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Mechanism and Forecasting Methods for Severe Droughts and Floods in Songhua River Basin in China

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Abstract: The influence of various factors, mechanisms, and principles affecting runoff are summarized as periodic law, random law, and basin-wide law. Periodic law is restricted by astronomical factors, random law is restricted by atmospheric circulation, and basin-wide law is restricted by underlying surface. The commensurability method was used to identify the almost period law, the wave method was applied to deducing the random law, and the precursor method was applied in order to forecast runoff magnitude for the current year. These three methods can be used to assess each other and to forecast runoff. The system can also be applied to forecasting wet years, normal years and dry years for a particular year as well as forecasting years when floods with similar characteristics of previous floods, can be expected. Based on hydrological climate data of Baishan (1933–2009) and Nierji (1886–2009) in the Songhua River Basin, the forecasting results for 2010 show that it was a wet year in the Baishan Reservoir, similar to the year of 1995; it was a secondary dry year in the Nierji Reservoir, similar to the year of 1980. The actual water inflow into the Baishan Reservoir was 1.178×10^{10} m^3 in 2010, which was markedly higher than average inflows, ranking as the second highest in history since records began. The actual water inflow at the Nierji station in 2010 was 9.96×10^9 m^3, which was lower than the average over a period of many years. These results indicate a preliminary conclusion that the methods proposed in this paper have been proved to be reasonable and reliable, which will encourage the application of the chief reporter release system for each basin. This system was also used to forecast inflows for 2011, indicating a secondary wet year for the Baishan Reservoir in 2011, similar to that experienced in 1991. A secondary wet year was also forecast for the Nierji station in 2011, similar to that experienced during 1983. According to the nature of influencing factors, mechanisms and forecasting methods and the service objects, mid- to long-term hydrological forecasting can be divided into two classes: mid- to long-term runoff forecasting, and severe floods and droughts forecasting. The former can be applied to quantitative forecasting of runoff, which has important applications for water release schedules. The latter, i.e., qualitative disaster forecasting, is important for flood control and drought relief. Practical methods for forecasting severe droughts and floods are discussed in this paper.

Keywords: Songhua River Basin; runoff; drought and flood; forecasting

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1 Introduction

China is located in the monsoon region where the climate varies considerably. Due to the unique monsoon circulation of East Asia, the formation of which is influenced by geographical factors, sea and land location, and the Tibetian Plateau, rainfall in China is distributed unevenly in terms of season and location. Because of such variability, as well as anthropological impacts associated with the large human population, droughts and

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floods are frequent in China, occasionally resulting in serious disasters (Fan *et al*., 2008). Developing reliable methods of forecasting runoff anomalies would provide the government and relevant departments with crucial information that would facilitate planning and amelioration of damage due to natural hazards such as floods and droughts. Such forecasting methods would be of great practical significance.

A series of variables, such as astronomical factors, weather conditions, hydrology, geography, geology and human activity, can affect rainfall (Zhang and Fan, 1996; Huang and Jin, 2005). Climatic factors (rainfall and evaporation) are the most important variables that affect runoff (assuming no significant changes in the underlying surface) (Tang and Xiong, 1998). Runoff is the product of synoptic processes and climate conditions. Factors that cause short term climate change can affect water regimes in watersheds. Thus, short term climate forecasting is the theoretical foundation for predicting drought and flood disasters. Runoff is thus a main focus of hydrological research. In terms of long time scales, rainfall, runoff and evaporation are interacting factors within hydrological cycles that closely link hydrological and climate processes. In the late 1980s, the concept of hydro-climate was proposed for the first time. The main focus of hydro-climate forecasting was estimating trends in drought and flood events, according to total monthly rainfall, seasonal rainfall and annual rainfall, as well as the relationship between variations in hydrological characteristics and physical factors. The hydro-climate concept is different from mid- to long-term runoff forecasting of monthly and seasonal runoff changes, since it pays more attention to runoff anomalies, namely the two extreme cases: severe droughts and floods.

Long-term variation of hydrology and water regimes has been recorded as far back as the Han Dynasty in the 'Social Economy Commentary section of Historical Records'. During the Song Dynasty previous conditions were used as a basis for forecasting future water regimes, as described in 'History of Song Dynasty · the History of Rivers and Canals'. This marks the beginning of long term hydrological forecasting at its most rudimentary stage. Recent mid- to long-term hydrological forecasting, worldwide, started in the late 19th century and early 20th century (Fan, 1999) and was first applied to spring flood forecasting in the downstream reaches of the Nile River. Such forecasting was later widely used in some Europe and North American countries. In the 1930s, prediction of hydrological conditions in the Yangtze River Basin, based on previous records of prevailing atmospheric activity centers in East Asia, was carried out in China. In 1951, the method of 'historical development' was applied to long-term flood forecasting in the Yellow River Basin. It is worth mentioning that research into early drought and flood disasters was carried out by the meteorological department. Since the 1960s, with the development of climate science and the implementation of the Global Atmospheric Research Program by the World Meteorological Organization, knowledge of large scale atmospheric and climate processes has increased significantly, particularly relating to large-scale climatic conditions overtime scales longer than one month and one year. Nevertheless, these scales are still inadequate since only the atmospheric circulation is considered. In 1974, the concept of a climatic system was proposed for the first time at an international conference (Cao *et al*., 1982), entitled 'Physical Basis of Climate and Climate Modeling', in Stockholm, Sweden. On this basis, long-term weather forecasting concept, that had been based on time-scales of one month, season or year, or longer, was replaced by short-term climate forecasting. At this stage hydro-climate forecasting, under the auspices of water resources departments, came to be linked with advanced studies of hydrological cycles and climate processes and applied to the Yangtze River Basin for the first time (Huang and Jin, 2005).

Researches on drought and flood disasters in foreign countries focused mainly on simulation of uncertainty relating to hydrological phenomenon. For example, Chaotic theory was used to analyze the dynamic characteristics of the runoff time series (Breaford *et al*., 1991; Jayawardena and Feizhou, 1993; Jayawardena and Feizhou, 1994; Amilcare and Luca, 1997). The noise problem of runoff time series and its treatment were discussed by Sivakurnar *et al*. (1999) and wavelet transformation and fractal methods were used by Shozo *et al*. (1997) to forecast time series. Forecasting of drought and flood disasters is, however, rare. In some countries, particular emphasis is placed on the scientific exploration into the forming mechanisms of flood and drought disasters, performance law, and organization and management of disaster prevention and mitigation. However, it is imperative that China pays more attention to forecaste drought and flood disasters. This is mainly because of the great variety of differences, in terms of geographical environments, population and social development situations, between China and other countries.

Before the 1970s, there was a focus on the development of synoptic meteorological methods, mathematical statistics, and empirical methods for hydro-climate forecasting. With the development, after the 1980s, of short-term climate forecasting theory and methods, as well as the widespread application of computer networks, hydro-climatic forecasting entered a new development period. At present, the main forecasting methods involve mathematical statistics, physical statistics, long-term numerical forecasting, and statistical-dynamic forecasting.

Mathematical statistics method considers the variation law of hydro-climate implied by an examination of historical data. Commonly applied in the 1970s, the historical evolution method was the first mathematical statistics method used for forecasting. People soon found that there was a high degree of fitting when the method was used for historical simulations but its precision was too low for actual forecasting. Lack of physical cause analysis is a disadvantage of mathematical statistics forecasting, which can not be overcome. Nevertheless, the mathematical statistics method is still used universally. A large number of stochastic simulation methods have been developed: time series analysis (Box *et al*., 1976), blurred theory (Wang, 1992), stochastic simulation (Zhao *et al*., 1998; Li *et al*., 1999; Wang *et al*., 2005; Li *et al*., 2006; Lin and Cheng, 2006) and grey theory (Xia, 1993; Chen and Li, 1996).

The main factors, and the evolutionary process, that affect drought and flood trends are becoming clear. Physical statistics method was studied based on climatic system theory, through research into the physical factors that affect climate change, such as sea water temperature (Lu, 1950; Lu, 1951; Reid, 1987), the geothermal state of the Qinghai-Tibet Plateau (Ye, 1952; Ye and Gu, 1955; Ye *et al*., 1957; Huang, 1979; Huang *et al*., 1985; Huang, 1986), solar activity (Weng, 1963; Geophysical statistical forecasting group of Peking University, 1973; Wang, 1978; Friis-Christensen and Lassen, 1991), and seasonal variations in atmosphere circumfluence (Tao *et al*., 1958; Wang, 1973; Si *et al*., 1974). Drought and flood characteristics and the variation law are preliminarily determined through researches into variation trends of physical factors. Various statistical methods, such as regression analysis (Tang *et al*., 2007; Cao *et al*., 2009), intelligent algorithm simulation, and artificial neural networks (Hsu *et al*., 1995; Hu *et al*., 1995; Huang *et al*., 2004) are used. In 1975, the original Lanzhou Institute of Plateau Atmospheric Physics of Chinese Academy of Sciences used ground temperature to forecast rainfall in the flood season in China (Tang *et al*., 2004). Results showed that the following systems can reflect interactions between atmospheric systems and territorial systems: a geothermal vortex (Tang and Gao, 1995a; 1995b), an underground cold vortex, a deformation front, and others that together are referred to as a ′territorial-atmospheric map′ (Tang, 1998). Variation laws of territorial-atmospheric maps are used to forecast climate with better results (Xin, 1985; Tang *et al*., 1989; Tang *et al*., 1997). In 1982, Peng *et al*. (1982) undertook the research into the reliability of geophysical factors as predictors of rainfall and temperature, using a correlation coefficient test and regression analysis; he compared forecasting results with two different time scales, of 72 years and 24 years, respectively. The results of the research indicated that, compared with short series of samples, geophysical factors have a predominant influence on long-term simulations. In a way, this also confirmed that factors outside the hydrological cycle system have a long term and deterministic influence on runoff. In short, this method takes physical factors and their mechanisms into account and, as a result, helps to overcome the dependence on mathematical statistics. Due to complicated mechanisms relating to physical factors, however, some problems need to be further researched.

Long-term numerical forecasting method, whose framework relates to atmospheric dynamics equations and ocean dynamics equations, is based on kinetic theory. This method was first proposed and performed before the 1950s, but it ended in failure and it is still in the pilot phase. Theoretically speaking, the lack of consideration of astronomical factors that affect the climate process represents one of the problems associated with this method (Tang *et al*., 2004).

Statistical-dynamic forecasting method tied to select some important variables of dynamical equations, such as kinetic energy, heat energy, water vapor conditions, ocean and atmospheric conditions, and geothermal conditions, as forecasting factors. A forecasting model was then built up, based on statistical methods. At present, it is difficult to deal with dynamic variables, which ultimately affects practical application of this method.

Based on basic principles of the hydrological cycle, and the achievements of short-term climate theory, this paper identified the main physical factors and their performance laws that led to runoff anomaly. Combined with the hydro-climate characters of the study area, forecasts of droughts and floods were formulated by means of comprehensive analysis.

2 Mechanism Analyses

Research into the climatic factors affecting the distribution of water resources in time and space, laws of climate change, and catastrophic impacts on humankind's living environment, are the concerns of hydro-climate study. The spatial scale of this research is the river basin, and the time scales are month, season and year (Marlyn, 2008). Information extracted from the law of the influencing performance can be used to summarize the time-based runoff evolution, according to the way in which physical factors and their sources and laws of performance affect the hydrological cycle and runoff.

2.1 Physical factors

A series of factors can affect the formation of runoff. The different sources of these factors, spheres of influence, and degree of influence need to be examined.

(1) Astronomical factors

Astronomical factors originate outside the hydrological cycle system and refer mainly to solar activity. Relative sunspot number is selected as a deliberated index. The activity of sunspots on the solar disk is very regular with a remarkable 11-year cycle. The polarity of the sunspot magnetic field in the adjacent 11-year cycle is opposite. The cycle mentioned above is called the magnetic cycle. The 11-year cycle is called the positive (negative) half period of the 22-year cycle. Thus the effect rule of astronomical factors relates to its periodicity.

(2) Atmospheric circulation

Weather and climate process are direct products of atmospheric circulation**.** All physical factors impact on the climate through their influence on distribution of atmospheric circulation and variation characteristics. Large-scale (hemisphere, even worldwide) and long-term (seasonal) atmospheric circulation variation are essential to hydro-climate variation. This includes variation in the location of the action centre of the atmosphere and seasonal myriametric wave, as well as teleconnection of atmospheric circulation in space (three main oscillations) and the quasi-periodical oscillation and circulation law in time. A monthly mean circulation map of the northern hemisphere, or of the whole planet, is the most common circulation data used. Due to frequent thermal exchange between atmospheric circulation and the land-sea system, the effects of these factors are obviously random.

(3) Underlying surface characteristics

The underlying surface is where runoff develops and where all physical factors interact. Geographic position, the relationships between land and sea, topography, vegetation cover, land use, and the distribution patterns associated with human activities reflect underlying surface characteristics. Such characteristics are relatively stable for specific periods, during which time the influence of above factors have some consistency in runoff.

2.2 Hydrology-climate process

Differences occur in the mechanism of action and performance of each factor affecting the hydrology-climate processes. The interactions and combined influence of such factors are influenced by three different time scale variations in hydrology-climate processes (Huang and Jin, 2005).

(1) Inter-decadal variation The time scale varies from 26 months to 80–90 years. The possible physical causes are quasi-biennial oscillation of atmospheric circulation, ocean-atmosphere interaction (ENSO cycle), solar activity, and dry-wet changes in climate.

(2) Seasonal variation The time scale of seasonal variation varies from 3–6 months or 6–12 months. The physical causes are variation of atmospheric action center, interactions between earth and atmosphere, and variations in solar radiation.

(3) Low-frequency vibration of atmospheric circulation The time scale varies from 2 to 6 weeks. The physical cause of such vibration relates to the myriametric wave vibration and the atmospheric energy cycle.

2.3 Three main laws affecting runoff

Through the above analysis, the laws affecting runoff can be summarized into three categories. 1) Periodic law considers the effects that can be repeated in cycles.

These are normally astronomical factors. 2) Random law includes the factors that can be subject to random effects, mainly atmospheric circulation. 3) Basin-wide law is affected by basin-wide factors, mainly underlying surface characteristics.

The periodic law is the main law among the three laws, which reflects the basic state of hydro-climate processes. The random law interferes with the basic state of hydro-climate process leading to fluctuations. The basin-wide law reflects the combined action of all the laws, particularly in different river basins. The hydro-climate performance in a river basin, which is affected by the above laws, can be expressed as follows:

Hydro-climate process = *f*(*periodic law*, *random law*, *basin-wide law*) (1)

where, periodic law indicates periodic basic state; random law indicates random fluctuations; and basin-wide law indicates character of a river basin.

3 Forecasting Methods

3.1 Identification of periodic law

Research and practice show that the commensurability method can reveal the periodic law of runoff. Weng (1984) founded the forecasting theory, which was based on information forecasting; the commensurability forecasting method proposed by weng has advantages such as simple calculation, intuition, and effective information that involve a minimum level of distortion. Commensurability can be seen as a kind of natural order, an information system, and a cyclical expansion.

3.1.1 Commensurability

According to Weng *et al*. (1996), commensurability can be expressed as follows:

$$X_i = \sum_{j=1}^{L} (I_j X_{i_j}) + \varepsilon_0 \tag{2}$$

where $i_j \in \{i\}$, and $i_j \neq i$, that is to say i_j is an element that is different from i in the subscript set $\{i\} = \{1, 2, \ldots, n\}$; X_{i_j} is an element of $\{X\}$, which is different from X_j; I_j is an integer; L is the unit of commensurability; and ε_0 is the pre-determined feasibility threshold.

Equation (2) reveals the ′commensurability principle′, that is to say all real objects and all events are composed by their basic units, so they can be numbered. Some events can only happen time and again, and can not occur for half of the time. If the entity can be expressed by the function, it will not be continuous, so it can not be differential.

3.1.2 Commensurability and periodicity

Xu (2010) compiled the unpublished paper, ′From periodicity to commensurability′ written by Weng. The paper states that commensurability is the expansion of periodicity.

For a time variable $y(t)$, if there is p satisfying the following equation.

$$y(t+p) - y(t) = 0 \tag{3}$$

where p is regarded as a cycle. If there is a time interval ε_0, which makes the following equation true.

$$|y(t+p') - y(t)| < \varepsilon_0 \tag{4}$$

where p' is an almost period. If the almost period has physical meaning, then ε_0 must be less than a certain confidence level, thus denying its occasionality.

If the time variable $y(t)$ is reduced to one of its discrete special sections, time series $y(i)$, while the unary relation is extended to the multivariate polynomial, and there is:

$$\left|\sum a(i) \times y(i)\right| < \varepsilon_0 \tag{5}$$

where $a(i)$ is an integer, then the discrete time series $y(i)$ has an almost commensurability, and ε_0 is the same as the former. If $\varepsilon_0 = 0$, then $y(i)$ also has a commensurability.

For a periodic time series, there is a strictly maintained distance between each cycle. The relationship between each point and the periodicity in the time series collection has changed greatly after the degradation and expansion of the periodicity. Periodicity is only an extreme situation of the commensurability.

For hydrological disaster forecasting in practical application, the reader is encouraged to examine the detailed treatise by Xia (1991) for further information on how to examine the applicability of commensurability methods and ordinary steps for forecasting runoff.

3.2 Deduction of random law

The factors that affect random law are derived from the inner hydro-climate system. The interactions and feedback among the factors are complex. A series of factors affect random law, the mechanism of action is complicated, and none of the physical factors provides fundamental reasons that lead to randomicity (Wang, 1993). Practical study indicates that there are three situations: wet and dry years appeared in turn, wet years occur continuously for several years in an almost period, and dry years occur continuously for several years in an almost period. Though fluctuations exist, the tendency and range of such fluctuations have an obvious regularity. In an almost period, a complete fluctuation is called a cycle and small fluctuations are called waves. In the case of the Nenjiang River Basin and the Second Songhua River Basin in the text that follows, the cycle numbers in an almost period and the wave numbers conform to regularity. Thus, the random law can be studied by counting the number of cycles and waves, as mentioned above. The random forecasting methods can forecast the tendency of severe droughts and floods in an almost period.

Cycle and wave analysis need to combine with the process of runoff, the years of peaks and valleys, magnitude of discharge, and duration. In addition, the character of atmospheric circulation in a certain year, such as the position of a ridge of subtropical high, the northern boundary of the subtropical high, polar vortex area, polar vortex intensity index, the intensity of east Asian Trough and sea surface temperature (ENSO, La Nina phenomenon), should receive particular attention.

3.3 Basin-wide law analysis

The amount of water vapor condensation is the direct cause affecting severe droughts and floods. The formation and transformation of water vapor are prerequisites for the complex process of condensation of water vapor. Consequentially, there are precursors while water vapor accumulates in time and volume.

The river basin, which is significantly affected by the characteristics of the underlying surface, can directly respond to various physical factors and this is eventually indicated by severe droughts or floods. In spite of numerous physical factors and the complicated response mechanisms of the underlying surface, this kind of response abides by the laws of consistency, while taking no account of stochastic problems (Han, 2007) relating to the hydrological cycle system, i.e., there is homoplasy between input and response.

The presentation of precursors to water vapor condensation is extremely complicated. In general, experience is the most useful method for summarizing complex laws. Proverbs handed down for thousands of years often represent the experience of previous communities. People can judge whether there is a severe flood in a particular year through observations of the precursors that have been seen in the same year. In this way, they are able to forecast the flood magnitude.

Some ancient proverbs, such as, 'It will be rainy if there is water flowing on a willow tree in spring in Jilin area'; 'there will be rain in July or August if it is cold in May and hot in June'; and 'there will be floods if it is cold in spring, and there will be droughts if it is warm in spring', can help us to forecast the floods that occurred on the Second Songhua River (Xiong, 1991). In addition, there are also some proverbs for forecasting the floods in the Nenjiang River Basin: 'there will be little rainfall in summer if there is heavy snow in winter'; and 'there will heavy rain in autumn if there is little rainfall in spring'.

The mechanisms and forecasting methods for severe droughts and floods are shown in Table 1.

From the service perspective, the forecasting of severe floods and droughts are entirely different from mid- to long-term runoff forecasting. The former focuses on providing disaster information on severe floods or droughts for the purpose of assisting decision-making departments. Qualitative forecasting of wet years, normal years, and dry years can also help to determine the nature of disaster reduction programs. The latter strategy is aimed at developing a detailed dispatching distribution program for production sectors, such as power generation, irrigation, water supply and other departments, noting that quantitative forecasting based on process is operable. There are three levels of qualitative forecasting: wet years, normal years, and dry years. In the case of flood forecasting, information is also provi-

Table 1 Mechanisms and forecasting methods for severe droughts and floods

Law	Source	Method	Effect
Periodic law	Astronomical factors	Commensurability	Identify the disaster years (error of one or two years)
Random law	Atmospheric circulation	Wave methods	Deduce the trend of droughts or floods in an almost period
Basin-wide law	Underlying surface character	Precursor method	Forecast the runoff magnitude of current year

ded on the years when similar conditions prevailed, as managers can then learn from historical experience relating to the flood process and disaster conditions.

4 Case Study

4.1 Study area

The Songhua River Basin is located at the northern margin of the East Asian monsoon region, so its rainfall changes dramatically during an annual cycle, but is mainly concentrated around the flood season (June to September). Rainfall during the flood season accounts for more than 70% of total rainfall. It also has a large inter-annual variation, obvious gradual trends, and floods and droughts happen alternately. Summer rainfall is affected by the East Asian monsoon and by the mid and high latitude westerly circulation. The changing rate of climate is therefore large and impact factors are complex (Bai and Li, 2001). The Songhua River is formed by the confluence of the southern tributary, the Second Songhua River, and the northern Nenjiang River tributary. The length of the Songhua River Basin (north to south) is larger than the width (west to east), so latitude differences cause significant differences in climatic conditions in the two river basins. On the other hand, the Songhua River Basin is sheltered by hills from three directions: mountains have a great impact on the weather system in respect of moving path and stagnation periods as well as rainstorm formation and spatial-temporal distribution. As a result, a number of characteristics, storm flood characteristics, the type of weather causing rainstorms, the magnitude of rainstorms, and spatial-temporal distribution, are very different in the Nenjiang River Basin and the Second Songhua River Basin. Results from this studies showed that the Second Songhua River and the Nenjiang River belong to different weather systems, and atmospheric circulation factors affecting storm flood are also different. Rainfall in the Second Songhua River is mainly affected by the conditions in the south, such as typhoons, Hetao cyclone, low pressure systems from North China, and the Changjiang-Huaihe cyclone. When the Western Pacific subtropical high is generally strong, rainfall in the Nenjiang River is affected by the northern system, such as Mongolian cyclones and low pressure systems in Lake Baikal (Li *et al*., 2002).

4.2 Data sources

We monitored conditions in the Nierji Station in the Nenjiang River Basin and the Baishan Station in the Second Songhua River Basin; historical data (1933–2009) of annual runoff for the Second Songhua River Basin was provided by Baihan Power Plant of State Grid Xin Yuan Company Limited. Runoff data of the Nenjiang River Basin was provided by the Hydrological Bureau of Songliao water resources Committee. All data were compiled after corrective computation.

4.3 Periodicity identification

The classifying standards used to define severe droughts and floods in a river basin are in accordance with 'Hydrology information forecast norms' (GB/T 22482-2008). This system makes use of five grades to classify runoff, according to runoff anomaly (as a percentage of annual runoff minus annual average runoff, divided by annual average runoff) (Table 2).

Table 2 Standard classification of annual runoff

Grades	Anomaly (%)
Dry years	Anomaly < –20
Secondary dry years	–20 ≤ anomaly < –10
Normal years	–10 ≤ anomaly ≤ 10
Secondary wet years	10 < anomaly ≤ 20
Wet years	Anomaly > 20

Notes: Secondary wet year, runoff is more than that of a normal year and less than that of a wet year; secondary dry year, runoff is more than that of a dry year and less than that of a normal year; severe drought years are defined as dry years and severe flood years as wet years

4.3.1 Commensurability analysis

Commensurability analysis is generally used to examine whether hydrological disaster information can be identified by means of the commensurability method. There are usually three test indictors: commensurability coefficient m, error intervals of almost period $[-\varepsilon, +\varepsilon]$, and commensurability reliability. Theoretically, the larger the commensurability coefficient m, the more reliable is the forecasting; the smaller the error ε, the more reliable is the forecasting. It is also generally required that the time error ε is less than one year for hydrological disaster analysis. If the mean value of commensurability coefficients for measured series is $\overline{m}$, and the commensurability coefficient for forecasting series is m, then the set of $m/\overline{m} > 50\%$ is selected to forecast hydrological disasters. The commensurability network chart (Fig. 1) of flood years in Baishan is taken as an example for discussion on commensurability. It can be seen from Fig. 1 that transverse and vertical commensurability relationships can be built that satisfy the inequality $m > 1$. From transverse and vertical views, it can be seen that the almost period is 10, the error is [–1, +1]; and commensurability reliability is far above the requirement of 50%. Thus, the commensurability method can be applied to identify the almost period for hydrological disaster information. It is therefore not necessary to use other network charts to get this information.

4.3.2 Commensurability network chart

The use of the commensurability forecasting method enables a comprehensive analysis of annual runoff data of the Baishan and the Nierji reservoirs. If the vertical and horizontal axes of the flood time interval chain represent time axis, this can be used to construct a commensurability network chart of flood years (Fig. 1 and Fig. 2 for flood years in the Baishan and Nierji reservoirs, respectively). Dry years for these two basins are illustrated in Fig. 3 and Fig. 4, respectively.

It can be seen from Fig. 1 that flood years in the Baishan Reservoir have an obvious cycle of 10 years. We can thus infer the next high-incidence years of floods. The vertical is 2005 + 5, 6, 7 = 2010, 2011, 2012, and the horizontal is 2001 + 9, 10, 11 = 2010, 2011, 2012, so high-incidence years of floods can be expected in 2010, 2011, and 2012. From Fig. 2, flood years in Nierji have an obvious cycle of 22 years, thus enabling forecasts of the next high-incidence flood years. The vertical is 2009 +3, 4 = 2012, 2013, and the horizontal is 1991 + 21, 22 = 2012, 2013. By these means the high-incidence flood years are inferred.

Figure 3, which indicates dry years in Baishan, has an obvious cycle of 10 years: the years ending with 2 or 8, such as 1952 or 1962, were dominated by drought. This was the case from 1942 onwards, except for the years 1949 and 1970. To infer the next high-incidence year for droughts, the vertical is 2008 + 4 = 2012, and the horizontal is 2002 + 10 = 2012, so the next high-incidence year of drought is predicted to be in 2012. Figure 4 indicates that dry years in Nierji have a cycle of 22 years. The vertical axis indicates 2008 + 3, 4 = 2011, 2012, and the horizontal are 1990 + 21, 22 = 2011, 2012, so the high-incidence year for droughts is 2011 or 2012.

It should be noted that, according to drought and flood forecasting at the Baishan and Nierji stations, 2012 is the year with a high expected occurrence of both floods and droughts, so precursors and other indicators are needed to synthetically analyze drought or flood forecasts.

4.4 Deduction of randomicity

Annual flow hydrographs of Baishan and Nierji stations are shown in Fig. 5 and Fig. 6. This paper separates cycles into major cycles and minor cycles, based on the analysis of hydrological laws of annual runoff at Baishan Station. The major cycle has an average of 30 years which can be divided into three minor cycles with an average of 10 years, namely wet years, normal years and dry years. The ′cycle′ begins with the ′valley′ of annual runoff, and the ′wave′ can be judged by peaks of annual runoff, with one peak consisting of one ascending wave and one descending wave.

Major cycle: 1949–1978 (29 years), and 1978–2008 (30 years); Minor cycle: 1949–1958 (9 years, wet years), 1958–1970 (12 years, normal years), 1970–1978 (8 years, dry years), 1978–1988 (10 years, wet years), 1988–1998 (10 years, normal years), and 1998–2008 (10 years, dry years). Each minor cycle can be divided into two peaks and four waves, namely two peaks of water-coming years. The ascent stage of the first peak is referred to as the ′first ascending wave′, and the descent stage as the ′first descending wave′. Similarly, the ascent stage of the second peak is referred to as the ′second ascending wave′, and the descent stage as the ′second descending wave′.

Figure 5 indicates an obvious 30-year major cycle and a 10-year minor cycle of annual runoff at the Baishan hydrological station, as well as two peaks and four

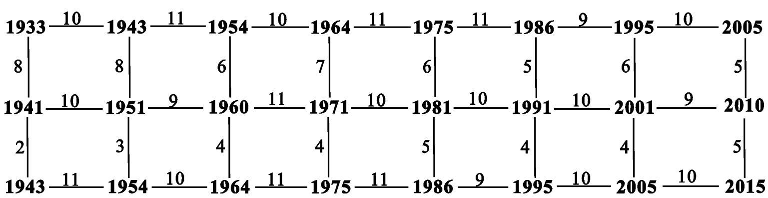


Fig. 1 Commensurability network chart of flood years in Baishan Reservoir

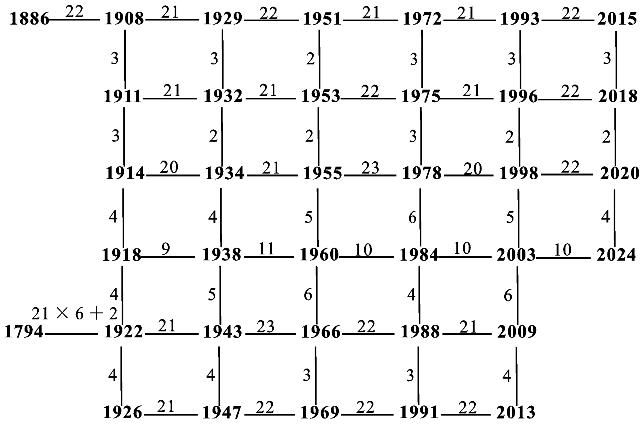


Fig. 2 Commensurability network chart of flood years in Nierji Reservoir

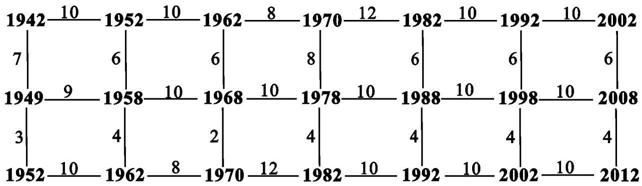


Fig. 3 Commensurability network chart of dry years in Baishan Reservoir

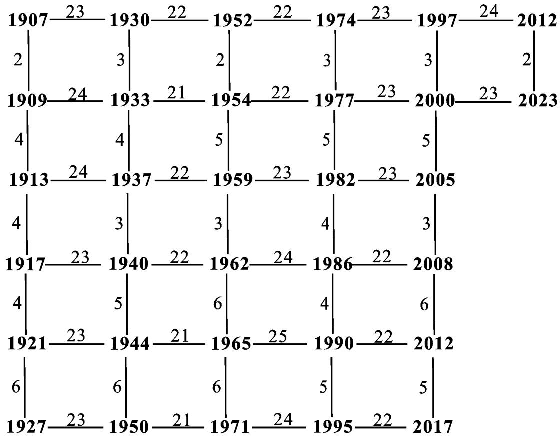


Fig. 4 Commensurability network chart of dry years in Nierji Reservoir

waves in a minor cycle. The year of 2010 is located in the first ascending wave of the first peak.

By analyzing the annual runoff at the Nierji Station, it can be seen that there is also a major cycle of 30 years, which is as also the case at the Baishan Station, but other laws are not the same as Baishan Station. Major

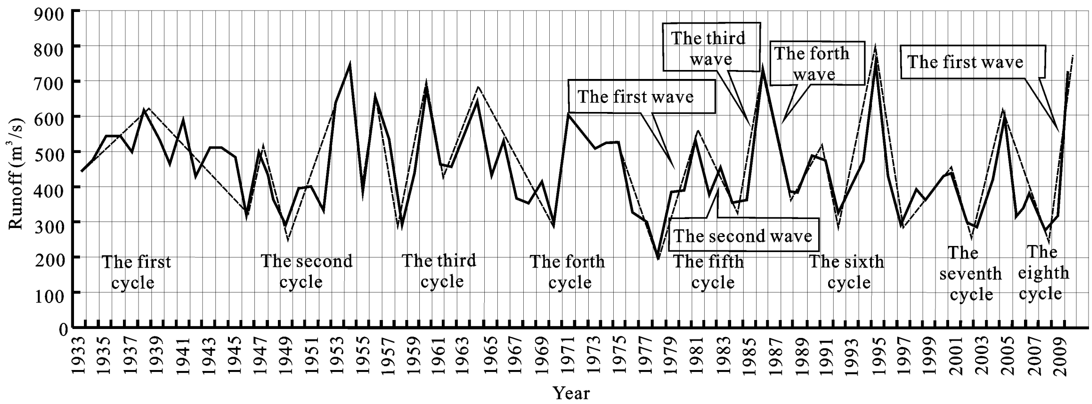
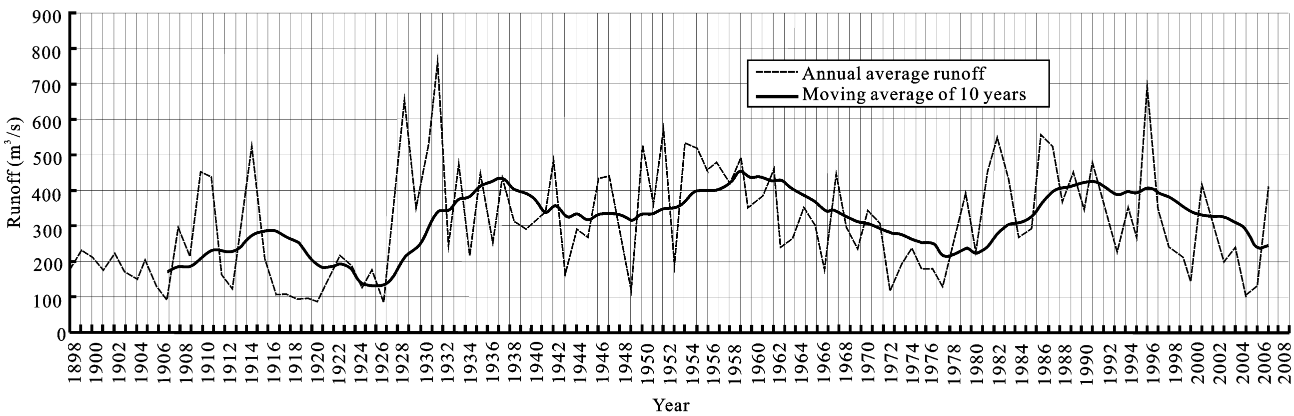


Fig. 5 Changing trends of annual runoff at Baishan station in an almost period



The computational method of moving average of 10 years: the value of 1907 is the average from 1898 to 1907, and the rest can be deduced by analogy

Fig. 6 Changing trends of annual runoff at Nierji station in an almost period cycle: 1920–1950 (30 years), 1950–1979 (29 years), and 1979–2008 (29 years). Results shown in Fig. 6 indicate that the runoff at the Nierji Station can be generalized to fit a pattern of seven peaks, seven valleys and 14 waves in a major cycle. The year of 2010 is located in the first descending wave.

4.5 Analysis based on precursors

Water flowed on the willow tree in early and mid June 2010 in Huadian City (Jilin Province) where Baishan station is located. This is a traditional proverb, meaning that such an observation can be taken as a precursor to the occurrence of severe floods. No such observations were noted (i.e., no such precursors were seen) in the Nenjiang River Basin.

4.6 Forecasting results

A summary of the mechanism, corresponding forecasting methods, and the forecasting results for the Second Songhua River and the Nenjiang River in 2010 is provided in Table 3. 1) 2010, 2011 and 2012 are the years when floods are most likely to occur at the Baishan hydrological station. The 2010 runoff at this station forms part of the first ascending wave of the 8th cycle. In addition, the spring floods and the observation of ′water flowing in the willow tree′ are very obvious occurrences in the Huadian City. Thus, this paper forecasts that 2010 is a wet year, similar to 1995. 2) 2012 and 2013 are the years when floods are most likely to occur at Nierji Sation. The 2010 runoff at this station forms part of the intermittent valley of the second wave. The spring floods and other observations described in ancient proverbs are not obvious in 2010. So this paper forecasts that water flow in 2010 would be a little less than normal, similar to conditions in 1980. The above forecasting results are true according to the actual incoming water of the Second Songhua River and the Nenjiang River in 2010.

5 Conclusions

The actual inflowing water of the Baishan Reservoir is 1.178×10^{10} m^3 in 2010. This is markedly more than the average over many years and it ranks as the second highest in recorded history. The actual water inflow at the Nierji Station was 9.96×10^9 m^3 in 2010. It is a little less than the average over many years. From these results we can come to the preliminary conclusion that the methods proposed in this paper have been proved to be reasonable and reliable.

This paper also provides forecasting results for 2011. The Baishan Reservoir entered a new major cycle in 2008. We forecasted wet years that were expected from 2008 to 2018 (namely the eighth minor cycle). The years of 2009 and 2010 represented the first ascending wave, 2010 the first peak, and 2011 the first descending wave. Moreover, the year of 2011 is not a node on the network chart of neither severe floods nor severe droughts in Baishan. This means that 2011 is not an extreme year in Baishan. Considering that 2010 was a rather wet year, it means that abundant water would have filtered down to the underlying surface in the previous period. The runoff coefficient would also be larger. Thus this paper forecasts that 2011 will be a secondary wet year, similarly to conditions during 1991. The Nierji Reservoir also entered a new major cycle in 2008. The year of 2009 is the ascending wave of the first peak, and 2010, belonging to a normal year, is the descending wave of the first peak. The year 2011 is the ascending wave of the second peak, is not node on the network chart and, in Nierji, is neither a severe flood year nor a severe drought year. It also means that 2011 does not indicate an extreme point. So the runoff of 2011 is slightly higher than that of normal years and less than that of wet years. This paper forecasts a secondary wet year, similar to 1983. The analysis only represents a preliminary conclusion, and the forecasting result will later

Table 3 Forecasting results of droughts and floods in Songhua River Basin

Laws	Methods	Forecast results	
		The Second Songhua River (Baishan station)	The Nenjiang River (Nierji station)
Periodic law	Commensurability	Severe flood years: 2010, 2011, 2012 Severe drought year: 2012	Severe flood years: 2012, 2013 Severe drought years: 2011, 2012
Random law	Wave method	The first ascending wave of the 8th cycle	Intermittent valley of the second wave
Basin-wide law	Precursor method (Associated with ancient proverbs)	Water flows on the willow trees	No obvious precursor
Comprehensive forecasting results of 2010		Wet year, similarly to 1995	Water is a little less than normal, similarly to 1980

be revised according to spring floods and other indices before floods.

In terms of the applicability of mid- to long-term hydrologic forecasting methods, the commensurability method was mainly applied to forecasting the node years. Even if it is a node year, there will be a time error of one year or more due to almost periodic property. Therefore, verifying and revising the method should be researched in the future.

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