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Temporal Variations in the Quantity of Groundwater Flow in Nam Co Lake

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Abstract: This paper aims to calculate and analyze the spatial and temporal variations in the groundwater flow quantity in Nam Co Lake based on the water balance principle. The results show that a large amount of groundwater was gradually lost and that, groundwater loss decreased from 1.9 billion m^3 to 1.5 billion m^3 from the period of 1980–1984 to 1995–2009. The comparative analysis in the current study indicates that the decrease in the groundwater index has a strong linear relationship with the temperature of the ground surface on the Tibetan Plateau, with a correlation coefficient as high as 0.92. Moreover, environmental variations such as large-scale engineering construction projects and increases in water storage may have played dominant roles in the sudden changes in the water quantities of plateau lakes (e.g., Nam Co Lake) during the periods of 1990–1995 and 2000–2009. The increased water levels resulted in reduced groundwater losses, which may lead to the substantial expansion or gradual shrinkage of the Qinghai–Tibet Plateau lakes over short periods of time. The results of this study provide an important reference for studying the mechanisms of lake water level changes on the Qinghai–Tibet Plateau.

Keywords: Nam Co Lake; groundwater loss; environmental variation; water level change mechanism; Qinghai–Tibet Plateau

1. Research Background

A lake is relatively independent and naturally complex and serves as a connecting point for interactions between the lithosphere, atmosphere, hydrosphere, and biosphere. Consequently, the lake records diverse environmental information. As an independent geographic unit, the Qinghai–Tibet Plateau has the highest averge elevation and the largest number and area of plateau lakes in the world [1]. Although the water balance of lakes on the Qinghai–Tibet Plateau is a heavily researched and discussed topic [2], temporal variations in the quantity of groundwater flow have not been thoroughly investigated. Moreover, plateau lakes in this region have a recharge effect on the downstream lakes, so the study on groundwater flow of the Qinghai–Tibet Plateau lakes is of great significance to water balance analysis of the secondary lakes. Because Nam co Lake is one of the largest lakes in the region and with the highest altitude in the world, it should provide an ideal archive of groundwater infiltration changes on the Qinghai–Tibet Plateau.

A number of studies have shown that a high level of groundwater infiltration exists in Nam Co Lake [3,4]. This infiltration is a key factor in maintaining the lake water balance. Analyses of the groundwater infiltration dynamics in Nam Co Lake have been a major focus in this research area [5]. In this context, many scholars have widely studied the groundwater recharge and the infiltration mechanism of the lake and have obtained beneficial results. For example, based on the principle of water balance, Zhou et al. [3] found that a large imbalance exists between the incoming and outgoing water quantities in Nam Co Lake. This imbalance is related to the groundwater infiltration process [6–8]. In addition, by developing a linear model to study its infiltration quantity, Du et al. [9] found that the groundwater infiltration amount approaches billions of cubic meters in this region and that drained groundwater is transported to downstream rivers and lakes via groundwater flow, which slows the rising water level in the studied lake [10,11]. They reported that the groundwater infiltration flow cannot be characterized using a simple parameter but should be quantified using a series of parameters, such as the water level, geological conditions, human activities, temperature, etc. From the perspective of the annual water balance, Wu et al. [12] observed that in the period of 1980–2010, the water quantity in Nam Co Lake was high, but that it decreased with increasing surface temperatures. Moreover, based on isotope tracers, Liu et al. [13] found that water in the Qinghai–Tibet Plateau lakes may serve as a source for Badan Jilin desert lakes. Chen et al. [14,15] sampled groundwater in the Qinghai–Tibet Plateau area, and based on analyses of isotopes and water chemistry, they determined that water in the Tibetan inland flow area (e.g., Nam Co Lake) drains over a wide area of the Tibetan Plateau. Notably, the drained water can be transported to the Alxa Plateau via underground fractures and fracture networks. Zhao et al. [16] showed that the frozen soil layer on the Tibetan Plateau continuously concentrates water in large quantities, which can be stored in the form of ice in the permafrost soil layer for a long time [17]. They found that the long-term repeated freezing process influences groundwater circulation in the Nam Co Lake area. Based on the infiltration theory of Nam Co Lake proposed by Zhou et al. [3], Xiang et al. [18] postulated that the groundwater beneath the surface of the Qinghai–Tibet Plateau may have a unique storage depth and that groundwater circulation can reach deep water-containing layers over a long distance in this area. Another study found that the water level increase or decrease varies on seasonal bases [19,20].

In the present study, we calculate analysis of the quantity of dynamic underground infiltration flow in the context of global warming based on the water balance principle and summarize the trends that govern spatial and temporal variations in the groundwater quantity in Nam Co Lake. Finally, the factors that influence groundwater quantity variations are systematically investigated with the aim of providing a reference for studies in cold regions.

2. Data Sources and Methodology

2.1. Research Area Background and Data Sources

Nam Co Lake is located on the Qinghai–Tibet Plateau at an elevation of 4720 m. The lake has a total area of 2026 km^2 and is the highest ranking lake on the plateau (Figure 1). The data for this study include meteorological data from the areas surrounding Nam Co Lake, hydrological data from the Nam Co working station, geological data extracted from samples collected 5 km from Zhahi in eastern Nam Co, an aerial photographic map, thematic mapper imaging data for the region, and data from the relevant literature on Nam Co Lake.

Figure 1. Location of Nam Co Lake.

2.2. Methodology

By analyzing the water quantity variations in Nam Co Lake from 1980–2009, we focus on calculating the groundwater quantity variations and identifying the factors that influence these variations in Nam Co Lake. For convenience, all water quantity parameters are given in units of mm. For instance, if a lake has an area of 100 km^2, an infiltration of the lake is 5×10^5 m^3 is equivalent to 5 mm. Because of its geographic situation, Nam Co Lake is seasonally frozen, and the frozen surface does not respond effectively to the water-level variations. Thus, we use the five-year average value in our calculative analysis.

The factors that affect the variations in the water level (ΔH) of Nam Co Lake can be divided into three types: those corresponding to variations in the surface water quantity (ΔH_{gw}); those corresponding to variations in the groundwater quantity (ΔH_{uw}); and those corresponding to geological change-induced water level variations (ΔH_g), as depicted in Figure 2.

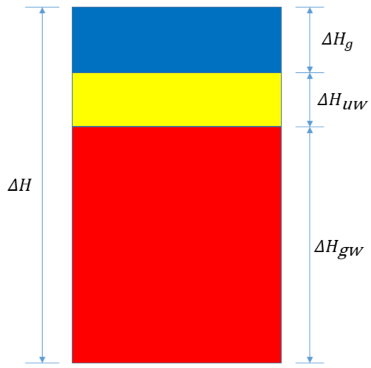

Figure 2. Sketch of factors affecting water level variations of Nam Co Lake.

(1) The variations in the surface water quantity of Nam Co Lake can be represented by four indices: annual precipitation, lake evaporation, glacier ablation, and the surface runoff, as expressed by the following equation:

$$\Delta H_{gw} = a_1 P(t) - a_2 E(t) + a_3 H_i(t) + a_4 H_s(t) \quad (1)$$

where ΔH_{gw} is the height of the water level variation caused by a change in the surface water quantity; a_i is the influence coefficient for each index (i = 1, 2, 3, 4) and is typically a constant value close to 1; $P(t)$ is the amount of annual precipitation; $E(t)$ is the annual lake water evaporation amount; $H_i(t)$ is the annual glacier ablation amount; and $H_s(t)$ is the annual non-glacier surface runoff amount in the area surrounding Nam Co Lake. Because of its geographic conditions, when Nam Co Lake is frozen, the surface does not respond to lake water level variations in some cases. Thus, the five-year average value is used in the quantitative analysis. According to the results in the literature [9], a_1–a_4 correspond to 1.17, 0.8, 0.9, and 1, respectively.

(2) The undergroundwater variations can be calculated using the following equation:

$$\Delta H_{uw} = H_u(t) - \varepsilon(t) \quad (2)$$

where ΔH_{uw} is the water level variation caused by the groundwater recharge and discharge; $H_u(t)$ is the amount of the groundwater recharge of Nam Co Lake and $\varepsilon(t)$ is the amount of groundwater discharge.

(3) The geological variations can be calculated according to the equation below:

$$\Delta H_g = cH + h \quad (3)$$

where ΔH_g is the water level variation caused by geological deformation; c is the influence coefficient, which is based on the volumetric change caused by lateral extrusion; H is the average depth of lake water; and h is homogeneous crustal thickening of the Tibetan Plateau.

The total water level variation in Nam Co Lake corresponds to the sum of the three indices above.

$$\Delta H = \Delta H_{gw} + \Delta H_{uw} + \Delta H_g \quad (4)$$

The water level changes caused by groundwater quantity variations can be calculated using the following equation:

$$\Delta H_{uw} = \Delta H - \Delta H_g - \Delta H_{gw} \quad (5)$$

Equation (5) can be used to calculate ΔH_{uw} in different years and analyze groundwater variations in Nam Co Lake at different stages.

3. Results and discussion

3.1. Surface Water Quantity Variations

Figure 3 shows the actual water level variations in Nam Co Lake from 1980–2009. Thus, the total water level variation (ΔH) in Nam Co Lake can be calculated.

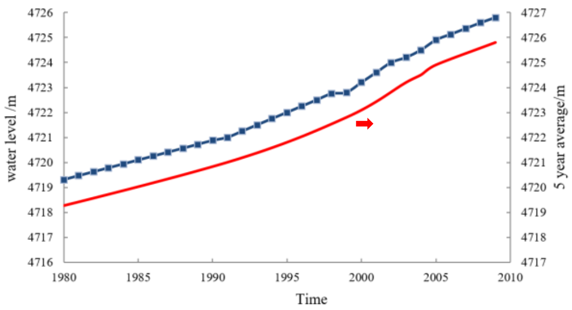

Figure 3. The actual water levels in Nam Co Lake from 1980–2009.

Figure 4 presents measured values of annual precipitation, evaporation, glacier runoff, and non-glacier runoff, as well as their corresponding five-year average values. According to Equation (1), ΔH_{gw} can be determined.

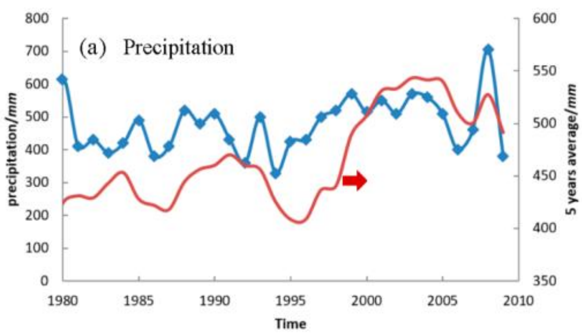

Figure 4. *Cont.*

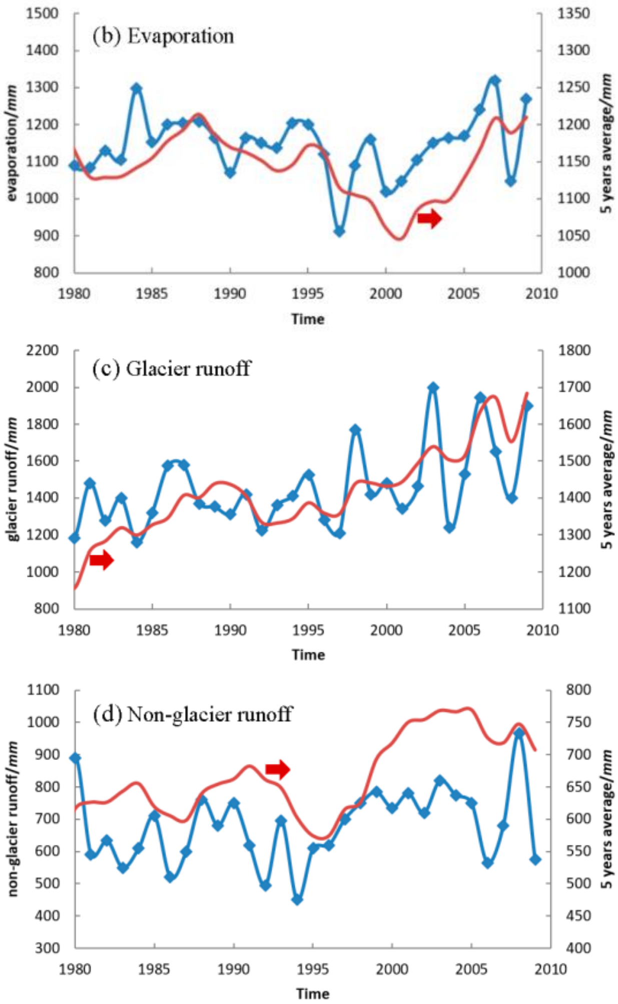

Figure 4. Time series for precipitation (**a**); evaporation (**b**); glacier runoff (**c**); and non-glacier runoff (**d**) in Nam Co Lake from 1980–2009.

3.2. Geological Variation

The area of Nam Co Lake increased along the east and west coasts from 1980–2009, with compression and concomitant geological uplift occurring along the N-S axis. According to Equation (3), the geological variations from 1980–2009 can be assessed and are summarized in Table 1.

Table 1. Geologically induced variations in Nam Co Lake from 1980–2009.

Years	1980–1984	1985–1989	1990–1994	1995–1999	2000–2004	2005–2009
ΔH_g	138 mm	138 mm	138 mm	93 mm	48 mm	3 mm

3.3. Groundwater Quantity Variations

The groundwater quantity variations in Nam Co Lake from 1980–2009 were evaluated based on Equation (5), and the results are shown in Figure 5. The groundwater loss decreased from 961 mm to 777 mm. Based on the lake area of 2026 km^2, this means the groundwater loss declined from 1.9 billion m^3 to 1.5 billion m^3.

Figure 5 shows that the groundwater quantities in Nam Co Lake were negative, which explains why the incoming water amount in Nam Co Lake was higher than the outgoing amount [3]. This difference indicates that a large amount of groundwater infiltration occurred in Nam Co Lake and that the infiltration process was likely the main cause of negative water quantities in the lake. It is also noted that the amounts of groundwater discharge decreased over time. In Figure 5, there are two periods of sudden change, which were 1990–1994 and 2005–2009, respectively. Compared with the previous data, the groundwater loss decreased significantly in the two periods, which need to be further discussed.

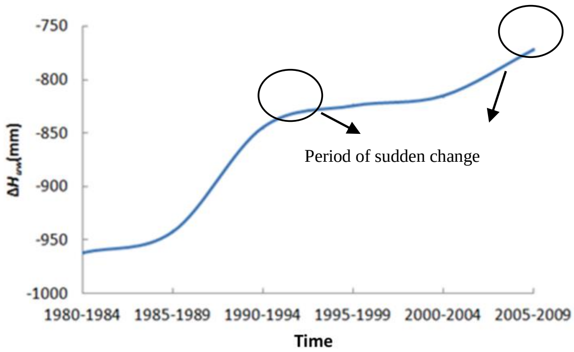

Figure 5. Variations in the groundwater quantity from 1980–2009.

4. Analysis of the Internal Causes of Variations in Groundwater Quantity

According to Equation (2), the decreased groundwater loss can be explained by two potential mechanisms: (1) an increased amount of groundwater recharge and/or (2) a decreased amount of groundwater discharge.

4.1. Increase in Incoming Groundwater Runoff

The changes in the volume of Nam Co Lake are related to the dynamics of other lakes in the Qinghai–Tibet Plateau area [21]. Since the 1980s, the number of low surface temperature events has decreased greatly in this area and the change has been accompanied by substantial increases in both the number of high surface temperature events [22] and the average surface temperature [23]. Such variations unavoidably lead to changes such as an increase in the amount of incoming groundwater supplied by frozen soils and, consequently, changes in groundwater storage [24]. A comparison of the 5-year averages of surface temperature and groundwater loss indicates a strong linear relationship, with a correlation coefficient as high as 0.92, as shown in Figure 6. The overall groundwater loss decreases with increasing surface temperature. Therefore, the temperature increase on the Tibetan Plateau enhanced the amount of incoming groundwater supplied by frozen soils and increased the amount of groundwater in the area surrounding Nam Co Lake.

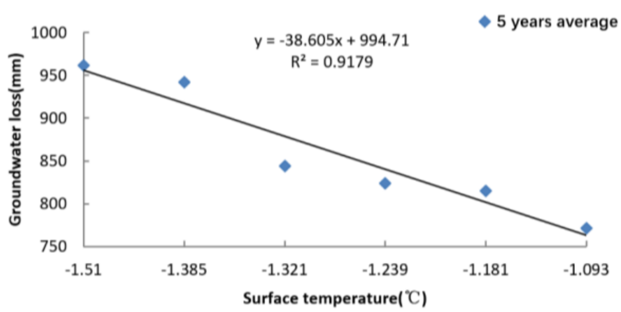

Figure 6. Comparison of the 5-year average of surface temperature and groundwater loss from 1980–2009.

4.2. Decrease in the Groundwater Infiltration Amount

A recent study [3] showed that in 2008, the incoming water amount in Nam Co Lake was higher than the outgoing amount. This difference indicates that a large amount of groundwater infiltration occurred in Nam Co Lake and that the infiltration process was likely the main cause of negative water quantities in the lake area, despite the increased groundwater recharge from frozen soils to Nam Co Lake.

Notably, substantial decreases in the quantity of groundwater occurred in Nam Co Lake from 1990–1994 and 2005–2009, as shown in Figure 5. A statistical analysis of large-scale water conservancy events indicates that the periods with sudden changes in the quantity of groundwater correspond to periods of intense engineering construction and rising water storage level events in secondary lakes, as shown in Figure 7.

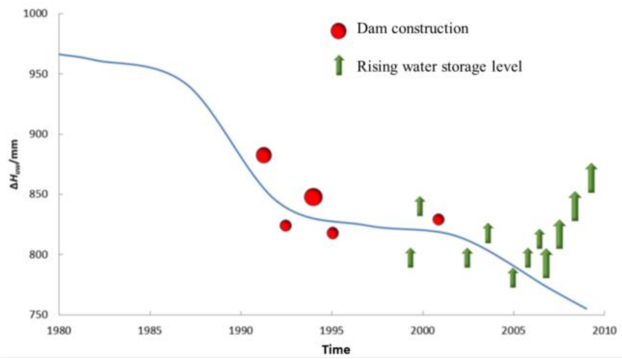

Figure 7. Important large water conservancy events along secondary lakes and rivers.

According to hydraulic theory, the infiltration velocity of Nam Co Lake can be calculated using the equation below:

$$v = \sqrt{2g\Delta H / \left(\lambda \frac{l}{d} + \sum \zeta\right)} \tag{6}$$

where λ is the friction coefficient along the interior of a pipe; l is the pipe length; d is the inner radius of the pipe; v is the flow velocity in the pipe; g is gravitational acceleration; and $\Sigma\zeta$ is the sum of all the local friction coefficients along the interior path of the pipe.

Equation (6) indicates that water storage from dams located along the reaches of secondary lakes resulted in an increase in the water level and reduced the difference between the upper and lower water levels, which consequently led to decreases in the infiltration velocity and infiltration amount. In reality, the water level of Nam Co Lake cannot infinitely increase; instead, it generally remains stable after reaching an infiltration equilibrium condition.

5. Influence of Dynamic Groundwater Quantity Variations

A substantial imbalance between incoming and outgoing water (evaporation and lake water level rise) exists in Nam Co Lake [3]. Because of the complexity of the groundwater quantity in Nam Co Lake, the total water quantity and the water level may increase under relatively arid conditions. Additionally, the lake water level can remain steady during relatively wet seasons. Our dynamic study of the groundwater quantity variations in Nam Co Lake identified another main factor that influences lake surface expansion.

Our results showed that the groundwater quantity of Nam Co Lake is not constant and is characterized by a decreasing loss trend. The data analysis shows that the continuous groundwater discharge reduced from 1.9 billion m^3 in the period of 1980–1984 to 1.5 billion m^3 in the period of 1995–2010. Furthermore, the factors that influence the groundwater quantity variations are discussed, including the temperature of the ground surface and the water levels of secondary lakes. The temperature increase on the Tibetan Plateau may enhance the groundwater recharge, such as the groundwater recharged by frozen soils. Moreover, the increase of the water levels of the secondary lakes may result in substantial decreases of the groundwater discharge. Thus, the temporal variations in the groundwater quantity should be considered when analyzing and simulating the water quantity of Nam Co Lake and its secondary lakes.

In addition to the surface water quantity variations caused by precipitation, glacier ablation [25,26], surface runoff [27] and evaporation, the water level rise and lake surface expansion in the Qinghai–Tibet Plateau lake area (e.g., Nam Co Lake) are affected by groundwater quantity variations caused by groundwater infiltration and the groundwater supply from frozen soil. The increase in surface temperature can increase the supply of groundwater runoff and lead to an increase in the groundwater volume. In addition, the impacts of the increased water levels of secondary lakes or rivers are not negligible. In summary, the combined increase in the surface water supply and decrease in groundwater loss led to the steady and rapid expansion of Nam Co Lake [27]. These lakes are mostly located in the upper reaches of large water control projects, such as the Three Gorges Dam. According to Equation (6), both the construction of water conservancy projects and increases in water storage can reduce water loss [9]. For example, the period of 2005–2009 corresponds to the second period of dam construction for the Three Gorges Dam project, during which the downstream water level increased by 175 m. This may result in a reduction in the potential energy of the water transported from Nam Co Lake to secondary lakes, which explains why the water quantity in Nam Co Lake increased under arid climate conditions and remained steady under wet climate conditions.

According to Equation (6), a rise in the water level of secondary lakes can consequently lead to a decrease in the groundwater runoff amount in Nam Co Lake, which in turn can impact the water quantity during a dam construction period or downstream water level rise. This finding provides an important reference for studying the water level variation mechanisms associated with Qinghai–Tibet Plateau lakes. For example, although Siling Co Lake exhibited an overall expansion trend, a sudden change occurred in the area from 1999–2004 [28]. In addition, although Peikucuo Lake exhibited an overall shrinking trend, the water level remained steady, with large water level increases occurring within short periods from 1990–1995 and 2002–2007 [29]. These periods correspond to periods of large water conservancy construction projects and increases in water storage levels in secondary lakes on the Qinghai–Tibet Plateau. Considering the effects of climate change and hydrological factors, the influence of large engineering projects on variations in the lake environment must be considered when studying the mechanisms of water level change for lake groups on the Qinghai–Tibet Plateau. Although lake groups on the Qinghai–Tibet Plateau are distinctly characterized by expanding and shrinking subregions [30,31], the effects of water quantity factors (e.g., precipitation and glacier ablation), as well as the periodic effects of environmental variations caused by water level changes, must be considered. These profound challenges have a profound effect on water resources and need to be effectively identified in a timely manner [32].

6. Conclusions

The study adopts the water balance principle for the derivation of temporal variations in groundwater for Nam Co Lake. The following conclusions were drawn from the results:

(1) From 1980–2009, groundwater in Nam Co Lake was continuously lost, and the amount of loss gradually decreased from 1.9 billion m^3 in 1980–1984 to 1.5 billion m^3 in 2005–2009.

(2) Based on a comparison with temperature variations, a strong linear relationship exists between the groundwater variation index and the surface temperature on the Qinghai–Tibet Plateau, with a correlation coefficient of 0.92. The temperature rise on the Qinghai–Tibet Plateau is one of the main reasons for the decreasing amount of groundwater loss in this region.

(3) Engineering project construction and the water level increases in downstream lakes and rivers are also partially responsible for the decreasing trend in the groundwater loss amount in Nam Co

Lake. In the period of 1990–1994 and 2005–2009, the groundwater discharge in the Nam Co Lake area was substantially reduced, and both periods corresponded to key periods of engineering construction, water control project implementation and water storage. When studying single lakes, the periodic influence of environmental variations on the lake water balance may need to be considered.

(4) The dynamic variations in the quantity of lake groundwater play a key role in creating weak or inverse correlations between the water quantity and climatic factors during specific periods of time in plateau lakes such as Nam Co Lake. The expansion of Nam Co Lake is related to incoming water supplies from precipitation, glacier ablation, and surface runoff, as well as the additional influence of reduced groundwater loss caused by environmental variations. These findings provide an important reference for studies of the mechanisms that govern the water level changes in Qinghai–Tibet Plateau lakes.

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