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On the linear trends of a water discharge data under temporal variation. Case study: the upper sector of the Buzău river (Romania)

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Abstract

The aim of this paper is to provide a statistic overview of the hydrological impact of the Siriu Dam on the Buzau River (Romania), taking into account the temporal variations. Our case study uses the daily mean discharges of the Buzau River (1st of January 1955 to 31st of December 2010), registered at Nehoiu hydrometric station. The building of the Siriu Dam in 1984 required the division of the study interval into two sub-periods, each being analyzed annually and seasonally, on the series themselves or on the pre-whitened ones when prior required. The existence of a linear trend on different periods and sub-periods has been studied by using the Mann-Kendall and Seasonal Mann-Kendall tests. In the case of the existence of a linear trend, the slopes have been calculated with Sen's Slope Estimator. The stationarity has been studied by using the Dickey-Fuller and Kwiatkowski–Phillips–Schmidt–Shin tests. According to our preliminary results, the stationarity in trend after the dam's construction, respectively increasing linear trends for almost all the data series and subseries was observed. The trend and stationarity outcomes proved that the Siriu Reservoir has a good impact on the homogeneity of the Buzau River's discharge and the increasing trends are related to human activity impact coupled with climate change/variability.

Keywords: *Buzau river, discharge, linear trend, Siriu Dam, seasonality, stationarity*

Rezumat. În legătură cu tendințele liniare ale debitelor râurilor în timp. Studiu de caz: sectorul superior al râului Buzău (România)

Acest articol dorește să ofere o imagine dinamică de ansamblu, din punct de vedere statistico-hidrologic, asupra impactului barajului Siriu asupra râului Buzău (România). Studiul de caz folosește debitele zilnice ale râului Buzău, colectate la stația hidrometrică Nehoiu în perioada 1 ianuarie 1955 - 31 decembrie 2010. Construcția barajului Siriu în 1984 a determinat împărțirea intervalului în două sub-perioade care să fie analizate anual și sezonal, pe seriile de date inițiale sau pe cele procesate, când este cazul. Existența tendinței liniare pe diferite perioade și sub-perioade a fost studiată cu ajutorul testelor Mann-Kendall și Mann-Kendall Sezonal. În cazul existenței trendului linear, panta a fost calculată cu Evaluatorul de pantă Sen. Staționaritatea a fost studiată cu ajutorul testelor Dickey-Fuller și Kwiatkowski–Phillips–Schmidt–Shin. Conform rezultatelor obținute, a fost observată staționaritatea în tendință după construcția barajului, respectiv liniar crescătoare, pe aproape toate seriile și sub-seriile de date. Rezultatele referitoare la tendință și staționaritate demonstrează impactul pozitiv al construcției rezervorului lacului Siriu asupra omogenității debitului râului Buzău și tendințele crescătoare sunt corelate cu activitatea umană coroborată cu schimbările climatice.

Cuvinte-cheie: *râul Buzău, debit, tendință liniară, barajul Siriu, sezonalitate, staționaritate*

Introduction

Stationarity and trend studies offer a general overview of the river's discharge values, an image that helps in the implementation of adequate measures to diminish the effects of natural disasters.

Long term analysis of rivers' discharges reveals the effects of climate change, precipitation regime, human activity, exploitation of the water resources on the environment and helps in the adjustment of the consequences and implementation on management plans for better use. These studies have been carried out in Europe (Wang, Van Gelder, & Vrijling, 2005), Canada (Zhang et al., 2001), United States (McCabe & Wolock, 2002). In Romania, there have been studied trends at the country-scale (Birsan et al., 2014), or variability at local scale (Stefann et al., 2004).

Various studies based on Indicators of Hydrologic Alteration (IHA) of Richter, Baumgartner, Powell & Braun (1996), often used to assess dam construction on streamflow by means of comparing pre- and post-dam hydrographic characteristics. These studies have suggested that the natural flow of rivers has been substantially altered through dam construction, which resulted, for example, in reduced or increased flows, altered seasonality of flows, changed frequency, duration, and timing of flow events (Kendall, 1975).

Minea and Bărbulescu (2014) investigated the impact of the construction of Siriu dam on the Buzău river (i.e. 1955-1984 vs 1985-2010) and found the following aspects: i) the flow during the month of January increased by 30.2%; ii) significant changes occurred during the May-July period, when the flow decreased by 13–25%; iii) flow intensity was affected, e.g. extreme values registered the most significant decrement in the post-impact period: the (90-day max)'s minimum – from 28.6 to 16.4 m3/s, and the (90-day max)'s maximum – from 92.6 to 69.8 m3/s, and, in contradiction, the maximum of 90 - day minimum increased with 45.8%.

Žibienė, Žibas & Blažaitytė (2015) analyzed the impact on the Šušvė river (Lithuania) in relation to the Angiriai dam (1940-1979 vs 1981-2010) and found that the flow of every month, except for those of April, August and September, have increased; the change in the increased flows variated from 15.70% to 153.48%, while that of the decreased flows variated from 28.8 % to 35.67%; the maximum 1-day, 3-day, 7-day, and 30-day flows decreased by 25–32% and the minimum 30-day flow decreased by 8.86 %.

Recently, do Vasco, Netto & da Silva (2019) analyzed changes in the flow regime before and after the construction of the Xingó reservoir on the São Francisco river (1979–1994 vs 1995–2013) from Brazil and detected reduction values of 31%, 21% and 35% for the average, the minimum and the maximum flows of the study periods, indicating that the flow of the São Francisco river declined by more than thirty percent in the last 18 years.

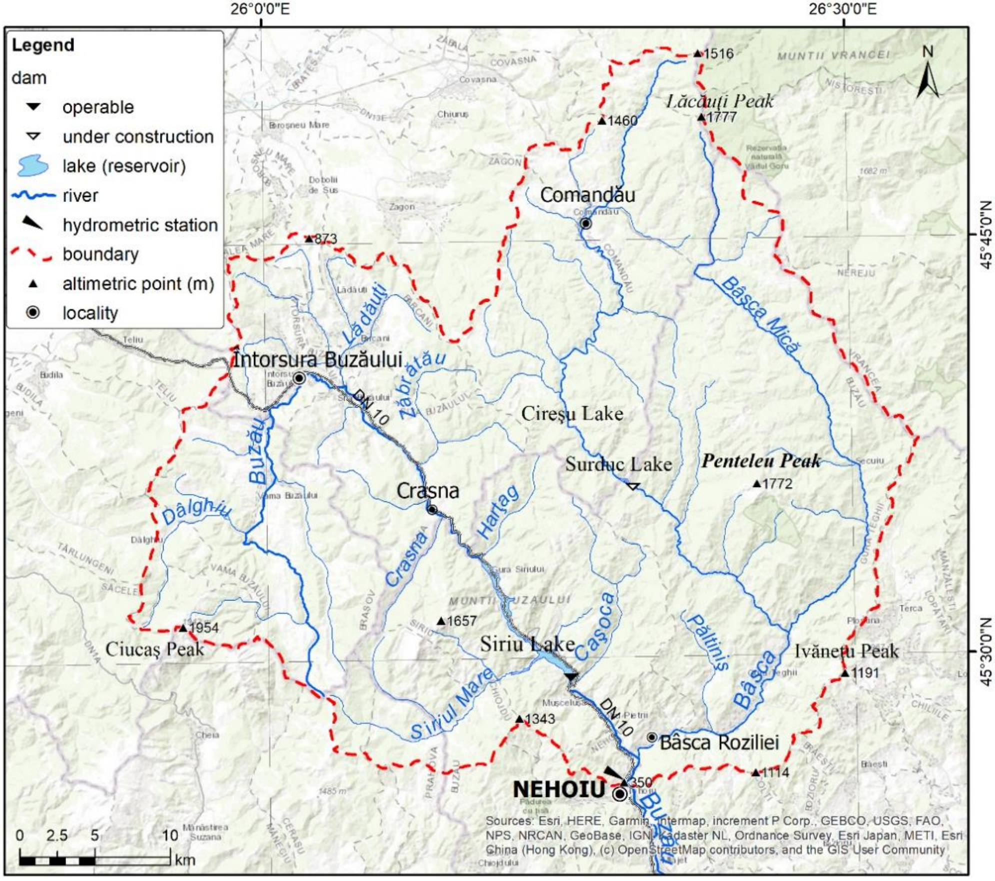
The Buzău river has also been a topic for other studies, which analyzed the monthly discharges (Mocanu-Vargancsik & Barbulescu, 2018), the maximum flow (Minea & Chendeș, 2013), the impact of the Siriu Dam and the characteristics before and after its construction (Minea & Barbulescu, 2014; Barbulescu, 2017). Various mathematical models have been used in modeling and forecasting a river discharge: from classical ones (Mocanu-Vargancsik & Barbulescu, 2018), to artificial intelligence (Postolache et al., 2010).

In this context, we observe that many studies evaluate the hydrological behavior, the impact of dam construction on hydrological regimes etc., but it has not been clarified yet which is the stationarity of a water discharge data under temporal variations. The aim of this paper is to provide a statistic overview on water discharge of the Buzău River (Romania), downstream the Siriu Dam, under temporal variations. At the same time, the focus was on trend and stationarity from the annually and seasonally scale.

Study area

Positioned in the external region of the Curvature Carpathians, the upper part of Buzău river catchment covers an area of 1,567 sq km. It lies at an average altitude of 1,043 m, between Lăcăuţi Peak (1,777 m a.s.l.) and Nehoiu hydrometric station - hs (385 m) (National Institute of Hydrology and Water Management Bucharest, 2013). The main tributaries of the Buzău river are the Dalgiu, the Lădăuți, the Crasna, the Siriul Mare, and the Bâsca (the most important) (Fig. 1.).

In 1985, the Siriu Dam started operating on the Buzău river, upstream Nehoiu h.s., so the station records the discharges after the streamflow has been modified by the passing through the dam. This station is located on the Buzău river, 45°25′29″ lat., 26°18′27" long., the multi-annual mean flow being 21.9 m³/s, and the specific mean being 17 l/s.km² (Fig. 1).



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Fig. 1: The upper part of the Buzău river catchment

The climate is in the temperate-continental class "dbf". The Föhn phenomena moderate the characteristic parameters of climatic elements (e.g. reduced precipitation amounts and moderate air temperature values).

The average multiannual temperature in the study area, at high elevation, ranges among 1.2°C at Lăcăuţi (1961-2006), 2.4°C at Penteleu (1988-2007), and 6.6°C at Întorsura Buzăului and 8.7°C at Nehoiu (1955-2010). According to Costache (2014), average multiannual precipitation values range between 595 and 961 mm/year. At both meteorological stations, summer is the wettest season, with 45% of the yearly amount of precipitation, followed by spring and autumn with comparable amounts (23% and 18% respectively), whilst winter is the driest, with 14% of the total annual amount of precipitation.

The pluviometric regime has a summer (June and July) torrential character, being favorable to flow occurrences, e.g., 105.7 mm in June at Întorsura Buzăului and 86.1 mm at Nehoiu (Fig. 2.). This study employs graphics related to precipitation and temperature (1955-2010), which were provided by https://climatecharts.net/ and the CRU at the University of East Anglia.

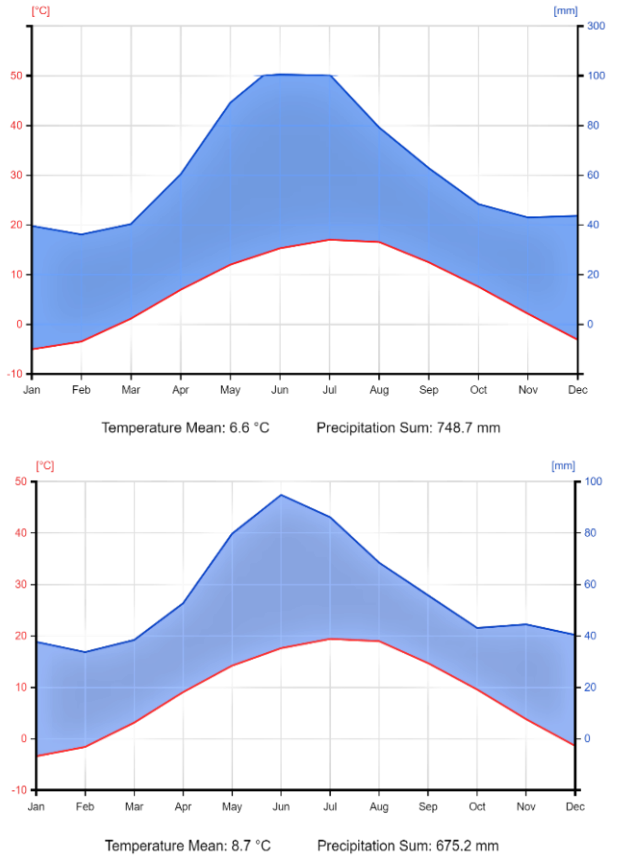


Fig. 2: Monthly average temperature and precipitation (1955-2010) at Întorsura Buzăului (up) and Nehoiu (down)

Data and methodology

Hydrological Data

The hydrologic data for the study spans on 56 years (from the 1st of January 1955 up to the 31st of December 2010) and consists of the daily mean water discharges registered at Nehoiu h.s., data provided by the National Institute of Hydrology and Water Management Bucharest, Romania. For a complete image, the time series is daily, monthly, seasonally, and annually investigated for trend and stationarity, at a global level and on the time subperiods imposed by the starting year of operation at the Siriu Dam. This date is late in 1984, so the subperiods are 1955-1984 and 1985-2010.

Trend estimation

One of the worldwide non-parametric methods for trend detection is Mann-Kendall (MK), which tests the null hypothesis of a non-existence trend against the alternative hypothesis that assumes existence. Counting the data entries in chronological order, the test statistic S is computed by Mann's formula (Mann, 1945):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \qquad (1)$$

where $sign(x_j - x_i) = \begin{cases} 1 \; if \; x_j - x_i > 0 \\ 0 \; if \; x_j - x_i = 0 \\ -1 \; if \; x_j - x_i < 0 \end{cases}$.

For n ≥10, the statistic S forms an approximate normal distribution with the mean zero E(S)=0 and the variance given by:

$$\sigma^2 = \frac{1}{18}[n(n-1)(2n+5) - \sum t_i(t_i - 1)(2t_i + 5)] \qquad (2)$$

where t_i denotes the number of ties to the extent i and the terms in the sum exist only the data series contains tied values. The standard test statistic z_S calculated as:

$$z_S = \begin{cases} \frac{S-1}{\sigma} \; if \; S > 0 \\ 0 \; if \; S = 0 \\ \frac{S+1}{\sigma} \; if \; S < 0 \end{cases} \qquad (3)$$

helps to draw the conclusion of the existence of a monotonic trend if $|z_S| > z_{\alpha/2}$.

The Seasonal Mann-Kendall test (SMK) ascertains the existence of a monotonic trend in seasonal data. SMK works as the MK test for each season (Hirsch, Slack, & Smith, 1982). For the same season, the individual mean and variance are added up and then applied (3) to find the test statistic. The outcomes of the Mann-Kendall test are affected by autocorrelation. More exactly, in the case of a positive autocorrelation, the resulting trend of the time series becomes significant random more often than the level of significance (Kulkami & Von Storch, 1995).

To eliminate this shortcoming, before applying the MK test, the "pre-whitening" has to be performed. The procedure implies the computation of lag-1 serial correlation. If it is smaller than 0.1, the MK test is applied to the series itself, otherwise, MK is applied to the new series. Each term of the new series is obtained by subtracting from the old series the term of the previous one multiplied by the lag-1, procedure starting with the second term (Storch & Navarra, 1999).

Sen's Slope Estimator

It is used to find the slope of a linear trend, if any, and works jointly with the MK trend test (Sen, 1968). The procedures assume that the estimation of the real slope is the median of all values of the paired data:

$$m_i = \frac{x_j - x_k}{j - k}, i = 1,2,\dots,n, j > k \qquad (4)$$

The method is robust, insensitive to outliers, more competitive than the linear regression for skewed and heteroskedastic data (Wilcox, 2010).

Stationarity

The study of stationarity helps to find out whether the mean value or the variance of a series undergoes changes in time. Actually, traditional methods in time series analysis and implementation of mathematical models require some type of stationarity. Moreover, non-stationarity can bring up some mechanisms, otherwise difficult to detect. In our case study, the stationarity has been tested annually and seasonally by using the augmented Dickey-Fuller (ADF) test and the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test.

The ADF test is an extension of the Dickey-Fuller test from 1979 (Dickey & Fuller, 1979), conducted through Ordinary Least Square (OLS) method that includes an AR (1):

$$x_t = \rho x_{t-1} + \varepsilon_t, t = \overline{1,N} \qquad (5)$$

where $(x_t)_{t-\overline{1,N}}$ is the time series, $x_t = 0, |\rho| \le 1$, and $(\varepsilon_t)_{t-\overline{1,N}\ t}$is the sequence of independent identically (iid) distributed random variables with mean zero and finite variance σ^2 called white noise (WN). The null hypothesis consists in $\rho = 1$, meaning the process has a unit root and is non-stationary, known as a random walk. The alternative hypothesis states that $|\rho| < 1$, equivalent the process is stationary. The test t-statistic is

$$t = \frac{\hat{\rho} - 1}{SE(\hat{\rho})} \qquad (6)$$

where $\hat{\rho} = \left(\sum_{t=1}^{N} x_{t-1}^2\right)^{-1} \sum_{t=1}^{N} x_t x_{t-1}$ is OLS estimation for the coefficient ρ and $SE(\hat{\rho})$ is its standard error. Under the null hypothesis, Dickey and Fuller (Dickey & Fuller, 1979) obtained the limiting distribution of the statistic with the percentiles presented in (Fuller, 1976). If *t* is "too negative", the null hypothesis is rejected. It has been demonstrated that this procedure remains valid asymptotically for a general ARIMA (*p,1,q*) process with unknown *p* and *q* orders (Hamilton, 1994).

It is to be noticed that under the same null and alternative hypotheses, the test works for the random walk with drift and random walk with drift and time trend with different regression testing and different distribution of the test statistics (Dickey & Fuller, 1979; Guilkey & Schmidt, 1991).

KPSS test. We assume that our time series can be decomposed into a sum (Kulkami & Von Storch, 1995) of the deterministic trend, a random walk, and a stationary error:

$$x_t = \beta t + r_t + \varepsilon_t,\ t = \overline{1,N} \qquad (7)$$

where: r_t is the random walk, i.e., $r_t = r_{t-1} + u_t$, u_t is i.i.d. (0, ${\sigma_u}^2$), βt is the deterministic trend and ε_t is a stationary error. For testing the stationarity in trend, the null hypothesis is ${\sigma_u}^2 = 0$, the meaning of the series is stationary around a deterministic trend. The alternative hypothesis is positive ${\sigma_u}^2$. In the case of testing the stationarity in level, the null hypothesis becomes $\beta = 0$. For trend stationarity, the residuals are $e_t = \varepsilon_t$, while for the level trend the residuals come only from an intercept, so $e_t = x_t - \bar{x}$. Let be $S_t = \sum_{j=1}^{t} e_j$ the partial sum of the errors and σ^2 the "long-run variance" of e_t, defined as $\sigma^2 = \lim_{N \to \infty} N^{-1} E[S_N^2]$, mean is the significance of E. A consistent estimator of σ^2 is given by:

$$\hat{\sigma}^2(p) = \frac{1}{N}\sum_{t=1}^{N} e_t^2 + \frac{2}{N}\sum_{j=1}^{p} w_j(p) \sum_{t=j+1}^{N} e_t e_{t-j} \qquad (8)$$

where p is the truncated lag, $w_j(p)$ is an optional weighting function that corresponds to the choice of a spectral window, e.g. Bartlett window $w_j(p) = 1 - j/(p+1)$. The statistic test is

$$KPSS = N^{-2} \sum_{t=1}^{N} S_t^2 / \hat{\sigma}^2(p) \qquad (9)$$

The KPSS statistics follow an asymptotic distribution in which upper tail values are given in (Kwiatkowskiv et al., 1992).

Results

The autocorrelation lag-1 has been performed for the monthly, seasonal and annual series, and for the subseries obtained by the Siriu Dam operation year. As per the XLStats findings, its construction increased the autocorrelation for all the series. Only for the Annual, the autocorrelation has become moderate (Table 1).

The applicability of the MK has been verified for winter, spring and fall, while the other series needed pre-whitening. The monthly, summer and 1955-1984 annual subseries, as well as all 1985-2010 subseries, except Summer, also required pre-whitening.

Table 1 ACF values for streamflow series

Series	Lag-1	Lag-1 1955-1984	Lag-1 1985-2010
Monthly	0.495	0.462	0.537
Winter	0.076	-0.203	0.433
Spring	0.018	-0.117	0.124
Summer	0.186	0.182	-0.106
Fall	-0.049	-0.162	0.231
Annual	0.292	0.407	0.148

Summer displays a significantly decreasing trend at a 10% level of significance (Sen's slope of -0.186). Its graphical representation is shown in Fig. 3.

The weak negative linear trend confirms the good influence of the Siriu Dam on smoothing the streamflow and gives evidence that few flooding summer episodes don't have a serious impact on the mean discharges.

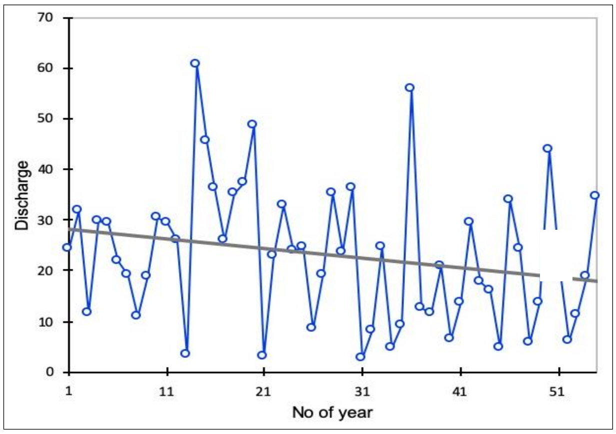


Fig. 3: Summer 1985-2010 pre-whited series with the trend

The subseries has significant trends only for 1985-2010 monthly, winter, fall and annual levels (Table 2).

Table 2 Significant MK test results and corresponding Sen's slopes for pre-whitened 1985-2010 series

Series	Conclusion
Monthly	Increasing trend. Slope=0.015
Winter	Increasing trend. Slope=0.330
Fall	Increasing trend. Slope=0.294
Annual	Increasing trend. Slope=0.419

The mean streamflow discharge for the monthly series has a slope almost equal to zero, so it is almost constant, while the winter, fall, and annual series display increasing trends (Fig. 4).

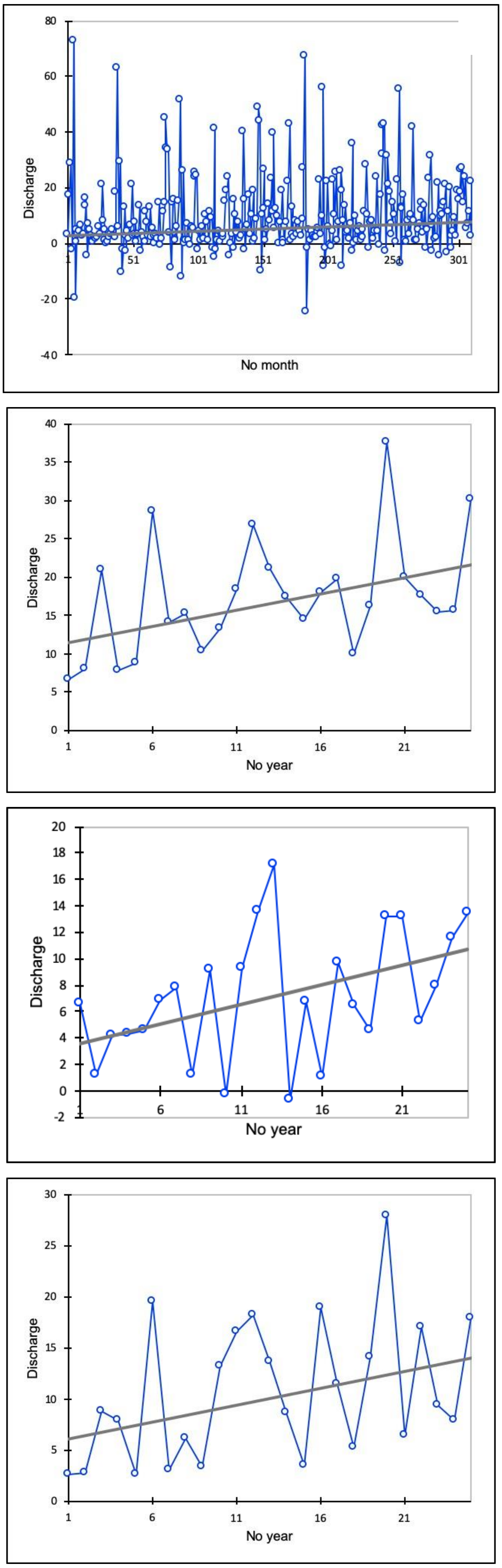


Fig. 4: Pre-whited series with significant trend 1985-2010 subseries a) Monthly b) Annual c) Winter d) Fall

The increase has occurred slowly; thus, it couldn’t be detected at a smaller scale, but it has become evident at a larger one. The annual growth is significant (slope=0.419), so globally speaking, the mean streamflow increases. For both ADF and KPSS tests, the choice for the lag length is very important, as it affects the power of the test. This shortcoming has been adjusted by Schwert (Schwert, 1988) and Harris (Harris, 1992). Their proposed formula is $p = \left[x\left(\frac{N}{100}\right)^{1/4}\right]$, with $x = 4;\ 12$, where $[x]$ represents the integer part. The stationarity ADF test results can be seen in Table 3 and those of KPSS test in Table 4. The tests have been performed at a 5% significance level. The lag length has been chosen according to the smallest tau-value/p-value. According to the results of our study, the entire streamflow processes on daily, monthly and annual timescale are basically non-stationary, lacking in trend (Table 3 and Table 4). The stationarity has occurred after 1985 (Table 5).

Table 3 ADF stationarity test results for streamflow series

Series	Lag	P-value	Test conclusion
Daily	15	<0.0001	No unit root. The series is stationary.
Monthly	6	<0.0001	
Winter	3	0.093	There is a unit root. The series is non-stationary.
Spring	3	0.093	
Summer	3	0.127	
Fall	3	0.262	
Annual	1	0.007	No unit root. The series is stationary.

Table 4 KPSS trend and level stationarity test results for streamflow series

Series	Lag	Trend P-value	Level P-value	Test conclusion
Daily	15	<0.0001	<0.0001	The series is non stationary in trend and non-stationary in level
Monthly	6	0.002	0.120	
Winter	3	0.060	0.413	The series is stationary in trend and level.
Spring	3	0.241	0.236	
Summer	3	0.200	0.016	The series is stationary in trend and non-stationary in level.
Fall	3	0.119	0.428	The series is stationary in trend and level.
Annual	1	0.023	0.291	The series is non-stationary in trend, but stationary in level.

Table 5 KPSS trend and level stationarity test results for streamflow 1985-2010 series

Series	Lag	Trend P-value	Level P-value	Test conclusion
Daily	12	<0.0001	<0.0001	The series non-stationary in trend and non-stationary in level.
Monthly	5	0.318	0.000	
Winter	2	0.568	0.001	The series is stationary in trend, but non-stationary in level.
Spring	2	0.776	0.058	The series is stationary in trend and level.
Summer	2	0.973	0.950	
Fall	2	0.544	0.006	The series is stationary in trend, but non stationary in level.
Annual	1	0.935	0.031	

Conclusions

The streamflow process on the Buzău river at Nehoiu h.s. has been investigated for trend and stationarity propose. The Mann-Kendall and Seasonal Mann-Kendall tests have been applied on the series themselves or on the pre-whitened ones. The slopes for the linear trends have been calculated by using Sen’s Slope Estimator.

Our results proved that after 1985, the streamflow has increasing trends at some seasonal, annual and monthly scales. The stationarity has been investigated by using ADF and KPSS tests and proved, with no exceptions, that after 1985 the streamflow series has become stationary in trend.

The daily series can pass neither the stationarity level nor the trend stationarity test at a 1% significance level. The results imply that the streamflow processes on the Buzău river have been globally impacted by the Siriu Dam.

Probably, the non-stationarity in trend and level after 1985 is more likely to be caused by human interventions and periods of flood and draught. The exploitation of the Siriu Dam, of its reservoir for water necessities, such as to produce electricity, also induces variations that may result in significant discharges at a short time scale.

The statistically non-significant increasing slopes of the seasonal series convey that the flood prone nature of this location doesn’t have a significant impact on the Buzău river discharge. In this regard, Retegan, Barbuc & Petre (2016), indicate in their research that the impact of the Siriu Reservoir upon the water discharge of the Buzău river is very low, the alteration of the natural conditions being insignificant (approximately 1%). At the same time, the annual series displays a statistically significant upward slope that suggests an important influence on the streamflow regime in this location. This statistically significant aspect may be due to climate change/variability. The studies showed that from 1901 to 2000, the average temperature has globally increased by $0.61 \pm 0.18°\mathrm{C}$, while for the northern hemisphere it increased by $0.71 \pm 0.31°\mathrm{C}$ (Cooper, Houghton, McCarthy, & Metz, 2002). To climate change can be added other factors such as topography, land use/land cover, anthropic intervention (e.g., deforestation). Moreover, it is known that, in the rainfall-runoff behavior, the key role is played by land cover, while in the flood event the soil and topography play this role.

We consider that during seasons, there are specific phenomena that disturb the streamflow process: heavy snows in winter, snow-melting in spring, short, heavy rains that produce floods or periods of drought in spring, summer, and fall. Therefore, we appreciate that our work provides a useful baseline for additional work (e.g., a detailed analysis of the relationship runoff-genetic factor, precipitation), and the authors did not pretend to find exhaustive clarification.

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