Temperature-based Evapotranspiration in the WSVI Drought Index Implementation
Case Study: Pannonian Basin

Slavisa Trajkovic¹, Milan Gocic¹

¹ Faculty of Civil Engineering and Architecture, University of Nis, 14 Aleksandra Medvedeva, 18000 Nis, Serbia

Abstract
Drought is a natural hazard that affects environmental and socio-economic development. In this study, the Water Surplus Variability Index (WSVI), which is based on both precipitation and Penman-Monteith (PM) evapotranspiration (ET) estimates, was used to quantify drought. The application of the WSVI is not possible in some locations because of the missing data for estimating ET. The key objectives of this research were to 1. compare the different temperature-based WSVIs for the 1-, 3-, 6- and 12-month timescales with the original PM-based WSVI; 2. improve the WSVI by replacing the full-set PM equation with the corresponding temperature-based ET equation, such as Hargreaves, adjusted Hargreaves, Thornthwaite, modified Thornthwaite or temperature-based PM; and 3. compare the best temperature-based WSVI with the Standardized Precipitation Index (SPI). The set of meteorological data was obtained from several stations from Pannonian Basin (Budapest, Debrecen, Novi Sad and Sombor). According to statistical indicators, the Hargreaves-based WSVI (WSVIH) was ranked first or second for each time period at all locations. The WSVIH was additionally tested using the SPI for each location and each timescale. The obtained results indicated the capability of the WSVIH to quantify drought frequency, duration and severity identified by the SPI. Finally, the WSVI can be recommended using the Hargreaves equation instead of the full-set PM equation in future WSVI implementations in the Pannonian Basin.

Keywords
drought, evapotranspiration, temperature, WSVI, Pannonian Basin, SPI

1 Introduction
Drought is a natural hazard that affects water resources, agricultural production and natural ecosystems. Deficit irrigation and drought-tolerant crops can become a sustainable strategy in a drought-prone environment [1–3]. Many drought indices have been introduced to characterize drought conditions. One of the most explored is the precipitation-based index, the Standardized Precipitation Index (SPI) [4]. Although precipitation is one of the main drought indicators, temperature is also an important factor that can characterize drought as it controls evapotranspiration (ET). Many indices use ET and precipitation in the process of drought assessment, monitoring and prediction: the Palmer Drought Severity Index (PDSI) [5], the Reconnaissance Drought Index (RDI) [6], the Standardized Precipitation Evapotranspiration Index (SPEI) [7], the Water Surplus Variability Index (WSVI) [8, 9], the Standardized Evapotranspiration Deficit Index (SEDI) [10], the Crop Reconnaissance Drought Index (CRDI) [11]. Many of these indices (PDSI, RDI, SPEI) use the temperature-based Thornthwaite equation [12] to estimate ET. However, the WSVI enforces the Penman-Monteith method (PM) [13] to calculate ET. The Food and Agriculture Organization of the United Nations (FAO) recommends PM as the standard ET equation. This equation requires numerous input data such as wind speed, temperature, solar radiation, and relative humidity. Therefore, the WSVI is not applicable in many sites because of missing data for estimating ET. There are many studies on applying different ET estimation methods to numerous drought indices [14–22]. The results suggested that the method used to estimate ET can have a significant role in quantifying drought for many regions of the world. If all input data are available, the Penman-Monteith equation is recommended for worldwide implementation of...
the Standardized Precipitation Evapotranspiration Index (SPEI), else the Hargreaves or Thornthwaite equations are recommended [23]. In the Loess Plateau (China), the two-source evapotranspiration method or Penman-Monteith equation is proposed instead of the Thornthwaite equation in the calculation of the SPEI [24]. The key objectives of this research were to:

1. compare the different temperature-based WSVIs for the 1–, 3–, 6– and 12– month timescales with the original PM-based WSVI;
2. improve the WSVI by replacing the full-set PM equation with the adequate temperature-based ET equation; and
3. compare the best temperature-based WSVI with the Standardized Precipitation Index (SPI).

Drought trends in Serbia (Novi Sad and Sombor) from 1980 to 2015 and Hungary (Budapest and Debrecen) from 1971 to 2010 were evaluated using five temperature-based versions of the WSVI. These WSVIs were calculated using ET values obtained by the various temperature-based equations (Hargreaves, adjusted Hargreaves, Thornthwaite, modified Thornthwaite and temperature-based Penman-Monteith).

2 Methodology and material

2.1 Study area

In this research, four meteorological stations in Serbia and Hungary were selected. The time series of the monthly mean of daily actual vapor pressure ($e_a$), sunshine hours ($n$), minimum temperature ($T_{min}$), maximum temperature ($T_{max}$), wind speed ($U_a$) and precipitation ($P$) during the period 1980–2015 were used for the Serbian stations (Novi Sad and Sombor). The time series of the monthly mean of daily sunshine hours ($n$), minimum temperature ($T_{min}$), maximum temperature ($T_{max}$) and precipitation ($P$) during the period 1971–2010 were used for the Hungarian stations (Budapest and Debrecen). The average temperature ranged from 10.2 °C to 12.2 °C, and the mean RH for these locations varied from 72% to 77%. The mean annual $U_a$ ranged from 1.25 m s$^{-1}$ to 2.82 m s$^{-1}$. Sunshine hours varied from 4.7 h day$^{-1}$ to 5.7 h day$^{-1}$. The mean annual sum of $P$ ranged from 563 mm to 710 mm.

2.2 Water surplus variability index

WSVI is calculated as:

$$\text{WSVI}_k^{ij} = \frac{D_k^{ij} - \mu}{\sigma}$$

where WSVI = water surplus variability index, $k$ = month, $i$ = year, $D$ = monthly water surplus or deficit, $\mu$ = mean and $\sigma$ = standard deviation.

Water surplus $D_k^{ij}$ is estimated as:

$$D_k^{ij} = \sum_{j=1}^{k} (P_j - ET_j)$$

where $P_j$ = precipitation and $ET_j$ = $ET$ of month $j$ for year $i$.

2.3 Penman-Monteith equation

The PM equation was explained in detail in [13]:

$$ET_0 = \frac{0.408 \times \Delta \times (R_n - G) + \frac{900}{T + 273} U_s \times (e_a - e_s)}{\Delta + \gamma (1 + 0.34 \times U_s)}$$

where $ET_0$ = reference evapotranspiration (mm day$^{-1}$), $T$ = mean temperature (°C), $R_n$ = net radiation (MJ m$^{-2}$ day$^{-1}$), $U_s$ = wind speed at a 2 m height (m s$^{-1}$), $G$ = soil heat flux density (MJ m$^{-2}$ day$^{-1}$), $e_a$ = saturation vapor pressure (kPa), $\Delta$ = slope of the saturation vapor pressure function (kPa °C$^{-1}$), $\gamma$ = psychometric constant (kPa °C$^{-1}$) and $e_s$ = actual vapor pressure (kPa).

2.4 Temperature-based PM equation

Alternative procedures for missing weather data estimation were proposed by [13]. When radiation data are missing, the temperature data are applied for the radiation estimation:

$$R_s(T) = K (T_{max} - T_{min})^{0.15} R_a$$

where $R_s(T) = $ temperature-based solar radiation (MJ m$^{-2}$ day$^{-1}$), $T_{max} = $ maximum temperature (°C), $T_{min} = $ minimum temperature (°C), $R_a = $ extraterrestrial radiation (MJ m$^{-2}$ day$^{-1}$) and $K = $ adjustment coefficient.

The extraterrestrial radiation is the solar radiation at the top of the atmosphere and depends only on latitude and day or month of the year. If the vapor pressure data are lacking, the minimum temperature can be used to calculate vapor pressure:

$$e_a(T) = 0.611 e^{-\frac{1727.2}{T_{min} + 257.5}}$$

where $e_a(T) = $ temperature-based actual vapor pressure (kPa), $T_{min} = $ minimum temperature (°C).

If the wind speed data are missing, the average wind speed can be used instead of measured wind speed values. Allen et al. [13] suggested using the global mean wind speed where $U_{2g} = 2.0$ m s$^{-1}$. The temperature-based PM equation (PMT) used in this research is:
\[ ET_0 (T) = \frac{0.408 \times \Delta \times R_s (T) + \gamma \frac{900}{T+273} U_{24} \times (e_s - e_v (T))}{\Delta + \gamma (1 + 0.34 \times U_{24})} \] (6)

2.5 Hargreaves equation

The frequent absence of weather data encouraged Hargreaves to present a simple temperature-based equation [25]:

\[ ET_{0,H} = 0.0023 \times (T_{\text{max}} - T_{\text{min}})^0.4 \left( \frac{T_{\text{max}} + T_{\text{min}}}{2} + 17.8 \right) \] (7)

where \( ET_{0,H} \) = Hargreaves-based \( ET_0 \) (mm day\(^{-1}\)) and \( HE \) = empirical Hargreaves exponent, \( T_{\text{max}} \) = maximum temperature (°C), \( T_{\text{min}} \) = minimum temperature (°C). Two Hargreaves approaches were presented in this study: \( H (HE = 0.5 [25]) \) and \( AH (HE = 0.424 [26, 27]). \)

2.6 Thornthwaite equation

Thornthwaite equation can be written as [12]:

\[ ET_{0,T} = \frac{16N}{360} \left( \frac{10T_i}{\sum_{j=1}^{k} (0.274)^{\frac{1}{1.514}}} \right) \] (8)

where \( N \) = maximum sunshine duration (hours) and \( T_i \) = mean temperature (°C).

Equation (8) can be improved by using an "effective" temperature \( T^*_i \) instead of the mean temperature [28]. The effective temperature can be estimated as:

\[ T^*_i = 0.5k (3T_{\text{max}} - T_{\text{min}}) \] (9)

where \( T^*_i \) = effective temperature (°C), \( T_{\text{max}} \) = maximum temperature (°C), \( T_{\text{min}} \) = minimum temperature (°C) and \( k \) = empirical coefficient. Camargo et al. [28] suggested \( k = 0.72 \) for Brazilian locations. Different values of \( k \) were tested in [29] and [30]. Pereira and Pruitt [29] proposed to replace \( T^*_i \) with adjusted effective temperature \( (T^*_j) \).

\[ T^*_j = T^*_i \frac{N}{24-N} \] (10)

with the following restriction: \( T \leq T^*_j \leq T_{\text{max}} \). Two Thornthwaite approaches were used in this study: TH with mean temperature \( T \) [12] and ATH with adjusted effective temperature \( (T^*_j) \) [29].

2.7 Evaluation criteria

In this study, the root-mean-square error (RMSE) and mean absolute error (MAE) were used as statistical indicators:

\[ \text{MAE} = \frac{\sum_{j=1}^{k} |\text{WSVI}_{pm,j} - \text{WSVI}_{eq,j}|}{K} \] (11)

\[ \text{RMSE} = \left[ \frac{\sum_{j=1}^{k} (|\text{WSVI}_{pm,j} - \text{WSVI}_{eq,j}|)^2}{K} \right]^{\frac{1}{2}} \] (12)

where \( \text{WSVI}_{pm} \) = PM-based WSVI, \( \text{WSVI}_{eq} \) = temperature-based WSVI and \( K \) = the number of data.

3 Results and discussion

The statistical summary of WSVI values calculated by the various \( ET \) methods for the 1-, 3-, 6- and 12–month timescales is presented in Table 1.

The Hargreaves-based WSVI (WSVIH) for each timescale was found to be in excellent agreement with the PM-based WSVI (WSVIPM) at all sites. The RMSE for the 1–, 3–, 6– and 12–month timescales was in the range of 3.8 – 7.1 \times 10^{-3}, 3.9 – 7.8 \times 10^{-3}, 4.3 – 8.5 \times 10^{-3} and 4.0 – 9.2 \times 10^{-3}, respectively. WSVIH yielded the smallest RMSE nine times (at one station for 1–month timescale, two stations for 3-month timescale, three stations for 6–month timescale, and three stations for 12–month timescale) and the second smallest RMSE seven times. In other words, WSVIH was ranked as either the first or second for each timescale at all stations. The temperature-based PM WSVI (WSVIPMT) yielded very good agreement with the WSVIPM at all sites with the RMSE for the 1–, 3–, 6– and 12–month timescales ranging 3.8 – 7.1 \times 10^{-3}, 3.8 – 7.9 \times 10^{-3}, 4.0 – 8.6 \times 10^{-3} and 4.2 – 9.4 \times 10^{-3}, respectively.

The WSVIPMT yielded the smallest RMSE four times in the case of Novi Sad (1–month time scale) and Debrecen (1–, 3–, and 6–month timescales) and the second smallest RMSE eight times.

The adjusted Hargreaves-based WSVI (WSVIAH) was reasonably good at all sites with the RMSE for the 1–, 3–, 6– and 12–month timescales ranging 4.1 – 6.9 \times 10^{-3}, 4.5 – 8.3 \times 10^{-3}, 4.8 – 9.2 \times 10^{-3} and 5.1 – 10.0 \times 10^{-3}, respectively. The WSVIAH yielded the smallest RMSE values only two times in the case of Sombor (1–month timescale) and Novi Sad (3–month timescale) and the second smallest RMSEs three times at Budapest (3–, 6– and 12–month timescales). The adjusted Thornthwaite-based WSVI (WSVIATH) was the second lowest ranking approach thirteen times with the RMSE for the 1–, 3–, 6– and 12–month timescales varying 6.0 – 8.0 \times 10^{-3},...
5.9 – 9.0 × 10⁻³, 5.8 – 9.4 × 10⁻³ and 5.4 – 9.9 × 10⁻³, respectively. The Thornthwaite-based WSVI (WSVITH) yielded the largest RMSE values fifteen times and the second largest RMSE in only one case (Sombor, 3-month timescale). In other words, the Thornthwaite-based WSVI was the lowest ranking for each timescale at all locations except WSVITH–3 for Sombor. The obtained WSVIs demonstrate that the Hargreaves equation performed much better than the other temperature-based equations. Overall, the results suggest using the Hargreaves equation instead of the full-set Penman-Monteith equation in calculating the WSVI drought index. In addition, the WSVIPM and WSVIH were compared with the Standardized Precipitation Index (SPI) for each location and for each timescale. The precipitation-based SPI index has been recommended by the World Meteorological Organization (WMO) as the standard meteorological drought index [31]. The characteristics of SPI, WSVIPM and WSVIH for the 1–, 3–, 6– and 12–month timescales during 1980–2015 at the Sombor station are presented in Table 2. The results indicate a perfect agreement between WSVIPM and WSVIH in both the wet and drought periods. Both WSVI versions were found to be in very good agreement with the SPI for each timescale. Results showed that the WSVI yielded a lower severity during drought episodes and a higher severity during wet episodes compared to the SPI.

The WSVI and SPI presented very similar drought frequencies and durations in each timescale. Similar results were obtained at the other locations. The drought indices that referred to six months of the growing season from April to September (WSVIPM–6, WSVIH–6 and SPI–6) for each year at the Sombor station are presented in Fig. 1. The perfect agreement between the two versions of WSVI and an excellent agreement between the SPI and WSVI for the most months are shown in this Fig. 1. The WSVI slightly overestimated the SPI during extreme wet periods and underestimated SPI during extreme drought periods, with the conclusion that the main differences in severity between the SPI and WSVI (Table 2) originated from extreme drought and wet episodes. The WSVI underestimation of extreme droughts is caused by the introduction of evapotranspiration in the WSVI estimation. The variation in the time series of precipitation (P) is higher compared to the time series P–ET₀. Similar results were obtained using other ET-based drought indices [8, 9, 32].
Conclusions
Evapotranspiration variability can play a significant role in quantifying drought. The key objective of this study was to present a simpler and more flexible approach to implement WSVI in the Pannonian basin by introducing the temperature-based instead of the PM-based ET estimation. Data from four meteorological stations in Serbia (Novi Sad and Sombor) and Hungary (Budapest and Debrecen) were used as the basis for computing the WSVI drought index. Thus, the five temperature-based ET equations (Hargreaves, adjusted Hargreaves, Thornthwaite, modified Thornthwaite, and temperature-based PM) were tested against the standard PM equation. The temperature-based ET WSVIs were compared to the original WSVIPM. The Hargreaves-based WSVI (WSVIH) yielded excellent agreement with the WSVIPM. This approach was the first ranking approach nine times and the second ranking seven times (out of the altogether 16 evaluated cases when counting stations and timescales). This means that the WSVIH was ranked first or second for each timescale at each location.

These results indicate that the WSVIH performed better than the other selected temperature-based WSVIs. The WSVIPM and WSVIH were additionally tested using the SPI. Overall, these results demonstrate the capability of WSVIPM and WSVIH to quantify the drought frequency, duration and severity identified by the SPI. The drought severity, duration and frequency of the WSVIH and WSVIPM are almost equal. Both versions of the WSVI presented a moderate severity compared to the SPI. The drought duration and frequency identified by the WSVIPM and WSVIH were quite similar to those obtained by the SPI.

One can conclude that using the Hargreaves equation instead of the full-set Penman-Monteith equation will not compromise the reliability of the WSVI drought index. In the future research, the same procedure can be performed for more Pannonian stations to confirm the obtained results in the present study. Also, in the future research, any missing weather variable could be estimated using numerical weather reanalysis.

Acknowledgement
The study is supported by the Serbian Ministry of Science, Technological Development and Innovation. The authors are grateful to reviewers for valuable comments that helped to improve original manuscript.
References


