IMPACT OF METEOROLOGICAL DROUGHT ON STREAMFLOW DROUGHT USING STANDARDIZED INDICES IN THE TRANS-BOUNDARY PRUT RIVER BASIN

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The trans-boundary Prut River Basin (PRB) is one of the most drought vulnerable areas in the Republic of Moldova, Romania and Ukraine due to high water exploitation. In the years with a lack of snow were caused water deficiencies in the high flow season. This paper focuses on the Moldavian portion of Prut River's catchment within in the framework of the project IMDROFLOOD. The main objective of this study was to exploring the link between the standardized precipitation evapotranspiration index (SPEI) and the standardized streamflow index (SSI) in the PRB. The main procedures were the following: 1) correlating the SSI and SPEI at various lags to select the most proper timescale of SPEI; 2) identifying meteorological and streamflow drought events using the SPEI and SSI, and 3) analyzing the corresponding relationship and the possible lag of occurrence time between meteorological and streamflow drought events. Hydrological excess (flood) or deficit availability of water in the SSI can be profoundly explained by dryness and wetness conditions in the SPEI. The magnitude of correlation between SPEI and SSI displays an evident seasonality within the Prut Basin. The results show the highest correlation for early spring (on preceding season snowmelt). The highest flow is registered in June and is equal to 117-127 $m^{-3}s^{-1}$, and the minimal flow, under 60 $m^{-3}s^{-1}$, is registered during winter months. In the lower course of the river Prut in extreme dry months (SSI≤-2.0) volume of the river flow was below the ecological flow, which affecting the hydrological regime.

***Keywords:** drought, floods, standardized precipitation evapotranspiration index, standardized streamflow index*

INTRODUCTION

Drought often manifests itself as a creeping phenomenon, as the effects of drought often accumulate slowly over a prolonged period and may linger for years after the main event ceases. In our study, therefore, this issue is addressed with two multiscalar drought indices, i.e., the standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano et al., 2010) and the standardized streamflow index (SSI; Modarres, 2007, Telesca et al., 2012), as it successfully allows for the evaluation of the time lag that exists between the onset of the water shortage and the identification of its consequences in the trans-boundary Prut River Basin (PRB). All droughts originate from a deficiency of precipitation but other types of drought and impacts cascade from this deficiency (Fig. 1). Drought is modified by hydrological catchment processes that are changed by human activities (Loon et al., 2016; Fig. 2). The drought types can be grouped together as "climate-induced" drought and drought types based on human processes can be termed "human-induced" drought. This parallels an existing widely referenced typology of floods, which includes man-made flood alongside natural floods (flash flood and snowmelt flood). Romanescu (2015) demonstrated the influence of Stânca-Costești reservoir on the manifestation of flood waves within the upper and the lower sector of PRB. The timing of floods and the shape of the hydrograph are signs of the influences exerted by genetic factors, precipitations, dam and runoff on the Prut River.

MATERIALS AND METHODS

Study area

The Prut River's catchment is shared by Moldova, Romania and Ukraine (Fig. 3), and it is a trans-border river with 952.9 km in length, the first 211 km of the river is on Ukrainian territory, 31 km represents border between Romania and Ukraine, and the remaining 711 km represent a natural border between Romania and Moldova (71.9% of its total length). In terms of length it is the second longest tributary of the Danube. It is the last important tributary of the Danube before the latter discharges into the Black Sea. The hydrographical network measures 11000 km, of which 3000 km are permanent (33%) and 8,000 km have intermittent runoff (67%). The network has a density of 0.41 km/km^2. The catchment basin is part of the temperate continental climate, where rains are heavy.

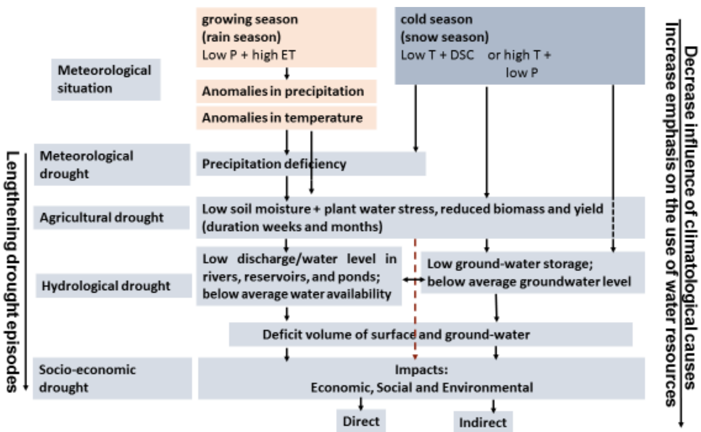


Figure 1. Drought types and their dependence on meteorological factors in the snow season and the growing season.

The flood waves of the upper sector are caused by the rains fallen in the Forested Carpathians. Because of slopes and high velocities, flood peaks are sharp, water levels are very high and they unfold within a very short time frame. Flood waves upstream from the Stânca-Costeşti reservoir (Sirauti st.) present natural forms, with steep peaks and slopes. Flood waves downstream from the Stânca-Costeşti reservoir (Ungheni st.) are artificial, controlled by the dam. The reservoir was constructed with a mitigation level of 550 millionm^3, allowing the mitigation of a 1% probability flood from 2940 to 700 m^{-3}s^{-1} (Romanescu and Stoleriu, 2017). After construction of the Stanca-Costetsti reservoir, floods on the Moldovian parts of the Prut diminished considerably.

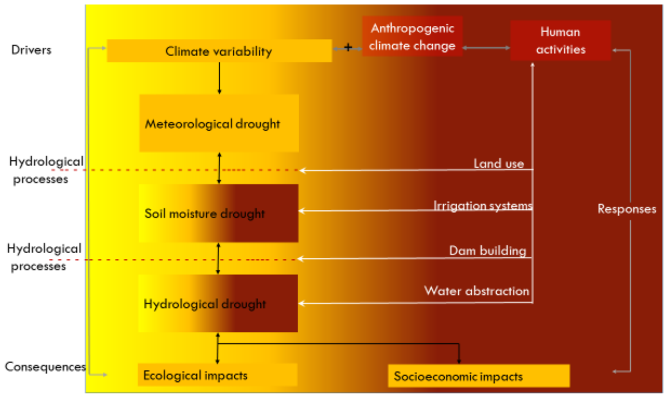


Figure 2. Drought propagation processes including natural and human drivers and feedbaks (modified from Loon et al., 2016).

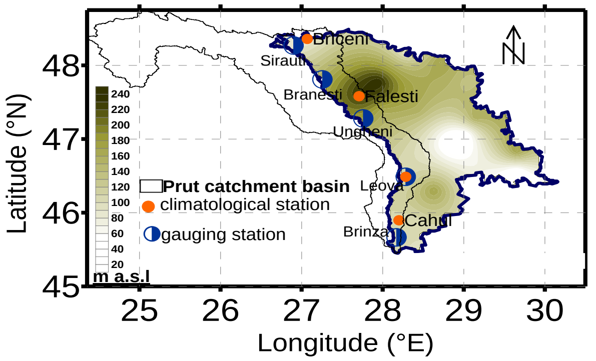


Figure 3. Distribution of the main climatological and hydrological stations in the Prut River's catchment.

Data and methods

Our study integrated hydrological and climatological observational networks such as five hydrological gauges (Sirauti, Braneste, Ungheni, Leova and Brinza) and four climatological stations (Briceni, Falesti, Leova and Cahul), which cover the PRB key area of the Republic of Moldova.

Table 1. Long-term of hydrological and climatological characteristics at the catchment level for the period 1986-2015.

	Winter	Spring	Summer	Autumn	Annual
		upstream sector			
Q, m^{-3}s^{-1}	38.2	100.5	103.0	53.5	73.7
H, cm	235	282	297	246	265
P, mm	104	149	244	123	621
ETo, mm	34.2	241.9	416.9	140.9	833.9
Tmean, °C	-3.0	8.7	18.8	8.6	8.3
Tmax, °C	0.0	13.9	24.7	13.4	13.0
Tmin, °C	-5.8	4.1	13.6	4.7	4.2
R, %	84	70	70	78	76
S, hours	198	567	818	407	1982
V, ms^{-1}	2.7	2.7	2.1	2.3	2.5
		downstream sector			
Q, m^{-3}s^{-1}	47.0	137.2	113.8	63.2	90.3
H, cm	156	218	219	164	189
P, mm	103	126	189	122	540
ETo, mm	45.4	264.1	447.6	162.9	920.0
Tmean, °C	-1.2	10.2	21.1	10.9	10.3
Tmax, °C	2.0	15.6	26.9	15.8	15.1
Tmin, °C	-3.8	5.8	16.0	7.0	6.3
R, %	84	70	70	78	76
S, hours	247	607	891	496	2236
V, ms^{-1}	4.1	4.1	3.3	3.5	3.8

Monthly data of 7 meteorological variables (the maximum [Tmax] and minimum [Tmin] temperatures, mean temperature [Tmean], wind speed [V], sunshine duration [S], relative air humidity [R], and precipitation amount [P]), and two hydrological variables (streamflow [Q] and water level [H]) over a 30-year period were used (Table 1). The application of the SPEI for the assessment of climate drought control and application of SSI to identify hydrological excess and deficit availability of water were applied. The SPEI from 1 to 24-month lags was calculated for the period 1961-2015, based on precipitation and input dataset for potential evapotranspiration (ETo) by the Penman-Montheith method. The monthly Q measured at the gauge stations were standardized (SSI), and then the correlation between SSI and multiple SPEI time scales was analysed. SPEI series that had the maximum correlation with the SSI was chosen to detect flood/drought event at the catchment level. Both indices are widely used, not only for purposes of drought identification, but also as an input to forecasting systems. SSI providing a perspective on high and low flow periods associated with drought and flood at multiple time scales was analysed.

RESULTS

The top years with the highest and lowest measured daily and monthly flow at Sirauti st. are shown in Table 2. The summer flood wave of 2008 was the highest in the history of the PRB, with a maximum discharge of 4090 m^3/s (30-31 July) – featured the most interesting characteristics: upstream from the dam, it was sharp, with extremely abrupt slopes; downstream from the dam, the flattened top maintained – with few alterations" (Romanescu, 2015). The top years with the highest and lowest observed daily water levels for five hydrological gauges are shown in Table 3.

Table 2. The top years with the highest and lowest measured daily and monthly flow at Sirauti st.

	Daily					Monthly			
	Min. flow, m^{-3}s^{-1}	Date min. flow	Max. flow, m^{-3}s^{-1}	Date max. flow	Normal	Min. flow, m^{-3}s^{-1}	year	Max. flow, m^{-3}s^{-1}	year
Jan	7.3	26.01.2004	716.0	30.01.2002	36.6	11.4	1993	80.1	2011
Feb	6.7	28-29.02.2012	210.0	09.02.2004	40.2	13.2	2003	91.1	2002
Mar	9.0	12.03.2005	868.0	31.03.2006	78.8	32.9	1991	210.0	1999
Apr	31.7	19.04.1990	1270.0	19.04.1996	115.0	43.8	1996	241.0	2006
May	26.4	30.05.2000	1980.0	22.05.1998	112.0	42.5	2000	242.0	1998
Jun	21.3	27.06.2003	1910.0	30.06.2010	127.0	27.7	2000	450.0	2010
Jul	17.0	24-25.07.2012	4090.0	30-31.07.2008	124.0	21.9	2000,2012	539.0	2010
Aug	16.0	29.08.2012	1820.0	21.08.2005	88.0	23.5	2012	268.0	2005
Sep	15.2	15,18.09.2012	1260.0	10.09.1996	72.5	17.7	2012	170.0	1996
Oct	15.8	27-29.10.2012	784.0	07.10.2008	55.0	16.9	2012	132.0	2008
Nov	11.2	30.11.1993	468.0	19.11.1995	50.9	17.6	2011	96.8	1998
Dec	9.6	18.12.2012	290.0	11.12.2010	40.7	14.7	2012	73.3	1996

Table 3. The top years with the highest and lowest observed daily water levels (H, cm)

Gauging station	Normal	H_{max}		H_{min}	
	cm	cm	date	cm	date
Şirăuţi	111	1164	28.07.2008	22	15-18.09.2012(2)
Brăneşti	268	832	31.07.2008	170	12-22.1994(2)
Ungheni	97	699	09.07.2010	-86	19.02.1983, 27.12.1984
Leova	107	620	05-06.05.1996	-114	16-17.12.2015
Brînza	203	527	20.07.2010	0	13-14.02.1984

To select the most suitable time scale of SPEI, Pearson correlations between SSI and different timescales of SPEI have been conducted. The result indicates that the increasing of time scales from 1-month to 3-month raises the correlation coefficient significantly. After 3-month, it goes almost steady till 12-month and then decreases. Thus, the 1- and 3-month is selected as the most suitable time scale of SPEI to identify the meteorological drought regarding of its relation with streamflow drought. These results indicate that in the PRB, discharge is more determinates by precipitation and/or climate water balance of previouse 2 months than over longer periods. The next question arises, namely how quickly and/or slowly responding of streamflow to climate variables and drought signal? Hydrological excess (flood) or deficit availability of water in the SSI can be profoundly explained by dryness and wetness conditions in the SPEI (Fig. 4-5). In the PRB, SSI is quickly responding to precipitation, but storage in reservoir (regulate water flows) causes some delay in downstream sector. These stores create a long memory in the hydrological system, which determines the transformation of the drought signal. Streamflow drought of year 2007 is followed by a long period with sufficient discharge to let the system recover to its original state (Fig. 5).

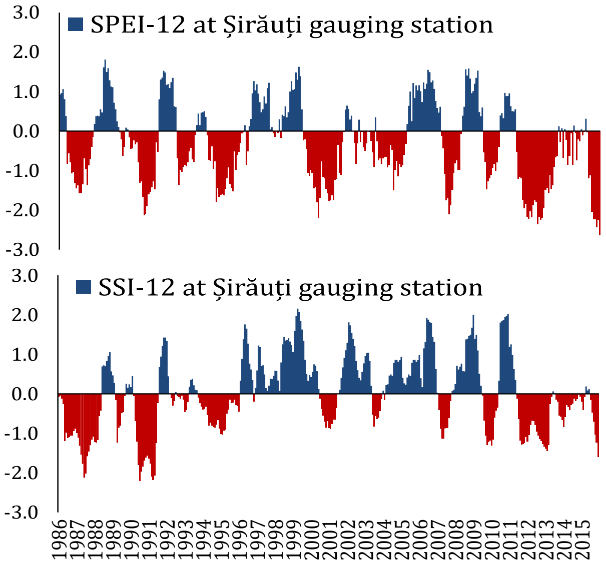


Figure 4. Temporal evolution of the SPEI and SSI at 12-month lag during January 1986 to December 2015 in the downstream sector.

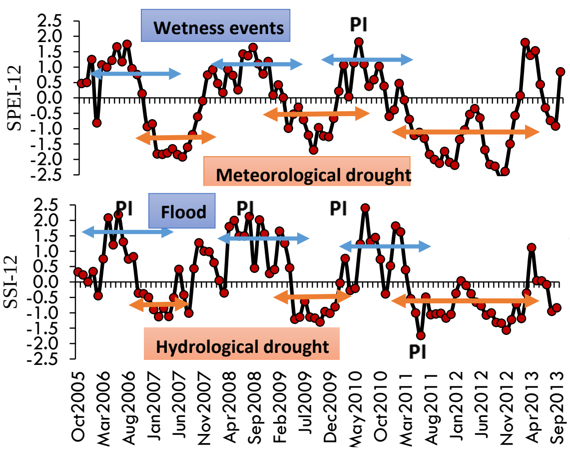
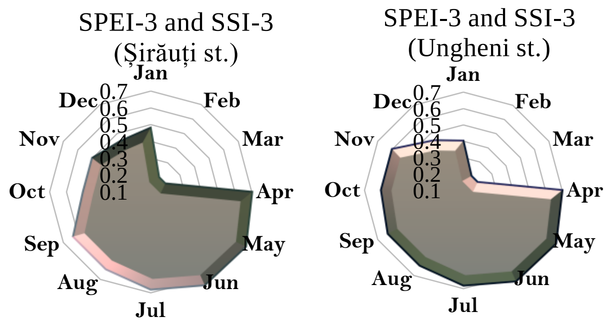


Figure 5. The time lag between meteorological drought and streamflow drought events in the downstream sector.

Multiyear drought is not compensated by sufficient discharge to assure a complete recovery of the system. The high precipitation after the multiyear drought is almost completely used to recover soil moisture and little remains for recovering streamflow level. If the system does not recover before the next meteorological drought develops it turns into a multiyear drought (2011-2012 and 2014-2015). Q shows high correlation with variables related to climate. The high precipitation results in high Q, which the strongest correlation was found from May to August (r =0.68 to 0.73). According to the hydrological drought typology, the most severe streamflow droughts in PRB are classical rainfall deficit droughts. Although other climate variables play an important role as well (temperatures and ETo). In winter with below-zero temperatures and snow accumulation, snow-related processes play a role in drought development. Snow accumulation and frozen soils cause storage of water and prevent recharge to the groundwater, resulting in decreasing groundwater levels and streamflow throughout the winter. During the summer season, potential evapotranspiration is generally higher than precipitation, which potentially gives evapotranspiration a larger role in drought development. At shorter time scales, the maximum correlation between SPEI and SSI was found at the 3-month lag in May-June (r=0.74). In summary, high correlation (r>0.65) were found during later spring and early summer, and low correlations were found during later autumn and winter (Fig. 6).



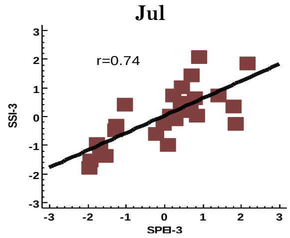


Figure 6. The spider plot summarized the correlation coefficients (r) between the monthly SSI-3 and SPEI-3 for two hydrological gauges. Linear regression plot between SSI-3 and SPEI-3 for June (as an example).

CONCLUSION

To identify streamflow drought′s response to meteorological drought, the relationships between SSI and SPEI has been investigated. The relationship between precipitation, temperatures, potential evapotranspiration and streamflow has also been analysed. Consecutive meteorological drought events have an essential impact on the lasting of streamflow drought. How is the time lag affected by rainfall, temperatures, ETo, vegetation cover, and anthropogenic activity? These issues would be a logical next step after this research.

Acknowledgement

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