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Long-term Forecasting of Extraordinary Spring Floods by Commensurability Method on the Dnipro River Near Kyiv City, Ukraine

Borys Khrystiuk*, Liudmyla Gorbachova
Ukrainian Hydrometeorological Institute, 37, Nauki Prospect, Kyiv-28, postal code 03028, Ukraine

***Corresponding author:** khryst@uhmi.org.ua

Kyiv is the capital of Ukraine, as well as its major administrative and industrial centre. Kyiv is located in the middle reaches of the Dnipro River, which is the largest river in Ukraine. In the past, Kyiv suffered from dangerous spring floods. Consequently, long-term forecasting of spring floods on the Dnipro River near Kyiv has an important scientific and practical significance. Existing quantitative methods for such forecasting are of limited forecast lead time and require many input hydrometeorological data. In the paper, the information method Weng Wen-Bo is applied, which is a qualitative forecasting method. The use of such a method allows determining the periods and specific years in which the following extraordinary spring floods on the Dnipro River near Kyiv can occur.

Keywords: extraordinary spring floods, long-term forecasting, method Weng Wen-Bo, commensurability.

Introduction

Long-term hydrological forecasts of spring flood are necessary for efficient management of water resources and hydrotechnical structures, mitigation and decrease of the territories' flooding consequences during extraordinary floods. Hydrological forecasting uses two main approaches: statistical and deterministic. The statistical approach considers the process of formation of spring flood as random. The deterministic approach is based on the analysis of factors and conditions of the flood formation (WMO, 2009). At present, methods of long-term forecasting are divided into quantitative and qualitative (Peng et al., 2017). The quantitative methods can be called the traditional methods, which are usually used for forecasting. They use statistical methods, correlation and regression analysis, etc. (Apel et al., 2004; Shevnina, 2009; Khrystyuk, 2012; Scitovski et al., 2012; Khrystyuk et al., 2017). Hydrological forecasts with the warning lead time on one year, two years, or a decade have low accuracy. The qualitative approaches are used to reduce such a disadvantage (Hongyan et al., 2011; Su et al.; 2015; Peng et al., 2017). In general, long-term forecasting of extreme natural phenomena (catastrophic floods, droughts, earthquakes, etc.) remains an unresolved problem in the world to this day. However, in 1984, the Chinese scientist Weng Wen-Bo proposed a method of long-term forecasting, which was called the information method. This method uses the dates in which the values of extreme natural phenomena were observed (Weng, 1984). Method Weng Wen-Bo is characterised by calculation simplicity, graphical visualisation and the use of the researcher intuition.

On basis of the Weng Wen-Bo method, the dates of several large earthquakes on the territory of China, Japan and USA were successfully forecasted (Su et al., 2015). The Weng Wen-Bo method was also used for forecasting the wet and dry years in the Songhua River basin and the floods in the northeast of China (Hongyan et al., 2011; Peng et al., 2017).

Kyiv is the capital of Ukraine, located on the Dnipro River (Fig. 1). A spring flood is a typical feature of the hydrological regime of the Dnipro River, which is observed every year. In this period, the largest discharges occur, which can lead to catastrophic consequences. On the Dnipro River, the formation conditions of spring floods are quite various and complicated. It is determined by many factors (climatic, geomorphological, anthropogenic, etc.) in the basins of such large rivers as Upper Dnipro, Pripyat and Desna. In general, near Kyiv, this occurs as follows. The spring flood peak of the Upper Dnipro and the flood peaks of the rivers Berezina and Sozh are consistently joining.

Fig. 1

Fragment of the Dnipro River Basin

Then, in the upper reaches of the Kyiv reservoir, these are consistently joined with the spring flood peaks of the rivers Pripyat and Teteriv. After the Kyiv reservoir, this common peak combines with the flood peak of the Desna River. The value resulting peak depends on the values of all individual peaks of the rivers.

On the Dnipro River near Kyiv according to archival data and hydrometric observations, several extraordinary spring floods were recorded. During these floods, water from the river was flooding the floodplain, which caused destruction of urban infrastructure, houses, and sometimes human casualties. From such spring floods, the left-bank part of Kyiv city was particularly affected (Khrystiuk, 2018). In 1970, on the Dnipro River near Kyiv city, the last dangerous spring flood was observed. After the flooding of 1970, 48 years have passed. The statistics of former floods indicate that the probability of occurrence of the next extraordinary flood is increasing every year. Thus, on the Dnipro River near Kyiv, the forecasting of occurrence of extraordinary spring floods is an actual task.

In Ukraine, the existing methods of forecasting maximum discharges of spring flood are based on the traditional approach, i.e., the use of quantitative methods (Shakirzanova, 2011; Sosedko et al., 2011; Kholoptsev, 2011). For the Dnipro River, the long-term forecast of spring flood is created at the end of winter and has the warning lead time of 2–3 months (Shakirzanova, 2011). To produce such a forecast, it is necessary to use fairly large volumes of hydrometeorological information. At the same time, an approach of long-term forecasting that uses quantitative methods (statistical methods, correlation and regression analysis, etc.) do not allow increasing significantly the warning lead time of the forecast. They cannot also answer the simple question: when will the next dangerous spring flood be observed on the Dnipro River near Kyiv?

The objective of this paper is to use the Weng Wen-Bo information method for long-term forecasting of extraordinary spring floods and to determine the possible years in which these floods will occur on the Dnipro River near Kyiv.

Methods

In the 1766, German physicist and mathematician I.D.Titius discovered that the distance of the solar system planets from the Sun (R_n) (Fig. 2) obeys a simple empirical rule:

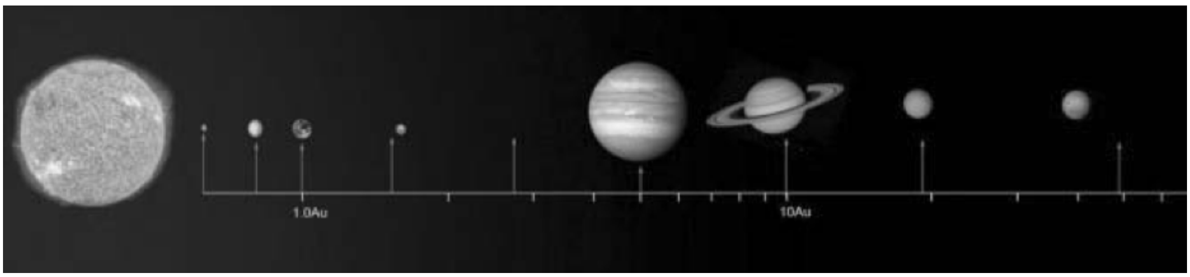
$$R_n = 4+3*2^n \quad (1)$$

where $n = -\infty$ for the planet Mercury and $n = 0, 1, 2...$ for the other planets.

By studying this astronomical rule, which is also called the Titius-Bode Law, Weng Wen-Bo suggested that the similar order is universal in the world. Thus, various natural phenomena are submitted to the Titius-Bode Law.

Fig. 2

Illustration of the Titius-Bode Law



The equation (1) can be written as follows:

$$\beta = a_{n-1}/a_n \quad (2)$$

where β – the value of commensurability for the solar system planets; a_n – the distance of the planet n from the Sun, expressed in the astronomical units.

According to the hypothesis of Weng Wen-Bo, the occurrence dates of various natural disasters have a periodicity which is created by cosmic reasons. Weng Wen-Bo used the term commensurability, which at one time was proposed by Titius. Equation (2) itself brings to light the distribution law of the matter in a space region, and for time domain the commensurability (ΔX) can be expressed as follows (Su et al., 2015):

$$\Delta X = (X_i - X_{i-1})/K \quad (3)$$

where K – an integer (1, 2, ...); X_i is an element of the data set.

If K is equal to 1, then ΔX is the period of the data set.

As of today, for long-term forecasting of extreme natural events, the method of Weng Wen-Bo can be used in several ways. We used four methods of forecasting:

1. by the calculated value of commensurability;
2. by the two-dimensional graph of commensurability;
3. by the time intervals between floods that occurred in the past;
4. by the number of commensurability equations with three components.

The first method requires calculating the commensurability value by the existing date array in which the extreme events occurred, using equation (3). Forecast for the future is given in the form of points on the time axis, when the next event can occur taking into account the forecast error.

The second method requires detecting commensurability values in the date array of extreme events and the creation of a two-dimensional commensurability graph. Forecast for the future is provided using the values of commensurability on the horizontal and vertical axis of the graph.

The third method is to determine the time intervals between the floods that occurred in the past and the extrapolation of these time intervals for the future. The forecast can be visualised by the creation of the graph.

By the fourth way, need to draw up the commensurability equations with three components that will indicate the date of the upcoming extreme event:

$$X_i + X_j - X_k = X_l \quad (4)$$

where X_i, X_j, X_k, X_l – the date array of the extreme events; i, j, k, l = 1, 2, ..., n – the integers; n – the number of dates in the extreme events array.

Dates that have the largest number of such equations are the dates of a possible extreme event.

Results and Discussion

Forecasting results by the calculated value of commensurability

Applying equation (3), we calculated the commensurability values of ten extreme spring floods, which were observed on the Dnipro near Kyiv during the period from 1789 to 1970 (Table 1). The value of commensurability (ΔX) is 6.70 years, the value of *K* is varying in the range 1–8, and the forecast error is ± 2 years. The value ΔX was determined by successive approximation, that allowed receiving the minimisation of the error.

The results of calculations allow determining the dates of possible extraordinary floods after 1970, taking into account the error ± 2 years (Table 2).

It is worth noting that relatively extraordinary spring floods were observed in 1979, 2004 and 2010 on the Dnipro River near Kyiv. This shows good consistency with the forecast dates from Table 2. The presented results in Table 2 showed that the following extraordinary floods should be expected in 2015–2019 and/or 2022–2026 and 2028–2032.

Table 1

The commensurability values of extraordinary spring floods on the Dnipro River near Kyiv for the period 1789–1970

№	Years (X_i)	(X_i–X_{i-1})	*K*	*K**Δ*X*	Error:(X_i–X_{i-1}) – *K**Δ*X*
1	2	3	4	5	6
1	1789	–	–	–	–
2	1845	56	8	53.6	2
3	1877	32	5	33.5	–2
4	1882	5	1	6.7	–2
5	1895	13	2	13.4	0
6	1908	13	2	13.4	0
7	1917	9	1	6.7	2
8	1931	14	2	13.4	1
9	1942	11	2	13.4	–2
10	1970	28	4	26.8	1

Table 2

Prediction of possible extraordinary spring floods on the Dnipro River near Kyiv after 1970

K	*K**Δ*X*	Date of a possible extraordinary flood: 1970 + *K**Δ*X*	The period when an extraordinary flood can occur
1	2	3	4
1	7	1977	1975–1979
2	13	1983	1981–1985
3	20	1990	1988–1992
4	27	1997	1995–1999
5	34	2004	2002–2006
6	40	2010	2008–2012
7	47	2017	2015–2019
8	54	2024	2022–2026
9	60	2030	2028–2032

Forecasting results by the two-dimensional graph of commensurability

An analysis of the extraordinary spring flood date array on the Dnipro River near Kyiv showed that the time intervals between individual floods have very close values: 1970–1917=**53**, 1931–1977=**54**, 1845–1789=**56**, 1917–1877=**40** and 1970–1931=**39**. This allows creating the two-dimensional graph of commensurability of extraordinary spring floods on the Dnipro River near Kyiv (Fig. 3).

Fig. 3

The two-dimensional graph of commensurability of extraordinary spring floods on the Dnipro River near Kyiv

1789	56	1845		
		32		
		1877	54	1931
		40		39
		1917	53	1970

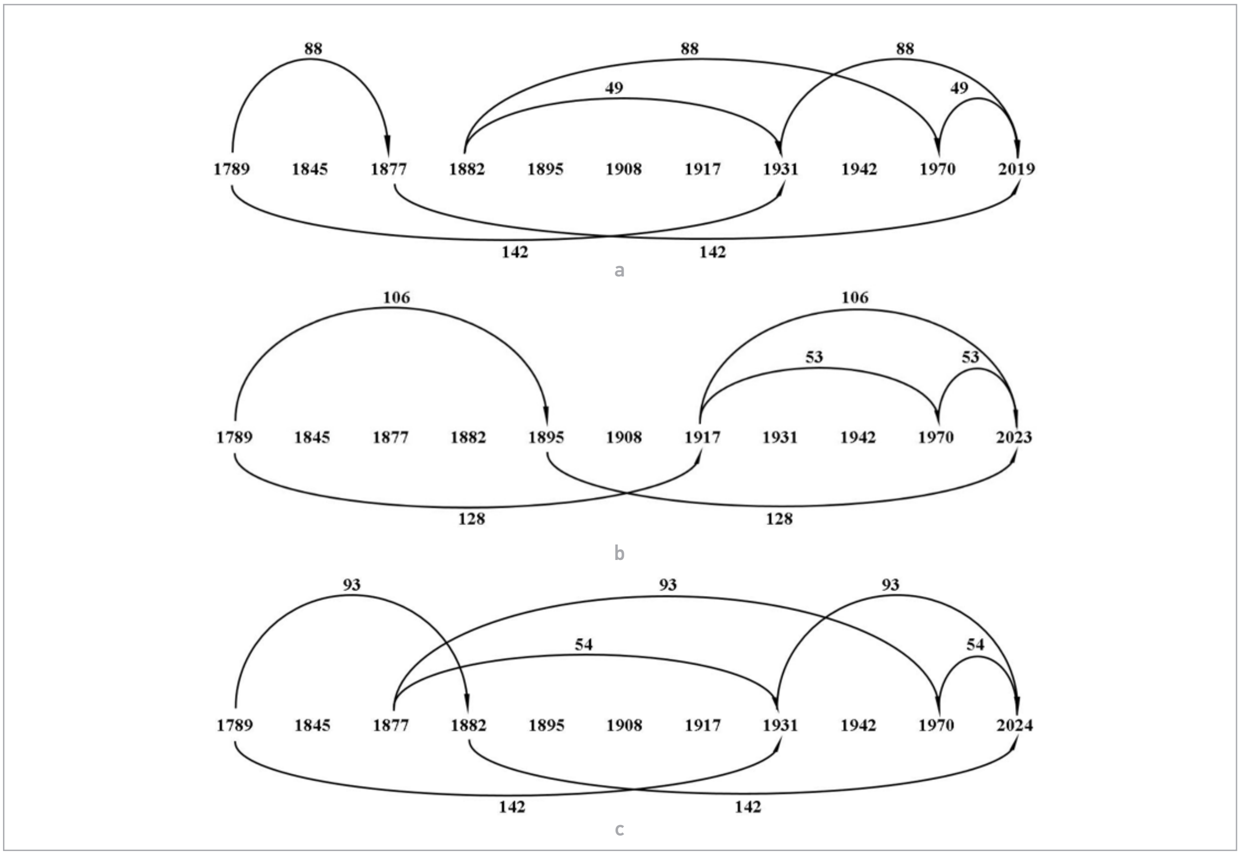
According to this graph, we can predict the following extraordinary floods: vertically 1970 + 39 = 2009 and 1970 + 40 = 2010, and horizontally 1970 + 53 = 2023, and 1970 + 54 = 2024. As with the first method, the two-dimensional graph of commensurability showed us the year 2010, when there was indeed a relatively extraordinary spring flood on the Dnipro River near Kyiv.

Forecasting results by the time intervals between floods that occurred in the past

The time intervals between the individual extraordinary spring floods that occurred in the past were determined. We extrapolated these time intervals for the future for determining the dates of extraordinary spring floods that may occur in the coming years (Fig. 4a–c).

Fig. 4

The commensurability graph of extraordinary spring floods on the Dnipro River near Kyiv



Three time intervals (49, 88 and 142) indicate that an extraordinary spring flood can occur in 2019 (Fig. 4 *a*, Table 4). It should be noted that the time interval of 88 years was repeated twice in the past.

Table 4

Time intervals for forecasting an extraordinary spring flood on the Dnipro River near Kyiv in 2019

Time interval, years		
49	88	142
1	2	3
1931 – 1882 = 49 **2019 – 1970 = 49**	1877 – 1789 = 88 1931 – 1882 = 88 **2019 – 1931 = 88**	1931 – 1789 = 142 **2019 – 1877 = 142**

An extraordinary spring flood can also occur in 2023. This is confirmed by the following three time intervals: 53, 106, and 128 (Fig. 4 *b*, Table 5).

Table 5

Time intervals for forecasting an extraordinary spring flood on the Dnipro River near Kyiv in 2023

Time interval, years		
53	106	128
1	2	3
1970 – 1917 = 53 **2023 – 1970 = 53**	1895 – 1789 = 106 **2023 – 1917 = 106**	1917 – 1789 = 128 **2023 – 1895 = 128**

As in the previous cases, three time intervals (54, 93 and 142) indicate that the extraordinary spring flood can occur in 2024 (Fig. 4 *c*, Table 6). The time interval of 93 years was repeated twice in the past.

Table 6

Time intervals for forecasting an extraordinary spring flood on the Dnipro River near Kyiv in 2024

Time interval, years		
54	93	142
1	2	3
1931 – 1877 = 54 **2024 – 1970 = 54**	1882 – 1789 = 93 1970 – 1877 = 93 **2024 – 1931 = 93**	1931 – 1789 = 142 **2024 – 1882 = 142**

Forecasting results by the number of commensurability equations with the three components

For the period 2019–2026, we created all possible commensurability equations with the three components using the dates of extraordinary spring floods that occurred in the past on the Dnipro River near Kyiv (Table 7).

Table 7

The calculation result by formula (4) of the dates of extraordinary spring floods on the Dnipro River near Kyiv for the period 2019–2026

Year	Equation
1	2
2019	1877 + 1931 – 1789 = 2019 1931 + 1970 – 1882 = 2019
2020	1895 + 1970 – 1845 = 2020
2021	–
2022	–
2023	1895 + 1917 – 1789 = 2023 1970 + 1970 – 1917 = 2023
2024	1882 + 1931 – 1789 = 2024 1931 + 1970 – 1877 = 2024
2025	–
2026	1845 + 1970 – 1789 = 2026

For 2019, 2023 and 2024, two equations are created, while for 2026 only one equation is created; meanwhile, for 2021, 2022 and 2025, the equations cannot be created. Thus, 2019, 2023 and 2024 are the years when the next extraordinary spring floods on the Dnipro River near Kyiv may occur.

The use of the Weng Wen-Bo method allowed predicting the dates of extraordinary spring floods on the Dnipro River near Kyiv in the coming years. Of course, these results are approximate. Yet, the reliability of such results is confirmed by the use of four ways of forecasting by the commensurability method, as well as the good coincidence of the dates of extraordinary spring floods that occurred after 1970. In our opinion, the commensurability method has the advantages over other methods, since it allowed creating the predictions based on the minimum array of data. This is particularly relevant for Ukraine, since the methods of long-term forecasting of spring floods on the rivers use a lot of information: moisture content of the catchment in the autumn-winter period, the maximum water equivalent of snow pack and the maximum depth of soil freezing before the beginning of the spring snow melt at the catchment, forecasted rainfall and air temperature for the forecast lead time (Shakirzanova, 2011). The Dnipro River basin is transboundary and is located on the territory of three countries: Russian Federation, Republic of Belarus and Ukraine. Therefore, the necessary information is not always available. The commensurability method is also characterised by the simplicity of the calculations. The results can be presented graphically. In addition, even an approximate knowledge about the possible dangerous spring flood can be used to minimise the negative effects for the densely populated city.

Conclusions

The method of commensurability allows predicting dangerous natural phenomena, including floods. In Ukraine, it was first used for the Dnipro River. The periods (2015–2019, 2022–2026, 2028–2032), as well as years (2019, 2023 and 2024) were received, when extraordinary spring floods on the Dnipro River near Kyiv may occur. These results illustrate that Weng Wen-Bo's methodological approaches allow carrying out the forecasting of the dates of extraordinary spring floods for the rivers of Ukraine.

The application of the commensurability method allows to carry out the long-term forecasting, which can have the warning lead time in several years. This approach is characterised by the simplicity of the calculations and the use of input information minimum array.

The method of commensurability can be used for long-term forecasting of occurrence dates of various extreme hydrological events like snow melt floods, rain floods, dry years, etc.

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