

**HOMOGENEITY AND STATIONARITY ANALYSIS
OF THE SNOW-RAIN FLOODS IN THE DANUBE BASIN WITHIN UKRAINE**

Liudmyla Gorbachova, Tetiana Zabolotnia, Borys Khrystyuk

The assessment of the homogeneity and stationarity of the observation series is an initial, but no less important stage of research. From its results depends our understanding of the processes and conditions of the formation of the rivers water flow in time and space. In this paper, we carried out the assessment of the homogeneity and stationarity of the maximum discharges of the snow-rain floods of the Danube basin within Ukraine (34 gauging stations) during a long period (since the beginning of the observations to 2015). A hydro-genetic analysis was used for this. This methodological approach is using the mass curve, the residual mass curve and the combined graphs. The presented results illustrate that the observation series that have a full cycle of long-term cyclical fluctuations (decrease and increase phases) are homogeneous and stationary, while other observation series are quasi-homogeneous and quasi-stationary. The maximum discharges of the snow-rain floods in the Danube basin within Ukraine have the four types of the long-term fluctuations. Such types have the different duration of cycles.

KEY WORDS: cyclical fluctuations, stationarity, homogeneity, snow-rain flood, hydro-genetic analysis

HOMOGENITA A ANALÝZA STACIONÁRNOSTI POVODNÍ V POVODÍ DUNAJA NA UKRAJINE.
Hodnotenie homogenity a stacionarity pozorovaných radoch je počiatocnou, no nie menej dôležitou etapou výskumu. Od jeho výsledkov závisí naše chápanie procesov a podmienok tvorby rieky v čase a priestore. V tomto článku sme vykonali zhodnotenie homogenity a stacionarity maximálneho výtoku snehovo-dažďových povodní povodia Dunaja na Ukrajine (34 meracích staníc) počas dlhého obdobia (od začiatku pozorovaní do roku 2015). Na tento účel bola použitá hydrogenetická analýza. Tento metodologický prístup využíva hmotnostnú krivku, krivku reziduálnych hmotností a kombinované grafy. Prezentované výsledky ilustrujú, že rady pozorovaní, ktoré majú celý cyklus dlhodobých cyklických výkyvov (fázy poklesu a vzrášenia), sú homogénne a stacionárne, zatiaľ čo ostatné pozorované rady sú kvázi-homogénne a kvázi-stacionárne. Maximálny výtok snehovo-dažďových povodní v povodí Dunaja na Ukrajine má štyri typy dlhodobých výkyvov. Takéto typy majú rôzne trvanie cyklov.

KLÚČOVÉ SLOVÁ: cyklické výkyvy, stacionárnosť, homogenita, snehovo-dažďová povodeň, hydrogenetická analýza

Introduction

Analysis of the homogeneity and stationarity of the hydrological data are utmost importance since the choice of further methods of investigation depends on the results obtained. Now, such studies are very actual because different scientists have demonstrated that global and regional climate changes have impact not only on water resources (Mimikou et al., 2000; Dery, 2005), but also cause to the break of the homogeneity and stationary processes in the river flow formation (Zhang et al., 2014).

There are two methodical approaches that the wide use in the world to detect changes in the hydrological series of observations: deterministic and statistical. Each of them reflects the idea about the mechanisms for the formation of water flow of rivers. The statistical approach, based on the use of mathematical apparatus in accordance with the multifactorial of the formation conditions of water flow, allows us to consider this process as a stochastic. Statistical methods are providing only a quantitative assessment of the parameters, ranks under which the study is conducted. The analysis of hydrological series based on the deterministic (genetic)

approach allows us to study the regularities of the formation conditions of water flow and, accordingly, their changes in time and space (WMO-No. 168, 2009). The deterministic approach is presented the graphic methods that mainly include various correlation graphs, frequency of values, histograms, mass curve, double mass curve, residual mass curve, chronological charts. The mass curve, double mass curve, residual mass curve are very often used. The numerous researchers the methodical approaches on using these methods were developed. Among them, the most contribution is created: Rippl Y., 1883; Merriam C.F., 1937; Searcy J.K. & Hardison C.H., 1960 et al. The guidelines for these methods were developed separately for each method and for solving a particular problem. In this paper the methodological approaches of the assessments of the homogeneity and stationarity of the hydrological data based on the hydro-genetic analysis are used. This approach was developed by Gorbachova (2013, 2014 a, 2014 b, 2015 a).

The goal of this paper is to study the homogeneity and stationarity of maximum discharges of the snow-rain floods of the Danube basin within Ukraine based on using hydro-genetic analysis. Such studies are important for hydrological and water management calculations.

Material and methods

Study area

In this paper, the Tysa, Prut and Siret rivers are investigated. They belong to the mountain rivers of the

Ukrainian Carpathians of the Danube basin within Ukraine (Fig. 1).

The Carpathian Mountains are the region with the hazard floods on the territory of Ukraine (Susidko & Luk'yanets, 2009). Ukrainian Carpathians are characterized by significant heterogeneity of the territory, and, accordingly, the different conditions of flow formation. The snow-rain floods on the Carpathians rivers are very dangerous and sometimes even catastrophic. It is causing the considerable damage to the economy (flooding lands, granaries, destruction of the roads, bridges and other engineering communications) and also is a threat for human life (Gorbachova & Bauzha, 2013). In this region the high floods are repeat 3-8 times per year. At the same time, Central and Western Europe are also suffering from these natural disasters (Susidko & Luk'yanets, 2009; Pekarova et al., 2014).

The Tysa, Prut and Siret Rivers within Ukraine are belonging to two hydrological regions, namely Uzh-Borzhava and Carpathian regions, according to hydrological regionalisation by intra-annual distribution of the flow that was carried out by Gorbachova (2015 b). For the rivers of the Carpathian region (the upper reaches of the Tysa River to the Rika River, including the Prut and Siret rivers) the wet period lasts from March to July, the autumn period is characterized by floods, and winter – by the smallest discharges per year. The rivers of the Ush-Borzhava region are characterized by intense floods of the cold period of the year. Thus, the lowest discharges are observed from August to October.

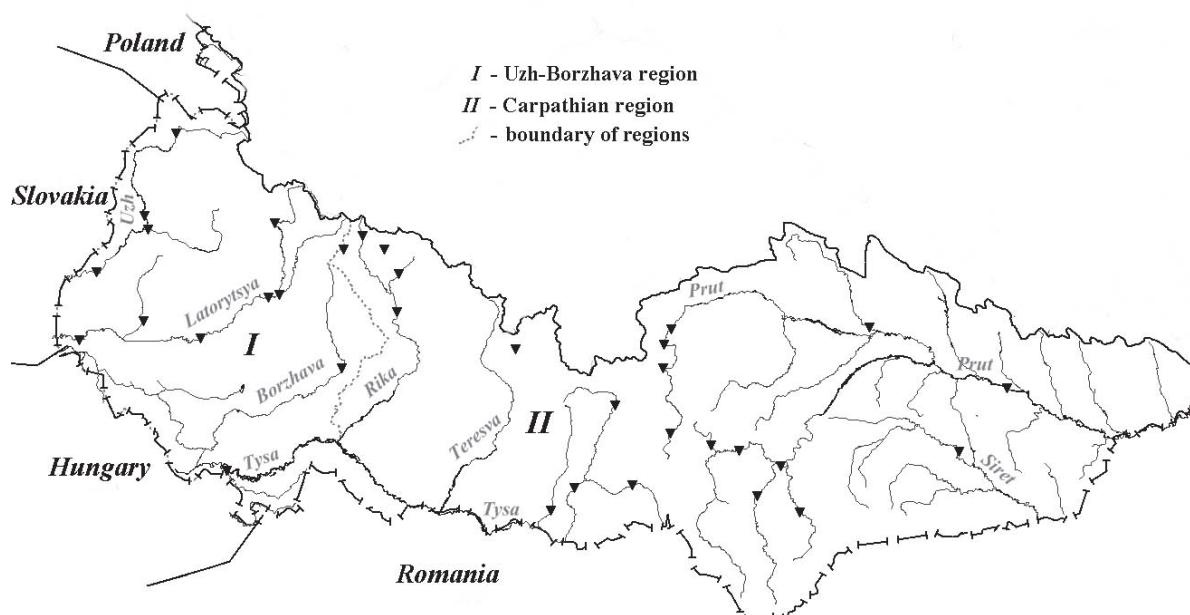


Fig. 1. Location of the 34 water gauging stations in the Danube basin within Ukraine.
Obr. 1. Umiestnenie 34 vodomerných staníc v povodí Dunaja na Ukrajine.

Data and methods

The homogeneity and stationarity of the maximum discharges of the snow-rain floods of the Danube basin within Ukraine (34 gauging stations) during a long period of time (since the beginning of the observations to 2015) was investigated. Such data were taken from the archive of Central Geophysical Observatory of Ukraine. The period of observation on these water bodies is from 27 (Chornaya river – Liubkivtsi village) to 104 (Prut river – Chernivtsi city) years.

The availability of flood observation data helps an improved understanding of flood processes and associated changes in flood characteristics and regimes (Hall et al., 2015). The analysis of homogeneity and stationarity of the observation data is the first step of any research. Hydrological data are characterized by some features (are depend on time, have distribution laws that are different from normal law and have long-term cyclic fluctuations). In the papers Kundzewicz and Robson (WMO-No. 168, 2009) showed that the classical formulas of the statistical criteria to analysis of hydrological series of observations should be used only after their transformation, namely using resampling methods, permutation testing and the bootstrap method. Those approaches are flexible and can be adapted to a wide range of data types, including hydrological series, and are relatively powerful. It is important to examine the test results by graphical methods and historical data. Therefore, in this paper the methodological approaches based on using hydro-genetic methods for estimation the homogeneity and stationarity of hydrological series are used.

From the view point of the hydro-genetic analysis the concepts such as change and variability, the homogeneity and stationarity of the hydrological series were defined. (Gorbachova, 2014 a; Gorbachova, & Khrystyuk, 2014 b; Gorbachova, 2015 a). *The homogeneity* of the time series is the absence of unidirectional changes of the hydrological characteristic (refers to a one genetic series - floods, rain floods etc.) over time against the backdrop its variability due to the long-term cyclical fluctuations. *The stationarity* of the time series is the constancy of average value hydrological characteristic over time if the time series has at least one full closed cycle (dry and wet phase) of long-period fluctuations. *The change* of the time series is the unidirectional deviation from a straight line of the hydrological characteristic, which is in such a state that the hydrological characteristic moves to a new quality, due to the state of factors that are formed by the hydrological characteristic or human activities. *The variability* of the time series is a temporary deviation from a straight line of the hydrological characteristic that is in such a state that the hydrological characteristic acquires a new quality only for a period. In the case of long-term cyclical fluctuations, this period can last for decades, but at the same, the hydrological characteristic from time to time

returns to its "old" state. This same scenario is relevant for short-term cyclical fluctuations, but the period is much shorter and is usually considered a few years.

The assessing of the homogeneity and stationarity of the hydrological series necessitated the following:

- in the hydrological series, the need to restore the gaps in observations and bring them to a long-time period, thus allowing the tracing of the temporal dynamics of hydrological characteristics over a longer time interval;
- the homogeneity of the hydrological characteristic over time is researched with mass curve;
- the stationarity of the hydrological characteristic is researched with residual mass curve.

To clarify the results obtained (if necessary) the other hydro-genetic methods and approaches can be used (the analysis of meteorological factors of the runoff formation, the combined graphics etc.).

For the assessment of the homogeneity of the observation series the mass curve was used. In 1883 W. Rippl developed the mass curve and the residual mass curve methods (Rippl, 1883). Now the mass curve used to detect the influence of anthropogenic factors (hydraulic structures, canals) and of climate change (the presence of trends in the data series). If "jumping", "emissions" or unidirectional deviation on the mass curve are not found, then the process of the forming of the runoff in the study area is homogeneous, and vice versa. The mass curve is defined with the formula:

$$W = \sum_{t=1}^T w(t), \quad (1)$$

where

W – the total runoff of river for time period T ;

$w(t)$ – the runoff of t -th year.

For the assessment of the spatio-temporal fluctuations of the maximum discharges of the snow-rain floods of the Danube basin within Ukraine the residual mass curve and combined graphs were used. The analysis of the residual mass curve allows the definition of the stationarity of data series, namely the sustainability of the average value of the hydrological characteristic in the course of time. The average value of the time series is stable in the presence of at least one complete closed cycle (dry and wet phases) of long-period fluctuations (Andreyanov, 1959). The residual mass curve is defined according to (Andreyanov, 1959):

$$f(t) = \frac{\sum_{t=1}^T (k(t)-1)}{C_v}, \quad (2)$$

where

C_v – the variation coefficients of runoff;

$k(t) = Q(t)/Q_0$ – the modulus coefficients;

$Q(t)$ and Q_0 – the discharge of t -th year and the average discharge for the period of time T.

Combined graphs of characteristics allow the definition of the synchrony/asynchrony of long-term fluctuations in different rivers within the one hydrological homogeneous area. In turn, the synchronous fluctuations are indicated on the homogeneous climatic conditions of formation runoff.

Results

Based on formulas (1) and (2) the graphs of the mass curves and residual mass curves of the maximum discharges of the snow-rain floods in the Danube basin within Ukraine for 34 catchments were created. Some examples of such curves are shown in Fig. 2. The analysis of the graphs shows that the series of observations are homogeneous. However, some of them may raise doubts about homogeneity, e.g. the observation series on Fig. 2 b. But, such shape of sum curve is determined by the structure of the observation series, namely, the presence of only the prolonged increase and decrease phases of cyclical fluctuations. This situation is typical for the observation series at the gauging station Stara river – Znyatsevo village (Fig. 2 e). Such situation is temporary. With the extension of the duration of observations, the data series will have several phases of cyclical fluctuations and the mass

curve will have the view as, e.g., on Fig. 2 a and c for the gauging stations Latorytsya river – Chop town and Tysa river – Rakhiv town. On these gauging stations the observations series have several phases (decrease and increase) of long-term cyclical fluctuations. The duration of full cycles is about 15-20 years. Therefore, the observations series of the maximum discharges of the snow-rain floods in the Danube basin within Ukraine are the homogeneous and quasi-homogeneous. The residual mass curves showed that the cyclical fluctuations of the maximum discharges of the snow-rain floods of water have similar and distinctive features in their configuration. (Fig. 2 d, e, f). Several types of cyclical fluctuations were identified. So, to the first type of long-term cyclical fluctuations are the observations series, which have only two phases: decrease and increase. Such fluctuations of the maximum discharges of snow-rain floods are characteristic for the Uzh river basin and some tributaries of the Rika river that are located on its upper reaches (Holyatynka and Pylypets). The increase phase began from the beginning of the observation and continued until 1968. The decrease phase began after 1968 and it continues to this day (Fig. 2 d). For some rivers which can also be attributed to the first type of fluctuation, e.g., Holyatynka river – Maidan village, Turia river – Simer village, Stara river – Znyatsevo village the increase phase continued until 1989 (Fig. 2 e). It should be noted that such observations series have incomplete cycle of long-term fluctuation, because we cannot see the begin of the increase phase and the end of the decrease phase. Such observations series can be attributed to quasi-stationary.

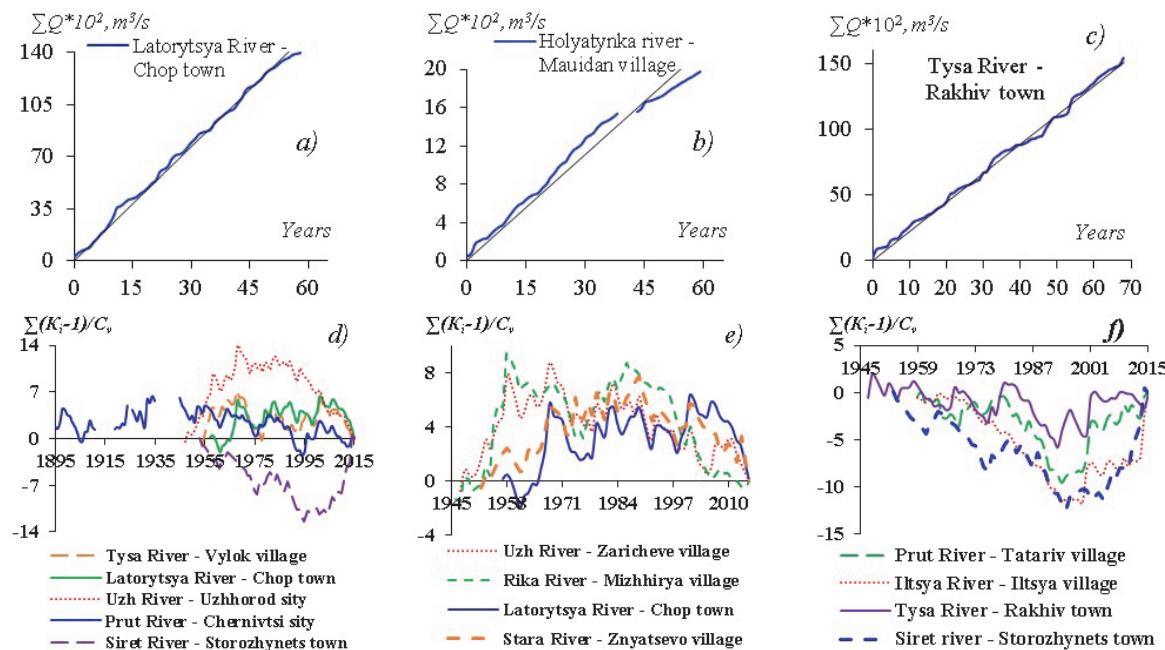


Fig. 2. Some mass curves (a, b, c) and residual mass curves (d, e, f) of the maximum discharges of the snow-rain floods in the Danube basin within Ukraine.

Obr. 2. Hmotnostné krivky (a, b, c) a reziduálne hmotnostné krivky (d, e, f) maximálnych prietokov zo snehovo-dažďových povodní v povodí Dunaja na Ukrajine.

The second type of long-term fluctuations have two full cycle. So, since the beginning of observations and to end of the 60th of XX century was observed the increase phase. Then, until the mid-70th of XX century was the decrease phase. After the 70th years again began the increase phase that continued until the mid-80th of XX century and then it has changed to the decrease phase of cyclical fluctuations. Last is continued till now. This type of fluctuation is seen in such rivers as Latorytsya, Borzhava, Rika (Fig. 2 e).

Such rivers as Upper Tysa, Siret and Upper Prut have the third type of fluctuations. They are characterized by the decrease phase from the beginning of the observation and until the mid-90th of XX century. Then such phase has changed into the increase phase with minor variations in some years (Fig. 2 f).

Analysis of the fluctuations the snow-rain floods of the rivers Tysa and Prut (the last gauging stations within Ukraine) can be attributed to the fourth type. Such observation series have the several full cycles of the fluctuations the duration about 15-20 years (Fig. 2 d). Consequently, they have the stable average value of the series in time and are stationary series. On Fig. 2 d it is also seen that the long-term cyclical fluctuations on gauging stations Tysa river – Vylok village and Prut river – Chernivtsi city have synchronous and in-phase fluctuations.

Analysis of the residual mass curves showed that in the Danube basin within Ukraine the fluctuations of the observations series of the snow-rain floods maximum discharges are characterized by synchronous fluctuations every year. However, these fluctuations are not always synchronous phases (Fig. 2 d). It can be assumed that the differences in the long-term cyclic fluctuations are caused by various conditions of the formation of the mountain watersheds water flow (the uneven distribution of precipitation, temperature and humidity in the basins; the presence of large forest areas and other). Besides, the data series that have the full cycle of long-term cyclical fluctuations (decrease and increase phases) are the stationary.

Conclusions

Analysis of homogeneity and stationarity snow-rain floods in the Danube basin within Ukraine by means of hydro-genetic methods has shown that the observation series are the homogeneous and quasi-homogeneous, because on all mass curves were not be found any significant points of the fracture of the directions ("jumping" or unidirectional deviation). Some uncertainties are associated with the structure of the observation series, namely, the presence of only the prolonged increase and decrease phases of long-term cyclical fluctuations. The observation series that have a full cycle of long-term cyclical fluctuations (decrease and increase phases) are stationary, while other observation series are quasi-stationary.

In the Danube basin within Ukraine the observations series of the maximum discharges of snow-rain floods were determined the 4 types of long-term cyclic fluctuations. Each type of cyclic fluctuations is characterized by the different durations. The reliably determine of homogeneity and stationarity of the observations series depend on their duration. Only for the observation series of the rivers Prut and Tysa such assessments are reliable since they have the several full cycles of fluctuations. For their tributaries and the Siret river the reliable determining of homogeneity and stationarity of the observation series will be possibly when the observation series become longer, since such data have incomplete increase and decrease phases of the long-term cyclic fluctuations. The observations series of the maximum discharges of snow-rain floods in the Danube basin within Ukraine are characterized by synchronous fluctuations, which do not always have synchronous phases.

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HOMOGENITA A ANALÝZA STACIONÁRNOSTI POVODNÍ V POVODÍ DUNAJA NA UKRAJINE

Hodnotenie homogenity a stacionarity radov pozorovaní je počiatocnou, no nie menej dôležitou etapou výskumu. Z jej výsledkov závisí naše chápanie procesov a podmienok vzniku toku riečnej vody v čase a priestore. Hydrologické údaje sú charakterizované niektorými vlastnosťami (závisia od času, majú distribučné zákony, ktoré sa líšia od bežného práva a majú dlhodobé cyklické výkyvy). V dokumentoch Kundzewicz a Robson (WMO č 168, 2009) sa ukázalo, že klasické vzorce štatistických kritérií na analýzu hydrologických radov pozorovaní by sa mali používať až po ich transformácii, pomocou metód opäťovného vzorkovania, permutačného testovania a metódy bootstrap. Tieto prístupy sú flexibilné a môžu byť prispôsobené širokej škále dátových typov vrátane hydrologických radov a sú pomerne silné. Je dôležité preskúmať výsledky testov pomocou grafických metód a historických údajov. Preto sa v tomto príspevku používajú metodologické prístupy založené na využití hydrogenetických metód na odhad homogenity a stacionárnosti hydrologických radov. Tento metodologický prístup využíva hmotnostnú krivku, krivku reziduálnych hmotností a kombinované grafy.

Z hľadiska hydrogenetickej analýzy boli definované pojmy ako zmena a variabilita, homogenita a stacionárnosť hydrologického radu. Homogénnosť časových radov je absencia jednosmerných zmien hydrologickej charakteristiky (vzťahuje sa na jeden genetický rad – záplavy, dažďové povodne atď.) v priebehu času na pozadí jeho variability v dôsledku dlhodobých cyklických výkyvov. Stacionárnosť časových radov je stálosť priemernej hodnoty hydrologickej charakteristiky v čase, ak má časový rad aspoň jeden úplne uzavretý cyklus (suchá a mokrá fáza) dlhodobých výkyvov. Zmena časových radov je jednostranná odchýlka od priamky hydrologickej charakteristiky, ktorá je v takom stave, že sa hydrologická charakteristika presúva na novú kvalitu v dôsledku stavu faktorov, ktoré sú tvorené hydrologickou charakteristikou alebo ľudskou činnosťou. Variabilita časových radov je dočasná odchýlka od priamky hydrologickej charakteristiky, ktorá je v takom stave, že hydrologickej charakteristiky,

ky nadobúdajú novú kvalitu len počas určitého obdobia. V prípade dlhodobých cyklických výkyvov môže toto obdobie trvať desaťročia, ale zároveň sa hydrologická charakteristika z času na čas vracia do "starého" stavu. Rovnaký scenár je relevantný pre krátkodobé cyklické výkyvy, ale obdobie je oveľa kratšie a zvyčajne sa považuje za niekoľko rokov.

Cieľom tohto článku je študovať homogenosť a stacionárnosť maximálneho vypúšťania snehovo-dažďových povodní v povodí Dunaja na Ukrajine na základe využitia hydrogenetických analýz. Takéto štúdie sú dôležité pre výpočty hydrologického a vodohospodárskeho manažmentu. Bola preskúmaná homogenita a stacionárnosť maximálneho vypúšťania povodní v povodí Dunaja na Ukrajine (34 meracích staníc) počas dlhého obdobia (od začiatku pozorovaní do roku 2015). Takéto údaje boli prevzaté z archívu Centrálneho Geofyzikálneho Observatória Ukrajiny. Obdobie pozorovania týchto vodných útvarov je od 27 (rieka Chornaya – obec Liubkvitsi) po 104 rokov (rieka Prut – Chernivtsi).

Analýza homogenity a stacionárneho snehovo-dažďových povodní v povodí Dunaja na Ukrajine prostredníctvom hydrogenetických metód ukázali, že rad pozorovaní je homogénny a kvázi-homogénny, pretože na všetkých hmotnostných krivkách sa nenachádzajú žiadne významné body zlomu smerov ("skakanie" alebo jednosmerná odchýlka). Niektoré neistoty súvisia so štruktúrou radu pozorovaní, a to s prítomnosťou iba dlhodobejšej fázy náрастu a znižovania dlhodobých cyklických výkyvov. Pozorované rady, ktoré majú celý cyklus dlhodobých cyklických výkyvov (fázy poklesu a nárástu) sú stacionárne, zatiaľ čo ostatné pozorované rady sú kvázistacionárne.

V povodí Dunaja na Ukrajine boli pozorované rady maximálnych vypúšťaní snehovo- dažďových záplav určených pre 4 typy dlhodobých cyklických výkyvov. Každý typ cyklických výkyvov sa vyznačuje rôznymi dobami trvania. Spoľahlivé určenie homogenity a stacionarity radov pozorovaní závisí od ich trvania. Iba pre pozorované rady riek Prut a Tysa sú takéto hodnotenia spoľahlivé, pretože majú niekoľko úplných cyklov

kolísania. Pre ich prítoky a rieku Siret bude pravdepodobne spoľahlivé určenie homogenity a stacionarity radu pozorovaní, ak sa rad pozorovania stane dlhší, pretože takéto údaje majú neúplné fázy nárastu a znižovania dlhodobých cyklických

výkyvov. Pozorované rady maximálnych vypúšťaní snehovo-dažďových povodní v povodí Dunaja na Ukrajine sú charakterizované synchrónnymi výkyvmi, ktoré nemajú vždy synchrónne fázy.

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