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Separating reservoir flood season into sub-seasons based on fractal theory

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ABSTRACT

Nowadays, flood season can be divided into several sub-seasons. Accordingly, reservoir operation should be conducted in stages with different flood control levels, which helps to take full use of flood resources and increase reservoir benefits. Reservoir operation in sub-seasons requires scientific separation of flood season. In this paper, the fractal theory is adopted to do a comprehensive study on Hongfeng Reservoir. First, Fractal theory is used to analyze the flood characteristics of Hongfeng Reservoir. Then, we divided its flood season into different sub-seasons based on its actual flood records by analyzing capacity and correlation coefficient with fractal theory. Meanwhile, different fixed values are set in different sub-season. Design floods and flood control levels of different sub-seasons were then calculated according to existed flood regulation rules in order to take full use of flood resources and increase reservoir benefits. The calculation results on flood regulation and electricity generation show that adopting different flood control levels in sub-seasons can bring about more economic benefits. These results are expected to be helpful for further understanding the seasonal characteristics of floods and application of Fractal theory in water resources management.

Keywords: Reservoir operation in stages; Fractal theory; Flood season separation; Flood control water level

1. Introduction

The ever-increasing demands on water supply has intensified water scarcity in China. Reservoirs have a significant role in resolving the tension between the water supply and demands. To fully use flood resources and reduce water shortages, many researchers propose increased "floodwater utilization" [1–3]. Separating the flood season of a reservoir into several sub-seasons and accordingly operating the reservoir in stages without raising flood risk can help take full use of flood resources and increase benefits by recharging the reservoir to normal water level at the end of flood season. With different control levels in each sub-season, reasonable separation of flood season is the key to increase comprehensive reservoir benefits in reservoir operation in stages. Regulation for calculating design flood of water resources and hydropower projects of China requires that, to calculate design floods of sub-seasons flood season separation should consider the design requirements of projects, as well as flood timing according to the general seasonal varying flood patterns. This means design floods of different sub-seasons should be calculated based on flood characteristics to meet project design for practical construction and operation.

Many conventional methods can be used to define the flood season, and explain how flood operations might vary

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in sub-seasons within the flood season, such as cause analysis method and statistical method. Many new methods also are available, such as fuzzy analysis, changing point analysis, fractal theory method etc. Chen [4] proposed a fuzzy set application to flood season definition, reflecting fuzziness of flood season boundaries in time. The fuzzy membership functions used to separate flood season and non-flood season are derived statistically, and the flood control level is calculated daily in the transition period to improve water utilization. Liu et al. [5] introduced the theory of changing point analysis and detailed the theory and analytical method of mean changing point and probabilistic changing point in flood sub-seasons for the Three Gorges Reservoir. Hou et al. [6] used fractal theory to analyze flood peak sequence and studied flood sub-seasons for Xiaodeshi Station. Fang et al. [7] reviewed flood sub-season analysis methods and discussed their comparative advantages and disadvantages. Wei et al. [8] used fractal theory in the study of flood sub-seasons for Bihe Reservoir. Fractal theory has been applied to hydrology and water resources, such as the fractal of morphological characteristics of watershed systems, the longitudinal channel profile, and flood forecasting and flood disaster prediction. Zhang et al. [9] also have applied fractal theory to develop flood sub-seasons only by analyzing capacity of dimensions. Alipoura [3] presented a systematic fractal approach that enables identifying flood regime in stream flow data and identifying flood formation factors that cause variations of fractal factors. So, the fractal theory is mainly applicable to what is often featured with randomness, nonlinearity, determinacy and self-similarity, where flood series have all these characteristics. Moreover, in the process of forming flood peak flow, the influence of the magnitude of precipitation, time and space distribution also contribute to the randomness and nonlinearity. At the same time, the flood peak flow and its flood process are also influenced by some invariable factors, which comply to the certainty and similarity of fractal theory. Therefore, the flood peak data series has randomness and nonlinearity, certainty and similarity, which is consistent with the objective of fractal theory research. Fractal theory can be applied to study these hydrological phenomena—the separation of flood season.

This paper analyzed the flood characteristics of Hongfeng Reservoir as an illustrative example, and divided its flood season into different sub-seasons based on its actual flood records by analyzing capacity and correlation coefficient with fractal theory. Meanwhile, different fixed values are set in different sub-season. Design floods and flood control levels of different sub-seasons were then calculated according to existed flood regulation rules in order to take full use of flood resources and increase reservoir benefits.

2. Methodology

2.1. Fractal theory

A fractal is a natural phenomenon or a mathematical set that has a repeating pattern at every scale, featured with self-similarity and scale-invariance. Fractal theory was established by Mandelbrot in the 1970s. It has been applied to many areas, including philosophy, mathematics, chemistry, physics, economics, geology, seismology, geography, music, and art. Fractal theory has been applied to hydrology and water resources [9], such as the fractal of morphological characteristics of watershed systems, the longitudinal channel profile, flood sub-seasons and flood forecasting and flood disaster prediction.

The current study of fractal is based on the qualitative understanding of the examined object's self-similarity. In physics and mathematics, the dimension of a mathematical space (or object) is informally defined as the minimum number of coordinates needed to specify any point within it. As for ordinary geometric shapes, points are 0-dimensional sets; lines are 1-dimensional sets which only have length; surfaces are 2-dimensional sets which have length and width; and cubes are 3-dimensional sets which have length, width and height. For complicated geometric forms whose details seem more important than the gross picture, fractal dimensions are applied as an index describing their complexity while the conventional Euclidean or topological dimension shows its limitation. If the theoretical fractal dimension of a set exceeds its topological dimension, the set is considered to have fractal geometry [10]. Unlike topological dimensions, the fractal index can take non-integer values [11]. Multiple algorithms for calculating fractal dimension exist in fractal theory. The Hausdorff dimension, also called gauge dimension, is the fundamental one. Others include information dimension, correlation dimension, spectral dimension, distribution dimension and Lyapunov dimension, etc. The box-counting dimension (or Minkowski dimension) based on the Hausdorff dimension is used in this paper.

2.2. Calculation of box-counting dimension

Using a ruler of length ε to measure a line segment of length L, $N(\varepsilon)$ as the ratio of L to ε can be obtained. Similarly, using cubes with side length ε to fill an object, $N(\varepsilon)$ is the number of cubes required to cover the object. The fractal dimension obtained in this way is called box-counting dimension Dc [12], and is defined as:

$$Dc = \lim_{n\to\infty} \frac{\ln N(\varepsilon)}{\ln(1/\varepsilon)} \tag{1}$$

When ε approaches 0, it becomes:

$$\ln N(\varepsilon) \approx -Dc\ln\varepsilon = Dc\ln(1/\varepsilon) \tag{2}$$

where ε is the scale at which the fractal is measured, Dc is the box-counting dimension, and $N(\varepsilon)$ is the covering number. If there is a straight part (clear correlation) on the lnNN(ε)–ln(ε) graph with linear fitting, the sequence can be conceived as a fractal. The slope of the straight part Dc is the fractal dimension. Smally [12] introduced a new variable (NN) when computing the fractal dimension of the earthquake spectrum series of New Hebrides, namely the relative measurement:

$$NN(\varepsilon) = N(\varepsilon) / NT \tag{3}$$

where $N(\varepsilon)$—absolute measurement, NT—total number of time intervals, T—total time length, ε—step length.

A fractal problem depends on the existence of a straight part (scale-invariant area) on the *lnNN(ε)–ln(ε)* curve [13–18]. Whether the shapes measured by ε belong to the same fractal depends on whether the fractal dimensions are close or not. If the slope of the straight part in the scale-invariant area is *b*, the capacity dimension can be given by the following equation:

$$Dc = d - b \tag{4}$$

where *d*—topological dimension. Points of flood peaks distribute on a *Q~t* two-dimensional surface, so *d* equals to 2, and then:

$$Dc = 2 - b \tag{5}$$

2.3. Calculation procedure of box-counting dimension

The detailed steps of calculating the capacity dimension of the flood time series are as follows (shown in Fig. 1):

(a) Sampling data series: $X_1, X_2, \ldots X_i, \ldots, X_n$;
(b) According to the time sequence of sample occurrence, the sample point data points are drawn in the coordinate system with time as the horizontal coordinate and sample value as the vertical coordinate, which is commonly referred to as the sample scatter diagram.
(c) Based on the time span of sample point data, the total time span *T* is determined;

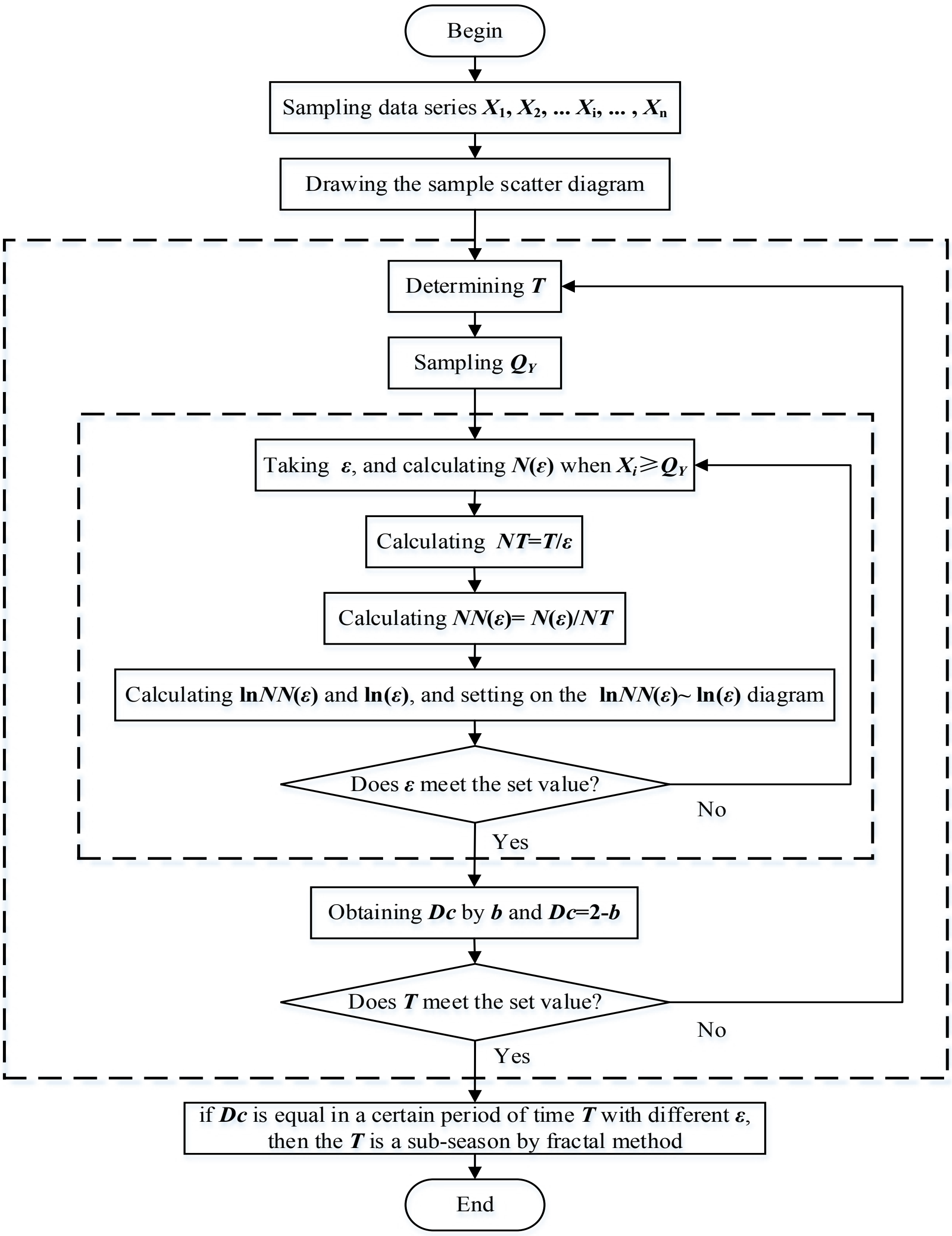


Fig. 1. Flow chart of fractal separating method for flood season.

(d) Sampling fixed value Q_Y which can reflect the flood size in a certain flood stage;
(e) Taking a certain period of time ε as the time scale, the number of time periods when the sample value X_i is greater than Q_Y denoted;
(f) According to the total time period T and time scale, the relative time scale $NT=T/\varepsilon$ diffusion is calculated.
(g) Calculating the relative measurement value $NN(\varepsilon) = N(\varepsilon)/NT$;
(h) $ln\ NN$ (ε), ln (ε), and the points according to (ln (ε), $ln\ NN$ (ε)) point in ln (ε) ~ ln NN (ε) related diagram, define a point;
(i) Taking the different time scale of ε and repeating steps (e) ~ (h) to determine a series of points;
(j) In the series of points, the capacity dimension of the sample fractal with a total time period of T can be calculated by determining the existing line gradient b and $Dc = 2–b$.
(k) Repeating the step (a) ~ (j), by the different time intervals for T, capacity dimension of Dc, if the Dc is equal in a certain period of time T with different ε, then the T is a sub-season according to fractal method.

Based on the separation, this paper also calculated the design floods of all the sub-seasons and determined the control range of their flood control levels. Under the requirement of flood control safety, adopting the new operation schemes can help increase the total generation percentage benefits of reservoir, especially in water shortage areas, which is necessary for water supply and ecological environment protection, etc.

2.4. Case study

2.4.1. Materials and data of Hongfeng reservoir

Built in 1960, Hongfeng reservoir is a large multi-year regulating storage reservoir for hydropower generation, flood control, water supply and recreation. As the leading reservoir of the cascade of hydropower stations along Maotiao River, Hongfeng reservoir is crucial to ensure the safety of the cascade system. The watershed area controlled by Hongfeng reservoir is 1596 km^2, with an average elevation of 1327.0 m, and an average river bed slope of 1.21‰. The Maotiao river flood season begins in May and ends in September, and rainfall in this period of time accounts for 70% of annual inflow. Annual maximum floods typically occur in June or July. The location of Hongfeng Reservoir is shown in Fig. 2.

The flood season of Hongfeng reservoir is from May 1st to September 30th (lasting for 153 d). This study used the historical hydrology record from 1960 to 2014. Earlier researches only sampled the sequence of the largest daily inflows, while this paper also considered the second and the third largest daily inflows. Distributions of the three largest daily inflows are shown in Fig. 3.

2.4.2. Flood season separation of Hongfeng reservoir

Fig. 3 shows large gaps between the ten-day period inflows of May and June, July and August, and August and

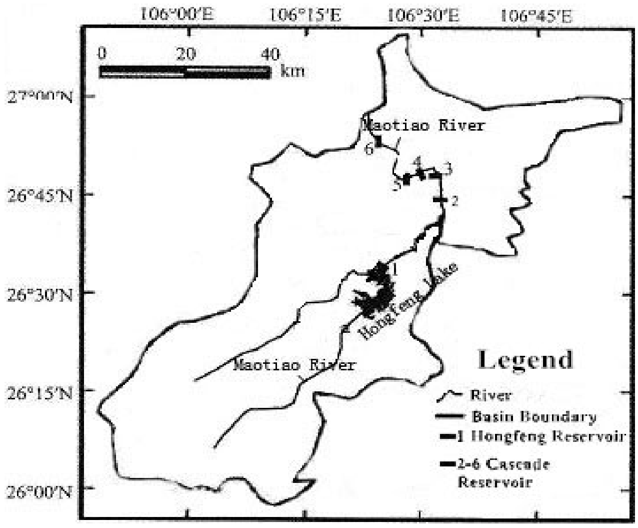


Fig. 2. The location of Hongfeng reservoir.

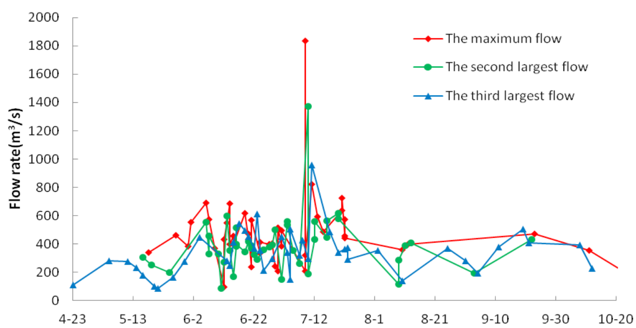
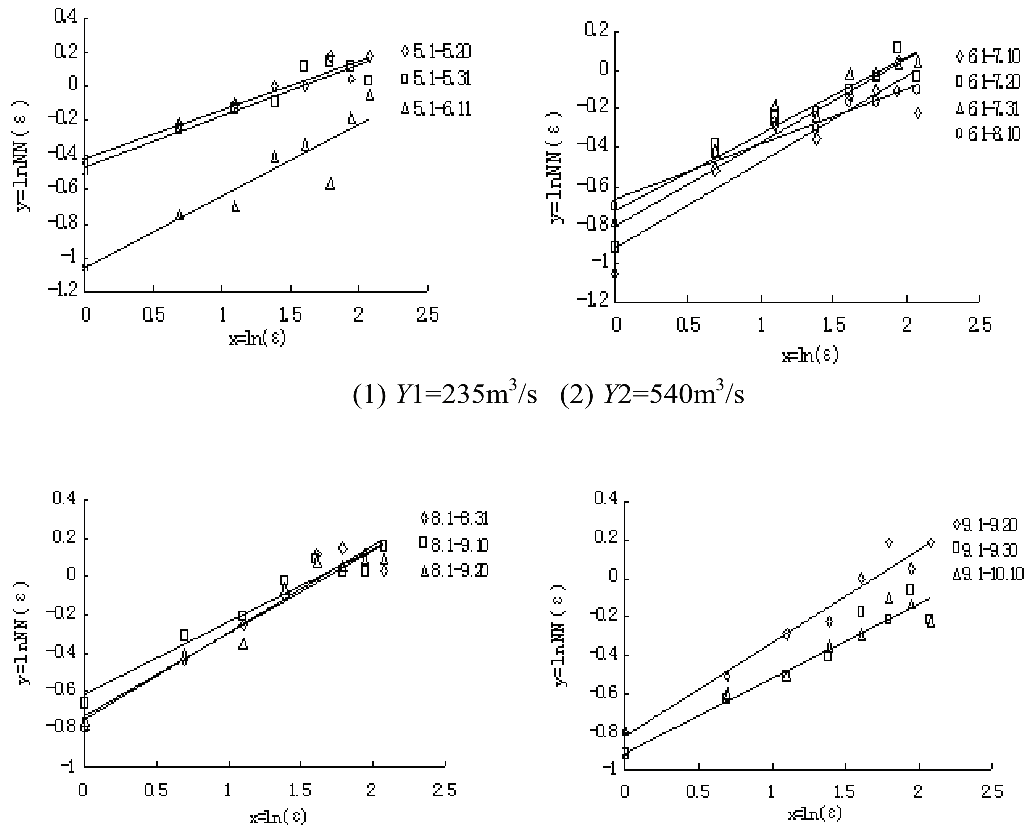


Fig. 3. Distributions of the three largest daily inflows.

September. Accordingly the flood season can be divided into four sub-seasons. Beginning from May 1st, the length of the first sub-season is determined as follows:

Shi et al. [19] suggest that the significant linear relation between lnNN(ε) and ln(ε) is inversely proportional to the length of the time scale ε and thus should not exceed 6. This case achieves the best result when ε is no larger than 8. Time scale ε is 1d, 2d, 3d... 7d. By setting a fixed value Y1 = 235 m^3/s (slightly larger than the sample average inflow) as a benchmark, T = 20, $N(\varepsilon)$ can be obtained under different time scales by counting the number of time intervals in which the average inflows are larger than Y1. The lnNN(ε)–ln(ε) graph can be plotted to determine slope b of the straight part and then obtain the box-counting dimension Dc (Dc = 2–b). Different lnNN(ε)–ln(ε) graphs can be plotted based on different values of T when changing the ending date of the first sub-season. Calculation of the latter three sub-seasons is similar to the first sub-season, and the benchmark inflows are as Y2 = 540 m^3/s (T = 40), Y3 = 265 m^3/s (T = 31), Y4 = 235 m^3/s (T = 20) respectively. All the Y1, Y2, Y3, Y4 as 235, 540, 265, 235 are slightly larger than the average flow of different sub-season. The decomposition principle is to set different time period T and calculate the capacity dimension. Since it is not clear whether the calculation period is the final installment result, in order to eliminate the uncertainty and to raise the screening level in the trial calculation process, the fixed value of the sample is slightly higher than the average value. The purpose is to eliminate the influence of the trial calculation on the uncertainty of the set results to a certain extent. The *lnNN(ε)–ln(ε)* graphs under different values of *T* are shown in Fig. 4.The calculated box-counting dimensions of the four sub-seasons are shown in Table 1.

It can be seen from table 1 that the box-counting dimensions of situation A and situation B have a slight difference



(1) $Y1=235m^3/s$ (2) $Y2=540m^3/s$

(3) $Y3=265m^3/s$ (4) $Y4=235m^3/s$

Fig. 4. Relationship between *NN(ε)* and ε with logarithmic coordinates.

Table 1
Box-counting dimensions of different flood sub-seasons(flood peak)

Sub-seasons	Situation	T (days)	Starting date (m/d)	Ending date (m/d)	Correlation coefficient *R*	Slope *b*	Box-counting dimension *Dc*
Pre-rainy season	A	20	May, 1st	May, 20th	0.97	0.29	1.71
	B	31	May, 1st	May, 31st	0.95	0.30	1.70
	C	42	May, 1st	June, 11st	0.93	0.42	1.58
Main flood season	D	40	June, 1st	July, 10th	0.92	0.44	1.56
	E	50	June, 1st	July, 20th	0.96	0.43	1.57
	F	61	June, 1st	July, 31st	0.97	0.40	1.60
	G	71	June, 1st	Aug., 10th	0.97	0.28	1.72
Late flood season I	H	31	Aug., 1st	Aug., 31st	0.96	0.46	1.54
	I	41	Aug., 1st	Sept., 10th	0.97	0.38	1.62
	J	51	Aug., 1st	Sept., 20th	0.97	0.44	1.56
Late flood season II	K	20	Sept., 1st	Sept., 20th	0.98	0.49	1.51
	L	30	Sept., 1st	Sept., 30th	0.97	0.39	1.61
	M	40	Sept., 1st	Oct., 10th	0.97	0.38	1.62

of 0.01 in the pre-rainy season, while situation C largely differs. According to the principle that the box-counting dimensions in the same sub-season should have similar magnitudes while successive sub-seasons do not, A and B should belong to the same sub-season. So it can be concluded that the pre-rainy season is from May 1st to May 31st.

Similarly, the box-counting dimensions of situation D, E and F are close with a relative difference less than 4% in the main flood season, while G is rather different. Sohe main flood season is from June 1st to July 31st, situation F. In the late-flood season I, there is a discontinuous part due to the comparatively large difference between the box-counting dimensions of situation I and situations H and J. So situation H is regarded as one sub-season and the late-flood season I is from August 1st to August 31st.

Under such circumstance, the late-flood season in the conventional sense is divided into two sub-seasons, including the late-flood season I and the late-flood season II. When determining the length of the late-flood season II, the inflow record of the first ten days of October is added for calculation because it leads to inaccuracy when inflow record for conducting separation is short. In the late-flood season II, the box-counting dimensions of situation L and M are close while situation *K* differs largely. But situation M should be counted out because October is not included in the flood season. It can only be concluded that the late-flood season II is from September 1st to September 20th, and the remaining ten days until September 30th should be regarded as another sub-season if the fractal principle is strictly followed. However, to make it convenient for reservoir management and operation, the late-flood season II should be from September 1st to September 30th.

The above separation was based on the sequence of the largest daily inflows. The calculation results of Box-counting dimension and correlation coefficient are based on the sequence of the second and the third daily inflows which are shown in Tables 2 and 3. Although, the changing fixed flow value and different sequence daily inflow result in different capacity of the fractal dimension value in different sub-season, there is no difference for the relative relationship. That means, it has no influence on the result of the flood season division. The separation results based on the sequences of the second and third largest daily inflows are similar and consistent to sub-season result shown in Table 1, which proves that taking sequence of only the largest daily inflows as research sample is reasonable for separation. And the separation result is also similar to that of conventional statistical method and it is possible to make better use of the reservoir water storage for power generation or water supply.

2.4.3. Calculation of design floods of sub-seasons

In this paper, design floods of sub-seasons are calculated based on inflow records. According to Standard of Flood Control and Standard for Classification and Flood Control of Water Resources and Hydroelectric Project published by China's ministry of water resources, 1% flood and the 0.02% flood are standards for calculating design flood and checking flood frequency respectively for Hongfeng Reservoir. According to the separation result, this paper selected the "1996.5"flood for the pre-rainy season, two floods "1991.7"and "1996.7" for the main flood season, the "2000.8" flood for the late-flood season I and the "1970.9" flood for the late-flood season II as typical sequence of floods. The fractal method calculates design floods of all sub-seasons by the same-frequency amplification method.

2.4.4. Flood regulation and ranges of different sub-seasons

According to Design Report of Cascade Hydropower Station in Maotiao River released in 1987 by the Ministry of water resources and Guiyang Engineering Corporation, the flood control level of Hongfeng reservoir was set at 1236.0 m, the highest reservoir water level and the maximum discharge for the design flood 1% were 1239.97 m and 1420 m^3/s respectively, and for the check flood frequency 0.02% were 1242.58 m and 2450 m^3/s respectively. Three flood

Table 2
Box-counting dimensions of different flood sub-seasons(second flood peak)

Sub-seasons	Situation	T (days)	Starting date (m/d)	Ending date (m/d)	Correlation coefficient *R*	Slope *b*	Box-counting dimension *Dc*
Pre-rainy season	A	20	May, 1st	May, 20th	0.95	0.29	1.64
	B	31	May, 1st	May, 31st	0.96	0.32	1.65
	C	42	May, 1st	June, 11st	0.91	0.42	1.52
Main flood season	D	40	June, 1st	July, 10th	0.92	0.43	1.53
	E	50	June, 1st	July, 20th	0.94	0.41	1.64
	F	61	June, 1st	July, 31st	0.97	0.45	1.66
	G	71	June, 1st	Aug., 10th	0.91	0.29	1.72
Late flood season I	H	31	Aug., 1st	Aug., 31st	0.96	0.43	1.54
	I	41	Aug., 1st	Sept., 10th	0.93	0.39	1.55
	J	51	Aug., 1st	Sept., 20th	0.90	0.40	1.42
Late flood season II	K	20	Sept., 1st	Sept., 20th	0.98	0.42	1.58
	L	30	Sept., 1st	Sept., 30th	0.97	0.39	1.61
	M	40	Sept., 1st	Oct., 10th	0.94	0.28	1.76

Table 3
Box-counting dimensions of different flood sub-seasons (Third flood peak)

Sub-seasons	Situation	T (days)	Starting date (m/d)	Ending date (m/d)	Correlation coefficient *R*	Slope *b*	Box-counting dimension *Dc*
Pre-rainy season	A	20	May, 1st	May, 20th	0.93	0.29	1.71
	B	31	May, 1st	May, 31st	0.97	0.30	1.70
	C	42	May, 1st	June, 11st	0.95	0.41	1.58
Main flood season	D	40	June, 1st	July, 10th	0.92	0.40	1.46
	E	50	June, 1st	July, 20th	0.96	0.42	1.57
	F	61	June, 1st	July, 31st	0.98	0.40	1.59
	G	71	June, 1st	Aug., 10th	0.97	0.27	1.71
Late flood season I	H	31	Aug., 1st	Aug., 31st	0.97	0.46	1.54
	I	41	Aug., 1st	Sept., 10th	0.97	0.41	1.52
	J	51	Aug., 1st	Sept., 20th	0.97	0.44	1.51
Late flood season II	K	20	Sept., 1st	Sept., 20th	0.96	0.45	1.50
	L	30	Sept., 1st	Sept., 30th	0.97	0.38	1.62
	M	40	Sept., 1st	Oct., 10th	0.95	0.39	1.63

Table 4
Three flood operating rules for Hongfeng reservoir .

	Water level (m)	Rule 1# (planning)	Rule 2# (operating strategy released in 1987)	Rule 3# (operating strategy released in 1990)
(1)	1236.0–1236.5	Opening all four gates	Opening 1 central gate	Not opening gate
(2)	1236.5–1237.0		Opening 2 central gates	Opening 2 central gates
(3)	1237.0–1238.0		Opening 1 central gate and 2 side gates	Opening 1 central gate and 2 side gates
(4)	1238.0–		Opening all four gates	Opening all four gates

Table 5
Flood regulation result of the "July 1996" design flood

Frequency (%)	Initial operating water level (m)	Rule 1#		Rule 2#		Rule 3#	
		Highest water level (m)	Maximum discharge (m^3/s)	Highest water level (m)	Maximum discharge (m^3/s)	Highest water level (m)	Maximum discharge (m^3/s)
1	1236.00	1239.70	1289.65	1239.83	1336.44	1239.84	1340.90
	1236.60	1239.82	1331.18	1239.92	1368.73	1239.92	1368.73
	1236.90	1239.87	1351.60	1239.96	1382.52	1239.96	1382.52
	1237.00	1239.89	1358.31	1239.98	1389.41	1239.98	1389.41
	1237.40	1239.98	1388.79	1240.05	1412.97	1240.05	1412.97
0.02	1236.00	1242.35	2312.35	1242.41	2337.80	1242.42	2339.79
	1237.00	1242.49	2371.79	1242.52	2384.04	1242.52	2384.04
	1237.40	1242.56	2397.89	1242.58	2407.38	1242.58	2408.75
	1237.50	1242.57	2404.56	1242.59	2411.17	1242.59	2411.17
	1237.60	1242.59	2411.17	1242.60	2418.35	1242.60	2418.35

operating rules were applied to the design floods calculated based on different typical floods, specifically open-discharge rule 1#, operating rule (1987, 2#) and checking operating rule(1990, 3#), which are shown in Table 4.

One of the flood regulation results of the design flood calculated based on the typical flood "1996.7" is shown in Table 5. It shows that the highest reservoir water levels and the maximum discharges for the 1% design flood with all three flood operating rules are less than 1239.97 m and 1420 m^3/s respectively when the initial operating water level is below 1236.90 m or equal to it, and when operating from 1237.00 m, the highest reservoir water levels with Rule 2# and 3# (1239.98 m) are higher than 1239.97 m while the maximum discharges with all three rules are less than 1420 m^3/s. For the 0.02% check flood, the highest reservoir water levels and the maximum discharges with all the three rules are less than 1242.58 m and 2450 m^3/s respectively when the initial operating water level is below 1237.40 m, and when operating from 1237.50 m, the highest reservoir water levels of Rule 2# and 3# (1242.59 m) are higher than 1242.58 m while the maximum discharges with all three rules are less than 2450 m^3/s. So it can be concluded that the flood control level for the main flood season of the design flood calculated from the typical flood of July 1996 should be set lower than 1237.0 m.

3. Discussion

For each sub-season the lowest initial operating water level obtained with the three flood operating rules is selected to be the flood control level. For safety, it recommends that the flood control levels of pre-rainy season, main flood season, late flood season I and late flood season II should be raised 2.0 m, 0.8 m, 3.5 m and 3.7 m respectively as their upper limits. Li et al. [20] concluded that the reservoir had potential to raise its flood control level (1236.0 m) to 1236.8 m (May,1st–July 31th), 1239.1 m (Aug.1st–31th) 1239.4 m (Sept.1st–30th) according to statistical method based on its safety requirements. The control range of flood control levels in all four sub-seasons from the original value to its upper limit are shown in Fig. 5. There is a certain change of flood control level ranges for each sub-seasons with different method. In Fig. 5, the flood control level of 4 sub-seasons obtained are not the same as the main flood season and all the 4 different water levels are shown in Fig. 5. It shows that reservoir had potential to raise its flood control level (1236.0 m) to 1238.0 m (May 1st–31th) , 1236.8 (June 1st–July 31th), 1239.5 m (Aug. 1st–31th) 1239.7 m (Sept. 1st–30th)according to Fractal method which fall into the safety range. However, the separation result of the flood season of Hongfeng Reservoir by the fractal theory is similar to that of the conventional method, but it's more objective, more accurate and can be better used for the reservoir water storage. Based on the fractal method, flood control levels in the pre-rainy season and the late-flood season are higher than that of the statistics method, which can increase the operating water level of Hongfeng reservoir in the former and the later of flood season. In addition,the reservoir could release surplus water later and effectively store more water for drought after the flood season.

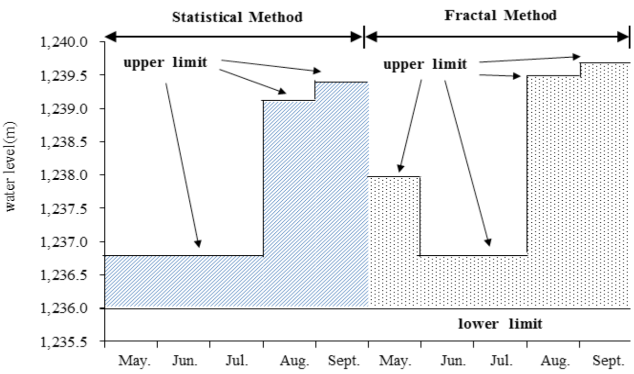


Fig. 5. Results of flood control levels of Hongfeng Reservoir by sub-seasons.

Moreover, with the separation results reservoir operation calculation is conducted and the results of generation (shown in Table 6) under flood sub-season control level is $6.625 \cdot 10^7$ kW·h, which is more than Original planning ($6.273 \cdot 10^7$ kW·h) and Actual case ($6.053 \cdot 10^7$ kW·h). Comparing with the original plan with a fixed flood control level at 1236 m and the actual case, the generation increase in percentage over the Original Planning and Actual Case are 3.95% and 9.45% respectively, showing sub-seasonal operation can increase the output, so as to obtain more economic benefits.

4. Conclusion

The aim of the separation of flood season of reservoir is to set up better flood regulation schemes, which can make better use of the surplus water in flood season and increase benefits. The sequence of daily inflow has a regular changing pattern and for different parts of the sequence there are different fractal dimensions, which represent their structural complexity. Therefore, it's reasonable to conduct the separation of flood season using fractal dimension as an indicator. The result of the fractal method is basically consistent with conventional empirical results. The fractal theory is mainly applicable to what is often featured with randomness nonlinearity, determinacy and similarity, where flood series have all these characteristics. Especially,

Table 6
Power generation increase with 2 methods over the original Plan and actual result

	Original plan	Actual case	Conventional statistical method	Fractal method
Electricity generated (10^6 Kw·h)	62.73	60.53	66.11	66.25
Absolute increase over the original plan (10^6 Kw·h)	/	/	2.38	2.52
Increase in percentage over the original plan (%)	/	/	3.73	3.95
Absolute increase over the actual result (10^6 Kw·h)	/	/	5.58	5.72
Increase in percentage over the actual result (%)	/	/	9.22	9.45

fractal theory has the quantitative and objective advantages with accurate and meticulous staging.

Fractal theory also provides a novel method to separate flood season in order to make better use of flood as water resources. This paper used the first three largest sequences of daily inflow as research samples for the fractal method to separate flood season into sub-season and compare the result with the statistical method to show a basic consistency. In addition, according to the sub-season result, the reservoir could release surplus water later and effectively store more water for drought after the flood season. Research significance can be shown by the follows: 1) Separating flood season into sub-season can make better use of flood as water resources; 2) Applying the fractal method to separate flood season into sub-season show a basic consistency with the statistical method and a validity; 3) By separating flood season into sub-season, we can increase the operating water level of Hongfeng reservoir in the former and the later of flood season and the reservoir could release surplus water later and effectively store more water for drought after the flood season; 4) Based on the separation, the calculation of power generation benefit of the phased operation shows that the total generation percentage benefits of reservoir increase by 3.95% and 9.45%; 5) In addition, for water shortage areas, water supply and ecological environment protection is particularly important.

This paper is mainly concerned about the separation of flood season for a reservoir by fractal theory, yet it also has a lot to do with the dynamic control of flood control level in flood season. Dynamic control of flood control level in flood season is an emerging field in which relevant researches are scarce, due to the deep-rooted conventional mindset that flood control level should be fixed in the whole flood season. But there still are a few researchers who have done some work of dynamic control of flood control level in flood season for a single reservoir, such as [21–23]. However, due to limited data and technical conditions and complexity of runoff, how to implement dynamic control of flood water level for cascade reservoir remains a challenge. The issues of duration length, effect on the upstream and downstream reservoirs, flood safety for the downstream, accuracy of flood forecasting information need to be addressed.

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