Hydrological Variability of Water Level of Dianchi Lake and Its Application

Deng Wen 1, Chen Jin 1, Gu Shixiang 1*, Chen Gang 1,2, Chen Jinming 1,3, Zhou Mi 1

1Yunnan Water Conservancy and Hydroelectric Survey Design and Research Institute, Kunming 650021, China;
2Hohai University, Nanjing 210098, China;
3Wuhan University, Wuhan 430072, China
*Corresponding author. Ph.d and Professor. E-mail: gushxang@qq.com, Tel: 86-871-68093889

Abstract: The water level is an important indicator for lake operation management, and the variability of lake water level will have an important impact on the ecological suitability of aquatic vegetation. The ecological water level of lakes is the minimum water level for maintaining the structural and functional integrity and biodiversity of lake ecosystems. Therefore, it is very important to determine the ecological water level of lakes for maintaining the harmony and stability of lake ecosystems. This paper analyzed the characteristics of water level, the lowest and suitable ecological water levels and the guarantee degree, by using the monthly water level data of Dianchi Lake from 1961 to 2016. The main conclusions are as follows: (1) The water level of Dianchi Lake mainly had a change period of about 15 years; (2) The abrupt change point of water level of Dianchi Lake occurred in 1994; (3) The lowest and suitable ecological water levels of Dianchi Lake and its actual water level had a typical unimodal distribution. The ecological water level in spring and winter was high, while that in summer and autumn was low. Thereinto, the lowest and suitable ecological water levels in May were lowest, 1885.86m and 1886.04m respectively, while those in November were highest, 1886.60m and 1886.78m respectively. (4) The guarantee degree of the lowest ecological water level of Dianchi Lake was as high as 93%~95% within the year, while the guarantee degree of the suitable ecological water level could only reach 46%~50%. The guarantee rate of the ecological water level during the low water level period was higher than that during the high water level period, and the guarantee degree of the interannual ecological water level varied greatly over the years. The lowest guarantee degree occurred in 1988 and 1989 with 0%, followed by the guarantee degrees of 50% and 8% in 1993, and they had reached 100% since 1994.

1. Introduction
Dianchi Lake is located on the southwest of Kunming City, the largest natural lake on the Yunnan-Guizhou Plateau. It is one of the 13 national key river-lake water systems under protection, with various functions such as being industrial and agricultural water, storage, flood control, tourism, shipping, aquaculture and backup water sources. The surface of Dianchi Lake has a slightly “bow” shape, with an average length of 40.4km from north to south, an average width of 7.5km from east to west, and a lakeshore of 163.2km. When the normal water level is 1887.50m, the average water depth
is 5.4m, and the lake surface area is 310km$^2$, while the lake capacity is 1.62 billion m$^3$. Haigeng Gate separates Dianchi Lake into two independent water bodies, Caohai and Waihai. Waihai lake surface has an area of 298km$^2$, accounting for 96.1% of the total area of Dianchi Lake. It is the main body of Dianchi Lake, and the lake water flows from the Haikou River into Tang Langchuan. The surface area of Caohai Lake is 12km$^2$, and the lake capacity is only 20 million m$^3$, however Caohai Lake receives most of the city's sewage in Kunming. The lake water is discharged into Tang Langchuan by the excavated Xiyuan Tunnel.

With the urban expansion of Kunming and the development of industrial and agricultural economy around the lake, the lake water resources have been overexploited and utilized. The water quality of Dianchi Lake has been reduced to the inferior Class V since the late 1980s, and the lake has become seriously eutrophic, turning into one of "Three Lakes and Three Rivers" under the state's key control and prevention. During the “Eleventh Five-Year Plan” period, Kunming City laid emphasis on implementing a series of projects to control Dianchi Lake, such as sewage interception and traffic engineering around the lake, water transfer and water saving projects in the outer basin, improvement project of river channel entering into the lake, agricultural non-point source treatment project, ecological restoration and construction project, and ecological dredging project. In the “Twelfth Five-Year Plan” period, it is further consolidated and upgraded. with the addition of implementing the “four returns and three repayments” policy in Dianchi Lake, the water quality of Dianchi Lake and the lakeside ecological environment were significantly improved, 4,402 hm$^2$ of wetland around Waihai of Dianchi Lake was restored, and the water quality of Dianchi Lake and the ecological environment of the lakeside were significantly improved [1-2]. By integrating the “six big projects” governed by Dianchi Lak as a system, the separation of clean stream and dirty stream made the clean water flowing into Dianchi Lake, and the healthy water cycle regulation mode in the Dianchi Lake basin was constructed. Under the water supply project of Niulan River—Dianchi Lake and the water diversion project in Dianzhong, the ecological water supply to Dianchi Lake was 0.7 billion m$^3$, and the water resources in Dianchi basin had more than doubled [3]. Therefore, the ecological water level of Dianchi Lake should be determined according to the water level in the approximate natural state.

2. Materials and Methods

2.1 Data materials
The monthly (daily) measured operating water level of Dianchi Lake and the flow out of the lake for a total of 56 years from 1961 to 2016. The monthly (daily) precipitation, average temperature, relative humidity, wind speed and other meteorological observed data of the Kunming meteorological station from 1950 to 2016.

2.2 Main analytical methods

2.2.1 Analysis of water level characteristics
(1) Periodic analysis method
The wavelet transform method [4] was used to calculate the wavelet transform coefficients and analyze the time variation characteristics of the water level sequence based on wavelet transform. In the case of the same scale, the positive wavelet transform coefficient corresponds to the period more than the normal, while the negative wavelet transform coefficient corresponds to the period less than the normal, and the wavelet transform coefficient of zero corresponds to the abrupt change point; The larger the absolute value of the wavelet transform coefficient, the more significant the time scale change is; The scale corresponding to the contour center is the main period of the sequence change.

(2) Trend analysis method
The method of moving average and difference-product curve analyses were used to filter out some short-term random and irregular changes in the observed data of water level, find out the long-term change law, and study the change trend of water level sequence. Furthermore, the Mann-Kendall rank
correlation method \cite{5} was utilized to test whether the overall sequence was rising or falling, and whether the trend was significant or not.

The fast wavelet transform algorithm is used to decompose the monthly average water level sequence and study the conversion tendency of high and low frequency signals after being decomposed.

(3) Variation point detecting method

The sequential clustering method \cite{6}, Lee-Heghinian method \cite{7}, the rank sum test method \cite{8} and the Mann-Kendall test method \cite{9} were used to detect the variation points of the annual average water level sequence, based on which, comprehensive analysis was carried out to obtain the detection conclusion.

2.2.2 Calculation of lake ecological water level

Water level is an important indicator of lake operation management. Periodical changes of seasonal water level within the year and interannual water level have an impact on the ecological suitability of aquatic vegetation. Long-term high and low water levels and the non-periodic seasonal changes of water level will destroy the normal growth, reproduction and succession of aquatic vegetation in the lake \cite{10}. The ecological water level of lakes maintains the structural and functional integrity and biodiversity of the lake's ecosystem \cite{11}. Therefore, determining the ecological water level of lakes is very essential for maintaining the harmony and stability of lake ecosystems. At present, the research on lake ecological water level mainly focuses on the lowest ecological water level or water volume of lakes. The methods of determining the lowest ecological water level of lakes are mainly natural water level information method, lake morphological method, biological minimum demand for space method, annual guarantee rate method, minimum annual average water level method, curve correlation method, functional method, water level diachronic method, etc. \cite{12-15} Their results all are a fixed water level, which is difficult to reflect the process of lake water level change during the year.

This paper took China’s sixth largest freshwater lake, Dianchi Lake, as the research object, and analyzed the abrupt change point of lake water level through the abrupt change point detecting method, approximately regarded the measured water level sequence before the abrupt change point as the natural water level sample data, arranged the monthly water levels data of these years in descending order, used the long series of data empirical frequency method to calculate the empirical frequency and cumulative probability of water level in each month, selected the natural water level of the lake corresponding to the appropriate guarantee rate to be the ecological water level of Dianchi Lake, and combined with the operating and regulating water level of Dianchi Lake to verify the determined lake ecological water level.

2.2.3 Analysis of guarantee degree

At present, there are few studies on the guarantee degree of lake ecological water level in China. This paper referred to Chen Yu et al. \cite{16} to define the guarantee degree of lake ecological water level. The guarantee degree of lake ecological water level is, within a certain period of time, the ratio of the measured water level of the lake minus the ecological water level to the total sequence length, which is calculated as follows:

\[
E_k = \frac{\sum_{i=1}^{12} \sum_{j=1}^{n} Sgn(h_{ij} - h_{ei})}{12} \times 100\% , \quad Sgn(h_{ij} - h_{ei}) = \begin{cases} 1, & \text{if } h_{ij} - h_{ei} \geq 0 \\ 0, & \text{if } h_{ij} - h_{ei} < 0 \end{cases}
\]

(1)

where: \( E_k \) is the guarantee degree of annual ecological water level (%) in the \( k \)th year, \( h_{ij} \) is the measured water level in the \( i \)th month of the \( k \)th year, \( h_{ei} \) is the ecological water level in the \( i \)th month. Then the guarantee degree of ecological water level over the years \( E_i \) is calculated by the equation:

\[
E_i = \frac{\sum_{k=1}^{5} \sum_{j=1}^{12} Sgn(h_{ij} - h_{ei})}{n} \times 100\% , \quad Sgn(h_{ij} - h_{ei}) = \begin{cases} 1, & \text{if } h_{ij} - h_{ei} \geq 0 \\ 0, & \text{if } h_{ij} - h_{ei} < 0 \end{cases}
\]

(2)

where: \( E_i \) is the guarantee degree of ecological water level over the years (%), \( n \) is the number of
statistical years.

3. Result analyses

3.1 Analysis of random variation characteristics of Dianchi Lake’s water level

3.1.1 Periodic analysis
The Morlet wavelet function was used to analyze the periodic variation characteristics of the annual water level sequence in Dianchi Lake. The time-frequency distribution of the real part of the wavelet transform coefficient is shown in Fig. 1(a). The solid line in the figure indicates that the real part of the wavelet transform coefficient is positive, corresponding to a rising water level; The dotted line indicates that the real part of the wavelet transform coefficient is negative, corresponding to a decreasing water level. The annual water level sequence of Dianchi Lake is obviously fluctuating on the scales of 5 years and 15 years, and several alternating shock centers of high and low water levels emerge. Among them, the water level fluctuation on the scale of 15 years has a characteristic of full time domain distribution, and the low center of the scale of 5 years is nested in that of 15 years.

(a) Morlet wavelet transform coefficient map of Dianchi’s annual water level sequence

(b) Wavelet variogram of Dianchi’s annual water level sequence

Fig.1 Wavelet analysis diagram
Fig. 1(b) shows the change process of the wavelet variance of Dianchi’s annual water level sequence with time scale. There are two peaks corresponding to the main periods of the scales of 5 years and 15 years. The maximum peak appears at 15 years, indicating that the oscillation period at this scale is the strongest, that is, 15 years is the first main period and 5 years is the second main period.

3.1.2 Detection of variation points
According to the sequential clustering method, Lee-Heghinian method, the rank sum test method and the Mann-Kendall test method, the variation points of the annual average water level sequence in Dianchi Lake were detected respectively, and the diagnosis results are shown in Table 1 and Figure 2. It can be seen that the four methods all detected the variation points near 1993 and 1994, and three methods detected the year of 1990 as a variation point. Obviously, from the perspective of mathematical statistics, the above two points are both variation points.

| test method             | test result | test method        | test result |
|-------------------------|-------------|--------------------|-------------|
| Sequential clustering   | 1990, 1993  | Rank sum test method| 1990, 1994  |
| Lee-Heghinian           | 1990, 1993  | Mann-Kendall       | 1994        |

![Sequential clustering statistics](image1)

![Lee-Heghinian statistics](image2)

![Rank sum test statistics](image3)

![The Mann-Kendall test method](image4)

Fig. 2 Variation point detecting graphs

3.1.3 Trend analysis
The 5-year moving average and difference product curve analyses were performed on Dianchi’s annual average water level sequence from 1961 to 2016, as shown in Fig. 3. It can be seen from Fig. 3(a) that the annual water level sequence generally shows an upward trend, with many rising and falling fluctuations. As seen in Fig. 3(b), 1994 is the dividing point of Dianchi Lake’s water level, and
it presents a declining segment before that year, while after that, the water level shows a rising tendency.

![Tendency change curve](image)

Fig. 3 Annual water level trend change curve

The Mann-Kendall rank correlation method was further used to analyze the overall change trend of the water level, and the calculation results of the statistic $U$ are shown in Table 2. It can be seen from the table that each $U$ value is greater than 0, indicating that the water level sequence has an upward trend on a whole, and the trend is significant at a significance level of $\alpha=5\%$.

Table 2 Mann-Kendall rank correlation test table for Dianchi’s annual average water level sequence

| project            | change trend | statistics $U$ | significant test |
|--------------------|--------------|----------------|------------------|
| Dianchi’s water level | up           | 6.3537         | significant level | $U_{\alpha/2}$ | 1.96 | significant or not | significant |

The wavelet decomposition of the monthly average water level sequence in Dianchi Lake from 1961 to 2016 (Fig. 4) shows that the high-frequency and low-frequency fluctuations of the water level sequence show a significant difference, with a time axis of 400 months (corresponding to 1994) as the boundary. The high-frequency and low-frequency fluctuations before the boundary are more intense, while those after the boundary are slowed down. The low-frequency part are weak, and only the high-frequency parts have large fluctuations. It reflects that the water level has increased since 1994, and the water volume of Dianchi Lake has increased. The adjustment of water level is similar to a low-pass filter, which makes the high-frequency and especially low-frequency fluctuations smooth.
3.1.4 Comprehensive analysis

According to the periodic analysis, Dianchi’s water level has a 5-years and a 15-years oscillation periods, and 15 years is the first main period, while 5 years is the second main period. As can be seen from abrupt change detection, there are two abrupt change points, the year of 1994 (1993) and 1990, especially 1994 (1993), at which the change is obvious. From the trend analysis, the water level of Dianchi Lake shows a significant upward trend, at the same time, it is bounded by 1994, with an overall declining trend before that and an overall increasing trend after that.

3.2 Characteristics of natural water level in Dianchi Lake

Although the abrupt change point obtained by the detection analysis is 1994, the impact of human activities on the abrupt change of the lake water level is a long-term comprehensive result. Before 1985, the water quality of Dianchi Lake was generally in good condition, and the water quality of Waihai was above the Class III of surface water. The changes of lake water level also belonged to normal periodic fluctuations, and the aquatic plant and animal species had not yet disappeared significantly. After 1986, the water quality of Waihai in Dianchi Lake deteriorated at a rapid rate, and it experienced the stages of rapid deterioration, slow improvement and fluctuations, always in the inferior Class V\[17\]. Especially after 2000, the aquatic animal and plant species in Dianchi Lake tend to be simplified, and only a few kinds of submerged plants with strong stain resistance and good stress resistance survived, such as Myriophyllum spicatum, Potamogeton Malayanus, Potamogeton pectinatus and Vallisneria natans. A large number of native and indigenous lake organisms, such as nemipterus virgatus and ottelia acuminate, gradually disappeared\[18\].

In addition, through the further analysis of the monthly water level data of Dianchi Lake since 1961, the falling depth sequence of the lake water level over the years is drawn in Fig. 5. Obviously, before 1987, the water level falling depth of Dianchi Lake was about 1.0m, while the annual water level has a
maximum variation of 1.55m and a minimum variation of 0.65m. Since 1987, the overall change trend of Dianchi Lake’s water level has been decreasing year by year, and it is only about 0.30m in 2016, which is close to the year of 1986 when the water quality of Waihai in Dianchi Lake fell to Class IV and showed signs of deterioration. Therefore, this paper selected the water level data of 25 years from 1961 to 1985 approximate to the natural water level sequence, calculated the lowest and suitable ecological water levels of the lake, and analyzed the guarantee degree of Dianchi’s ecological water level with the water level data of 31 years from 1961 to 1985.

Fig. 5 Schematic diagram of the annual change of Dianchi Lake falling depth

The annual change of Dianchi Lake’s water level is a typical unimodal distribution (Fig. 6). June is the boundary, and the water level increased from June to October, while the water level showed a downward trend from November to May. The average water level has an annual variation of about 0.78m over the years, and the highest water level over the years has an annual variation of about 1.17m, while the lowest water level over the years has an annual variation of about 0.92m. In general, the water level of Dianchi Lake is characterized by an annual increase in the flood season (June to October), an annual reduction in the non-flood period (November to May), and an interannual variation in the years of abundance and dryness.

Fig. 6 Monthly water level change in Dianchi Lake from 1961 to 1985

3.3 Ecological water level of Dianchi Lake

Based on the monthly water level sequence data of Dianchi Lake from 1961 to 1985, the empirical frequency method of long series of data was used to calculate the empirical frequency and cumulative probability of different monthly water levels (Fig. 7). According to the monthly guarantee rate method, the water levels at the guaranteed rates of 75% and 50% were selected as the lowest ecological water level and suitable ecological water level of Dianchi Lake respectively, and the corresponding Dianchi’s ecological water levels were obtained by interpolating from the frequency curves of monthly water level. The lowest and suitable ecological water levels of Dianchi Lake are the same as the
change trend of multi-year average water levels. The ecological water level in spring and winter is high, while that in summer and autumn is low. The lowest and suitable ecological water levels in May are lowest, 1885.86m and 1886.04m respectively, while the lowest and suitable ecological water levels in November are highest, 1886.60m and 1886.78m respectively.

According to the results of operating water level of Waihai in Dianchi Lake [19], in the main flood season in Waihai (June to October), it is operated at the limit of 1887.20m, and in the later flood season, the water level is increased to 1887.40m in November. From December to May, it is operated at the normal high water level of 1887.50m. The lowest working water level of Dianchi Lake is 1885.50m. The lowest and suitable ecological water levels and the operating characteristic water level of Dianchi Lake are plotted in one graph (Fig. 8). It can be seen that the operating water level of Dianchi Lake can meet the requirements of the lowest and suitable ecological water levels.
3.4 Guarantee degree of Dianchi’s ecological water level

According to the requirements of the lowest and suitable ecological water levels of Dianchi Lake, the guarantee degrees of the measured annual and interannual water levels from 1986 to 2016 were calculated according to the equation (1) and (2). From the annual change processes (Fig. 9) of the guarantee degrees of the lowest and suitable ecological water levels of Dianchi Lake, it can be seen that the guarantee degree of the lowest ecological water level of Dianchi Lake is as high as 93%–95% for each month, while that of the suitable ecological water level can only reach 46%–50%. The guarantee rate of the ecological water level during the low water level period (January to July) is higher than that during the high water level period (August to December). Therefore, the high water level period of Dianchi Lake is the dry season of the ecological water level.

Fig. 9 The guarantee degree of the monthly lowest ecological water level of Dianchi Lake

Fig. 10 The annual guarantee degree of the lowest ecological level of Dianchi Lake

From the interannual variation processes of the guarantee degrees of the lowest and suitable ecological water levels of Dianchi Lake (Fig. 10), it can be seen that the degree gradually increased from 1988 to 1991, and fell sharply in 1992. The lowest ecological water level in 1994–2016 has always kept at a guarantee degree of 100%. Within the 30 years from 1986 to 2016, the guarantee degree of the many annual average lowest ecological water level of Dianchi Lake was 84%. The lowest guarantee degree was 0% both in 1988 and 1989, followed by 50% in 1993 and 58% in 1987 and 1990; The guarantee degree of the average suitable ecological water level was 77% for many years. The guarantee degree in 1988 and 1989 were both 0%, followed by that of 8% in 1993, and 42% in 1987, 58% in 1990 and 1992, 83% in 1994, respectively. The guarantee degree of the ecological
The water level of Dianchi Lake is related to the years of abundance and dryness, but the guarantee degree of has reached 100% since 1994. The main reason is that the progressive implementation of the six big projects of sewage interception and traffic engineering around the lake, water transfer and water saving projects in the outer basin, improvement project of river channel entering into the lake, agricultural non-point source treatment project, ecological restoration and construction project, and ecological dredging project”, guarantee the ecological water level of Dianchi Lake. However, the water level of Dianchi Lake is at a high level for a long time, which is not conducive to the self-repair and improvement of the lake ecosystem. Therefore, after all the engineering measures for preventing and controlling water pollution of Dianchi Lake are completed and effective, the regulation of Dianchi Lake’s water level should restore the good quality of lake water like before 1985 and an approximately natural state where there were periodic fluctuations throughout the year. So that the restoration of lake water ecosystem can achieve the expected results.

4. Conclusions
(1) The abrupt change point of Dianchi Lake’s water level occurred in 1994, but the water quality of Dianchi Lake began to deteriorate since 1986. A large number of native and indigenous lake organisms gradually disappeared, and only a few submerged plants with strong stain resistance and good stress resistance survived. Before 1987, the water level falling depth of Dianchi Lake was about 1.0m, but the overall change trend of Dianchi Lake’s water level has been decreasing year by year, and it is only about 0.30m in 2016. Therefore, this paper selected the monthly water level sequence of 25 years from 1961 to 1985 approximate to the water level in the natural state of the lake, and calculated the guarantee degree of the lowest and suitable ecological water levels of Dianchi Lake, with the water level sequential data of 31 years from 1986 to 2016.

(2) The annual change of Dianchi Lake’s water level had a typical unimodal distribution, with an upward trend in the flood season (June to October) and a downward trend in the non-flood period (November to May). The average water level had a variation of about 0.78m over the years, and the highest water level over the years had an annual variation of about 1.17m, while the lowest water level over the years has an annual variation of about 0.92m.

(3) The annual change tend of the lowest ecological water of Dianchi Lake was basically consistent with its water level process. The ecological water level in spring and winter was high, while that in summer and autumn was low. Thereinto, the lowest and suitable ecological water levels in May are lowest, 1885.86m and 1886.04m respectively, while the lowest and suitable ecological water levels in November were highest, 1886.60m and 1886.78m respectively. The lowest and suitable ecological water levels obtained by the analysis were compared with the operating and regulating water level of Dianchi Lake, and the operating water level of Dianchi Lake could meet the requirements of the lowest ecological water level

(4) The guarantee degree of the ecological water level of Dianchi Lake was as high as 93%~95% for each month within the year, and the guarantee degree of the ecological water level during the high water level period was lower than that during the low water level period. The guarantee degree of the interannual ecological water level varied greatly over the years. The guarantee degree in 1988 and 1989 was lowest with 0%, and it had reached 100% since 1994. The long-term high water level of Dianchi Lake has violated the change law of lakes’ periodic fluctuation, which is not conducive to the restoration of lake water ecosystem.

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