higher than before. The warming rate in the Issyk-Kul basin is 0.369°C $\cdot$ (10a)$^{-1}$, greater than the global temperature change amplitude (-0.6~0.55°C $\cdot$ (10a)$^{-1}$). With intensified warming in high mountain areas, increased ice and snow meltwater supply to runoff has a positive effect on lake changes. Some scholars have revealed the fact of decreasing glacier mass balance in the Issyk-Kul basin based on observations of typical glaciers. From 1958–2016, the Tuyuksu Glacier on the north side of Issyk-Kul lost about $67.7 \pm 6.7 \times 10^6$ m^3 of ice, with the glacier surface lowering by 23.2 ± 2.2 m. Since 2000, the Kara-Batkak Glacier on the Terskey Ala mountain on the south side of Issyk-Kul has had a negative mass balance, and all snow and glacier-fed rivers have observed increased glacial runoff. The melting of 3 km^3 of glacier volume increased inflow runoff, equivalent to 1.26% of glaciers in the basin. This study extracted glacier area changes in the Issyk-Kul basin from 1990–2015 (Fig. 8), showing that the basin glacier area continuously decreased from 691 km^2 to 647 km^2, with a reduction rate of about 1.26 km^2 $\cdot$ a^{-1}.

Human activities dominated by irrigation water diversion are also important factors affecting Issyk-Kul Lake inflow. Land use development in the Issyk-Kul basin can be traced back to the late 19th to mid-20th centuries. By the mid-1980s, irrigation area reached 1540 km^2. The continuous decrease in inflow and rapid decline in lake water level during 1960–1986 are consistent with this period. Analysis by Shao Xinyuan shows that due to farmland, industrial, and urban water use, Issyk-Kul Lake's inflow decreased by 6.0$×10^{8}$ m^3 annually from 1970–1985, causing the water level to drop by about 13 cm per year. Wang Guoya et al. indicated that irrigation water consumption accounted for the largest proportion of water consumption in the basin, disrupting the natural balance of groundwater and surface water. From 1992–2015, cultivated land area in the Issyk-Kul basin decreased slightly from 184.56 km^2 to 180.72 km^2

(Fig. 9). Based on the net irrigation quota of the Issyk-Kul basin, the average water consumption from 1960-1986 was 20.72$×10^{8}$ m^3, which remained basically stable from 1987-2015.

The interactive relationship among water balance components such as inflow runoff, precipitation, and evapotranspiration determines the changes in Issyk-Kul Lake water volume. At the watershed scale, climate change and human activities indirectly drive lake water volume changes by altering inflow runoff. Therefore, selecting mountain precipitation and temperature, irrigation water diversion, lake area precipitation, and evaporation as the main driving factors, we calculated the contribution rate of each factor to Issyk-Kul Lake water volume changes through factor analysis (Table 2). The results show that climate change and human activity impacts on Issyk-Kul Lake water volume changes have significant phased differences. Human activities dominated by irrigation water diversion were the dominant factor driving the rapid lake water volume decrease from 1960-1986, with a contribution rate of 71.6%. Since 1987, the "warm-wet"climate change and reduced irrigation water diversion have promoted the continuous rise of Issyk-Kul Lake water level and entered a stable recovery state, with the cumulative contribution of climate change factors exceeding 80%. It is worth noting that under conditions of continuous basin warming and relatively large temperature increases in the lake area, the increase in lake area inevitably leads to continuously increasing evaporation. The negative effect of lake evaporation on water volume changes is significantly greater than the positive effects of inflow runoff and precipitation after 2010, causing recent slight fluctuations and decreases in Issyk-Kul Lake area, water level, and volume.

Table 2 Contribution of each factor to the variation of water volume in Issyk-Kul Lake

Period	Climate Change Contribution (%)	Human Activity Contribution (%)
1960-1986	28.4	71.6
1987-2020	82.3	17.7

Figure 8 [Figure 8: see original paper] Changes in temperature and precipitation in the Issyk-Kul from 1960 to 2020 (a) and change in glacier area from 1990 to 2015 (b)

Figure 9 [Figure 9: see original paper] Changes in cropland area in Issyk-Kul basin from 1992-2015 (a) and changes in irrigation water consumption in Issyk-Kul basin from 1960-2015 (b)

5. Conclusions

This study focused on Issyk-Kul Lake, reconstructing the time series of lake area, water level, and water volume changes in recent 60 years based on multi-source remote sensing data. Combined with long-term meteorological and hydrological observation data and land use data, we analyzed the changing characteristics of water balance components including precipitation, inflow runoff, evaporation, and groundwater, and quantitatively analyzed the impacts of multiple factors of climate change and human activities on Issyk-Kul Lake water volume changes. The main conclusions are as follows:

1) Since 1960, Issyk-Kul Lake area, water level, and water volume changes have shown strong synchrony, with a trend of first decreasing then increasing. From 1960–1986, the lake showed a rapid decreasing trend; the decreasing trend slowed from 1986–1998; after 1998, with increased precipitation, lake water level and area changes turned to an increasing trend. The year 1998 was the inflection point of Issyk-Kul Lake water volume change.

2) The water balance and its components showed significant differences in different periods. From 1960–1986, Issyk-Kul basin precipitation was generally at a low level, and inflow runoff was mainly affected by agricultural irrigation diversion and continued to decrease. From 1987–1998, precipitation in the Issyk-Kul basin increased rapidly, and inflow runoff increased due to the combined effects of increased precipitation and accelerated ice-snow melt caused by warming. In 1986, inflow runoff underwent a mutation from decrease to increase. Before the mid-1980s, lake water volume showed negative balance in most years, with groundwater continuously recharging the lake, peaking in the 1970s. Since 1986, the lake water budget deficit gradually decreased, and since 1998, Issyk-Kul Lake water balance has turned to positive balance.

3) At the lake scale, the interactive relationship among water balance components such as inflow runoff, precipitation, and evapotranspiration determines lake water volume changes. At the watershed scale, climate change and human activities indirectly drive lake water volume changes by altering inflow runoff. Human activities dominated by irrigation water diversion were the dominant factor driving Issyk-Kul Lake water volume changes from 1960–1986, with a contribution rate of 71.6%. Since 1987, the impact of climate change factors on Issyk-Kul Lake water volume changes has strengthened. Significantly increased precipitation and ice-snow melt caused by continuous warming have led to surging inflow runoff, which is the main reason for the reversal and continuous increase of lake water volume changes during this period. After 2010, the negative effect of lake evaporation on water volume has significantly exceeded the positive effects of inflow runoff and precipitation, causing recent slight fluctuations and decreases in Issyk-Kul Lake area, water level, and volume.

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