Statistical Analysis of Hydrological Regime of the Danube River at Ceatal Izmail Station

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Abstract. In the present study, we focused on the statistical analysis of changes in the characteristics of the minimum, average annual, and maximum discharge series of the Danube River at Ceatal Izmail water gauge. We have processed the series of annual average discharges during the whole water stage observation period 1840–2015, as well as the average daily discharge over the period 1931–2015. Firstly, we have identified changes in commonly used hydrological characteristics (such as long-term trends and variability of the annual averages, minimum annual discharges, occurrence of extremes, etc.). In the second part we divided the annual hydrogram of the daily discharges into individual flow events (waves) and we calculated their number and their duration in each year. Specifically, we have calculated the numbers and characteristics for extremely dry periods, as well as for small and large floods. The analysis of the discharge series of the Danube River evaluated at Ceatal Izmail shows: the long-term average discharge of the Danube River in the closing profile does not change. Annual regime has slightly changed - spring discharge peaks occur in the last years about 40 days earlier. From the statistical discharge analysis, we still do not know clearly whether this is the result of higher precipitation sums due to climate change or due to the channel training - reducing flood areas and draining acceleration. In the past, fluctuations in the Danube River flow were even higher than at present, in both directions - minimum and maximum discharge were more extreme in some periods. Therefore, it is necessary to focus on historical hydrology and analyze as many observations as possible. Statistical attention to the discharge, as well as precipitation and air temperature series needs to be continued.

1. Introduction
With the increase of population – and with the development of civilization in general – an increase of vulnerability of the society is closely connected. It concerns also the threats by high floods as well as by incidents of long periods of droughts. Economic prosperity of each country is closely connected with the availability of sufficient water resources. In general, the economic development and increase of living standard, leads to higher demands of the water consumption. From this perspective, it is important to closely monitor the long-term development of water in the country.
In the present study, we focused on the statistical analysis of changes in the characteristics of the minimum, average annual and maximum discharge series of the Danube River at Ceatal Izmail water gauge.

2. Data and methods
The Danube River with a total length of 2857 km and a long-term daily mean discharge of about 6500 m$^3$s$^{-1}$ is listed as the second biggest river in Europe. Nineteen countries share the Danube basin, though two thirds of the catchment lies within five countries (Romania, Hungary, Serbia, Austria and Germany). According to its geological structure and geographical layout the Danube basin can be conveniently divided into three regions, namely upper, middle, and lower Danube. The Danube Delta with a size of 6,750 km$^2$ is the most important wetland in the Danube River Basin.

For analysis of long-term multi-annual variability of the mean annual Danube basin discharges, we used two discharge time series. The first one is from the Ukrainian station Reni (Figure 1), (period 1841–1920) according to [1]. Second one is from Rumanian station Ceatal Izmail (period 1841–1920) according to [2], [3]. Basic characteristics of the water gauges are in Table 1. In Figure 2 there are presented the deviation time series of the individual mean annual discharges from the double 5-years moving averages of the mean discharge values, as well as decadal discharge.

The driest decade occurred in the period 1861–1870, the wettest in the years 1911–1920. The driest year was year 1863, the wettest one was year 1915. According to Bondar, maximal annual discharge in Ceatal Izmail station was calculated on July, 2, 1897 – 21 867 m$^3$s$^{-1}$, minimal was observed in October, 31, 1921 – 1350 m$^3$s$^{-1}$.

![Figure 1. Danube River scheme](image)

Table 1. Basic characteristics of the water gauges Reni and Ceatal Izmail, Danube River.

| River    | Water gauge | Country | Area [km$^2$] | River km | Altitude [m a.s.l.] | Discharge $Q_a$ [m$^3$s$^{-1}$] 1961–2010 |
|----------|-------------|---------|--------------|----------|-------------------|--------------------------------------|
| Danube   | Reni        | UKR     | 805 700      | 132      | 0.2               | 6 563                                |
| Danube   | Ceatal Izmail | RO     | 807 000      | 72       | 0                 | 6 535                                |
2.1. Identification of the long-term variability and trends

From Figure 2 it is evident, that annual discharge series are marked by the multi-annual cycles of the dry and wet periods (data are not independent). Linear trend of the cyclic series is expressively influenced by its values, both, at its begin and its end. In order to eliminate influence of this multi-annual cyclic component, it should be eliminated from the time series. The other way is to determine the linear trend, starting calculations beginning and ending at the local maxima (or minima).

It is possible to identify the cyclicity or randomness in the time series by auto-correlation and spectral analysis. Both methods were used to look for the long-term cycles of runoff decrease and increase in the analyzed runoff time series.

Estimation of both, the auto-covariance and the auto-correlation functions of given empirical series \( \{x_i\}_{i=1}^n \), is the base tool of time series analysis.
The auto-covariance function $R(\tau)$ can be estimated by the formula

$$R(\tau) = \frac{1}{n-\tau} \sum_{i=1}^{n-\tau} (x_i - \bar{x})(x_{i+\tau} - \bar{x}_{\tau}),$$

where: $\bar{x}$ – mean of $\{x_i\}$.

The normalized auto-covariance function (with respect to the standard deviation $s_x$) provides an estimation of the auto-correlation function $r(\tau)$ of the form

$$r(\tau) = \frac{R(\tau)}{s_x^2},$$

where: $\tau = 0, 1, 2, ..., m; \ m = n/2$.

Function $r(\tau)$ reaches its values within the interval $<-1, 1>$. 

The spectral analysis is used to examine the periodical properties of random processes $\{x_i\}_{i=1}^n$. The spectral analysis generalizes a classical harmonic analysis by introducing the mean value in time, of the periodogram obtained from the individual realizations. The fundamental statistical characteristic of a spectral analysis is its spectral density.

The basic tool in estimating the spectral density is the periodogram. A periodogram (a line spectrum) is a plot of frequency and ordinate pairs for a specific time period. This graph breaks a time series into a set of sine waves of various frequencies. It is used to construct a frequency spectrum. A periodogram can be helpful in identifying randomness and seasonality in time series data, and in recognizing the predominance of negative or positive autocorrelation—a help you often need to identify an appropriate model for forecasting a given time series. If the periodogram contains one spike, the data may not be random. The spectral density is defined as a mean value of the set of periodogram for $n \to \infty$.

The periodogram is calculated according to:

$$I(\lambda_j) = \frac{1}{2\pi n} \left| \sum_{i=1}^{n} x_i e^{-i\lambda_j i} \right|^2 = \frac{1}{2\pi n} \left\{ \left( \sum_{i=1}^{n} x_i \cdot \sin(\tau \lambda_j) \right)^2 + \left( \sum_{i=1}^{n} x_i \cdot \cos(\tau \lambda_j) \right)^2 \right\}. \quad (3)$$

We compute the squared correlation between the series and the sine/cosine waves of frequency $\lambda_j$. By the symmetry $I(\lambda_j) = I(-\lambda_j)$ we need only to consider $I(\lambda_j)$ on $0 \leq \lambda_j \leq \pi$.

For real centered series the periodogram $I(\lambda_j)$ can be estimated by auto-covariance function as

$$I(\lambda_j) = \frac{1}{2\pi} \left( R_0 + 2 \sum_{\tau=1}^{n-1} R_\tau \cdot \cos(\tau \lambda_j) \right), \quad (4)$$

for Fourier frequencies.
\[
\lambda_j = \frac{2\pi j}{n}, \quad \text{where} \quad j = \left\lceil \frac{n}{2} \right\rceil.
\]  

(5)

3. Results and discussions

3.1. Identification of the long-term variability and trends

Multiannual variability of yearly discharges was studied by means of the autocorrelation and spectral analysis. Figure 3 (left) show the autocorrelogram of the mean annual discharges of the Catal Izmail station. Autocorrelograms indicate a significant autocorrelation among the data of the time series. Negative autocorrelations were found for 6, and 9 year lags, positive ones were found for 13–14, 29–30, and 40–44 year lags. As the longer period lengths are not integers, it is not possible to identify them by means of the autocorrelograms of the annual values series. Therefore, the most significant period of 3.6 years does not noticeably show up on the autocorrelogram. It only slightly increases the autocorrelation coefficients for 3 and 4 years.

Therefore, the other significant periods were identified by combined periodogram method [4]. This method revealed periods of 2.4, 3.6, 4.2, and 7 years, as well as long periods of 14, 22, 30 and 44 years (Figure 3, right).

As indicated in other studies [5], the cycle of 2.4 years is probably connected to QBO phenomena. The cycle of about 3.6 years probably depends on the Southern Oscillation (SO) represented by the SO index. The 44, 22, and 11 years’ cycles are connected to solar activity. The cycle length of approx. 28–31 years is related to the Arctic oscillation (AO), expressed by the AO index. Finally, the cycle of about 13 years is connected to the North Atlantic Oscillation (NAO), represented by the NAO index.

3.1.1. Identification of the long-term trends

Generally, the null hypothesis $H_0$ that there is no trend, is to be tested against the alternative hypothesis $H_1$, that there is a trend. The parametric and non-parametric tests can be used for this purpose. We used two non-parametric tests for trend analysis: the Mann-Kendall test based on the statistic $S$, and the Spearman’s $\rho$ (rho) test. Generally, in stations Reni and Cezatal Izmail in Danube discharge series there doesn’t exist (from the statistical point of view), significant trend of discharges within the used 95-years period 1921–2015.

3.2. Identification of the changes in daily discharges

In the case of average monthly discharges, the annual march of discharges is changing on the Danube (Figure 4), the runoff decreases in the summer months of June, July, August, and the long-term maximum monthly discharge has shifted from May to April.

![Figure 3. Auto-correlograms (left), and normalized combined periodograms (right) of the mean annual discharges of the Danube River, significant periods.](image_url)
In the next step, the following procedure was used: all discharges that exceed 75th percentile of whole period was classified as high flows and all discharges that were below 50th percentile were classified as low flows. Between these two levels a high flow begun when discharge increased by more than 25 % per day and ended when discharge decreased by less than 7.5 % per day. A small flood event is defined as a high flow with peak discharge greater than 2 year return interval event, and a large flood event is defined as a high flow with peak discharge greater than 10 year return interval event.

Based on the above mentioned references and commonly used statistical methods of flow analysis, we analyzed following daily discharge time series characteristics (separately for categories of extreme low flow, low flow, high flow pulses, small floods, and large floods):

- Mean values of peak discharge during event for each year;
- Frequency of events during each year;
- Duration of flow events (mean duration of events in days);
- Rate of discharge changes (rise and fall rates: mean of all positive/negative differences between consecutive daily values).

For the calculation of selected high flow indices, the IHA software was used [6].

**Figure 4.** Annual run of the average monthly discharges of the Danube in three different periods at Ceatal Izmail gauge

**Figure 5.** Separation of mean daily discharge hydrograms of the Danube in Ceatal Izmail station into five categories
3.2.1. Results of the hydrological drought analyses

In the following Figure 6, there are graphically presented the results of the statistical calculations for the minimal annual discharge. Figure 6a shows, that the minimal annual discharge of the Danube is moderately increasing. The lowest annual discharges occurred in 1946–1947, 1986–1993 and in 2003. Discharge of the Danube decreased to 1970 m$^3$s$^{-1}$ in 1947. Minimal discharges are occurring at the end of October, about 20 days earlier nowadays than 100 years ago.

Figures 6b represent the characteristics of dry periods: mean value of extremely low discharges (discharge below 5% - 3180 m$^3$s$^{-1}$), frequency of hydrologic drought occurrence for each year, and duration of extremely low discharges in days for each calendar year. It is evident that if the drought occurs once per year, its duration is probably longer than if it is discontinued by several high flows. The most extreme drought period of the Danube occurred in 2003, and its duration was 102 days. If we select other threshold value of the minimal discharge, there might be different result, of course.

**Figure 6.** a) Minimal annual discharge; Julian day of annual minima occurrence; b) Mean values of extremely low discharges, duration of extremely low discharges in days for each calendar year, and frequency of hydrologic drought occurrence for each year.

The Danube, Ceval Izmail
3.2.2. Results of the floods analyses

Analogically, on the Figure 7, there are shown the maximal mean daily discharges of the Danube for each year. At the Lower Danube reach, there is the maximal mean daily discharge almost equal to the maximal peak discharge. At Figure 7a we can observe moderate increase of maximal annual discharge. The highest maximal annual discharges occurred in 1940–1942, 1970, 2005–2006 and in 2010 at the Lower Danube reach. The Danube discharge attained 15,000 m$^3$s$^{-1}$. The maximal annual discharge is mostly appearing on the 130th day of the year.

At Figure 7b, there are presented the characteristics of all the high flow pulses. We can observe that the longest duration of the high flows was in 1948 – up to 238 days. Peak discharges are moderately increasing during the high flows pulses, but their duration is shorter.

**Figure 7.** a) Maximal daily discharge of the year (1-day max); Julian day of annual maxima occurrence;

b) Pulses of the high flows (High1): mean value of high flows; duration of high flows in days for each calendar year, and frequency of high flows occurrence for each year.

The Danube, Ceatal Izmail
4. Conclusions
In the present paper, we focused on a detailed statistical analysis of changes in the average daily flow of the Danube in its final profile - at Ceatal Izmail water gauge, Romania. We first corrected these data from random errors by comparing with daily flows from the Reni station in Ukraine.

In general, in the Danube River basin it holds, that periods around years 1915, 1940, 1965, and 1980 were extremely rich with runoff. In contrary, the period around 1947 and the nineties of the twentieth century were extremely dry. But the period around the year 1863 was in the Danube River basin even drier.

The combined periodogram method revealed periods of 2.4, 3.6, 4.2, and 7 years, as well as long periods of 14, 22, 30, and 44 years (Figure 4). The cycle of 2.4 years is probably connected to QBO phenomena. The cycle of about 3.6 years probably depends on the Southern Oscillation (SO) represented by the SO index. The 44, 22, and 11 years’ cycles are connected to solar activity. The cycle length of approx. 28–31 years is related to the Arctic oscillation (AO), expressed by the AO index. Finally, the cycle of about 13 years is connected to the North Atlantic Oscillation (NAO), represented by the NAO index.

We analyzed not only the statistical characteristics of changes in the commonly used hydrological characteristics (annual average, minimum annual flow, maximum annual flow, day of occurrence of extremes, etc.), but we divided the annual hydrogram into individual flow waves and we calculated their number, average flow and duration in each year. We have also separately calculated numbers and characteristics for small and large floods.

The analysis of the daily discharge series of the Danube River at Ceatal Izmail shows a number of facts.
- The average annual discharge of Danube in the closing profile Ceatal Izmail does not change;
- Peak spring discharge occur in the last 30 years about 40 days earlier. Due to the influence of water flows on the Danube, we cannot clearly determine whether these are the consequences of warming - the earlier runoff of water from the melting of snow in the catchment area.
- The rate of increase and the rate of decline of both, small and large flood waves in the Danube are slightly increasing. The number of reversals representing the change from increase to decrease is decreasing. Flows are likely to be more balanced due to the construction of several water works across the Danube River.

In our calculation, for a whole 85-years daily series, we set uniform boundaries for dry period, as well as for floods. The entire calculation was automatically performed. This eliminated the subjective intervention of the processor on the separation of the hydrogram. For calculations, it should be noted that with other boundaries, the numbers and duration of individual waves will change [7].

New methods for assessing the occurrence of droughts and floods bring a lot of new knowledge. Statistical analyzes show that the number of large floods on the Danube will not increase, their peak and their duration will increase slightly. From the flow analysis, we still do not know clearly whether this is the result of higher precipitation sums due to climate change or technical adjustments to the river channel - reducing flood areas and draining acceleration.

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