Understanding the Complexity of Drought within the Soil Profile in Beech Ecosystems on Their Lower Altitudinal Limit in Slovakia

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Abstract: Due to the ongoing climate change, decreasing amounts of available water and increasing evapotranspiration during the growing season may impact the stability of some beech ecosystems at lower altitudes. This paper aims to evaluate the risk of drought from a meteorological point of view and the subsequent response in soil hydrology throughout hydrological years 2015 and 2016 in beech forests situated in Central Slovakia. Precipitation sufficiency was assessed by means of a climate irrigation index (CII). Hydrological modelling was carried out using GLOBAL, the simulation model of water movement in a soil profile with an emphasis on the root zone. The greatest drought risk occurs during the summer, when the ecosystem suffers from long periods of water deficiency according to the CII (>20 days). The water content in specific soil horizons responds differently to changing meteorological situations. Simulations indicated a later decrease (approx. 5 days) of the water content in the B horizon (main root zone) compared with the A horizon. Drought lasts longer in deeper layers and retreats only in the case of long-lasting rainfall. Sudden heavy rainfall has proven ineffective at moistening the entire soil profile and impacts only the upper few centimetres while the main root zone suffers from water shortage.

Keywords: beech ecosystems; drought; model GLOBAL; climate irrigation index

1. Introduction

European beech (Fagus sylvatica L.) is the most important and widespread broadleaved tree species in Slovakia, covering up to 33.9% of the forest area [1]. Generally, the natural area of beech is limited by the availability of water [2]. European beech prefers temperate climates with mild winters and moist summer conditions; a pronounced continental climate is not suitable, and summer drought seems to be a significant distribution limit [3,4]. However, due to their deep rooting systems, beech forests have a considerable capacity to access deep soil water [5]. Drought tolerance is influenced by the position of a given tree and specific site conditions, including soil properties [6,7]. In times of global climate change, extreme climatic conditions increase, which makes species, especially those growing in southern limits, more sensitive to them [8]. Drought is considered a creeping phenomenon with a gradual onset. Consequences in ecosystems are usually visible after some time has passed [9]. In Slovakia, we can observe a trend of decreasing rainfall during the growing season, rising temperatures and a saturation deficit at lower altitudes [10]. Climate change scenarios predict substantial drying in Slovakia’s southern regions [10,11]. The increasing risk of extremely dry years includes soil climate changes, resulting in increased soil erosion or lower productivity [12]. A key aspect of productivity in each ecosystem, including forests, is the water regime of the soil profile, which depends on the inflow and outflow of water in the unsaturated soil zone [13]. From a meteorological point of view, a simple method of water balance evaluation based on a climatic index of irrigation is widely used in Slovak conditions on a landscape scale [14,15]. However, since the calculations are based on
the differences between the water gained from precipitation and water that could evaporate from the fully saturated ecosystem (potential evapotranspiration), it does not provide information about how drought patterns differ among specific depths of the soil profile with different hydrophysical characteristics. For this purpose, it is needed to consider the water changes within the soil profile during the year, particularly during episodes with low water supplies, when the amount of water available for plants is limited [13]. Hydrolimits are helpful to calculate the water balance in the soil profile. A hydrolimit is the soil water content reached under certain conditions [16]. Theoretically, the total available water (extractable water) in the root zone is the difference between the water content at field capacity (FC) and the wilting point (WP). However, the water uptake is reduced well before the wilting point is reached. When the soil water content drops below a threshold value and water can no longer respond to the transpiration demand, the crop begins to experience stress [17,18]. The onset of drought in the root zone can be defined by reaching the point of decreased availability hydrolimit (PDA) at the water potential of pF 3.3. After reaching this state, the vegetation suffers from water stress [13,16]. However, direct measurements of water changes in the soil profile on a daily time step is often unavailable due to technical aspects. Therefore, modelling water changes in the vadose zone provides more detailed information about drought severity in the soil.

This study is focused on the characterisation of drought episodes from a meteorological point of view and the subsequent response in soil hydrology on the lower altitudinal ecological limit of beech occurrence in Slovakia, where the risk of drought is relevant [10, 11,19]. The aim was to understand the evolution of drought within the soil profile in response to extreme weather conditions during the vegetation season. The climatic index of irrigation (CII) was used in order to detect episodes of high evapotranspiration demands that are not met due to a lack of precipitation or their uneven distribution. Afterwards, hydrological modelling was carried out based on the meteorological characteristics, canopy parameters and hydrophysical properties of the soil profile. Changes in the availability of soil water during the hydrological year were assessed for the different horizons of the soil profile to find the differences in drought evolution.

2. Materials and Methods

2.1. Study Area

The study area, Bienska, is situated in Central Slovakia along the Southern Kremnica Mountains (450 m a.s.l.). It is a part of the oak–beech altitudinal forest zone, the lower edge of the beech occurrence in Slovakia. The forest stand is about 65 years old and lies on a research plot consisting solely of European beech (Fagus sylvatica L.) [5]. According to the Landscape Atlas of the Slovak Republic [20], Bienska belongs to a semi-humid, slightly warm climatic district with a mean annual temperature of 7.3 °C and mean annual precipitation of 690 mm. The geological substrate is composed of volcanic parent material (andesite and andesitic tuffs). The soil at the research plot was classified as Haplic Cambisol (Humic, Eutric, Endoskeletic and Silotic) [5,21]. The soil profile terminated around a depth of 66 cm, and four horizons were identified. The surface held leaf litter at a thickness of 5 cm. In the A horizon, the soil was dark brown, and the roots were abundant. Coarse fragments comprise less than 2% of the soil there. The textural classification was silt loam. At a depth of around 4 cm, there was a visible transition to the B horizon, which was brown-coloured and silt loam according to the textural class. The percentage of coarse gravel and stones was 10%, and the abundance of the roots was still relatively high. At a depth of 22 cm, there was a transition to the grey-brown B/C1 horizon, which was loamy sand comprising 30% of coarse fragments. The density of the roots of the B/C1 horizon decreased, and at a depth of 40 cm, where the B/C2 horizon occurred, the root zone was terminated. These depths were highly influenced by the volcanic parent material andesite, which was visible in a high content of coarse gravel and stones (60%).
2.2. Mathematical Model GLOBAL

In this study, the mathematical model GLOBAL was applied to model the water dynamics in the soil profile throughout the study period based on the soil characteristics and meteorological and phenological measurements. GLOBAL is a one-dimensional mathematical model of water movement in the soil aeration zone [22]. The model is based on solving the nonlinear partial differential equation of water transport in soil profiles. It is defined in Richard’s equation:

\[
\frac{\partial h_w}{\partial t} = \frac{1}{c(h_w)} \frac{\partial}{\partial z} \left[ k(h_w) \left( \frac{\partial h_w}{\partial z} + 1 \right) \right] - \frac{S(z, t)}{c(h_w)}
\]

where \( h_w \) is the soil water potential (cm), \( k(h_w) \) is the unsaturated hydraulic conductivity (cm\( \cdot \)s\(^{-1} \)), \( S(z, t) \) is the intensity of the root water uptake (cm\( \cdot \)s\(^{-1} \)), \( z \) is the vertical coordinate (cm), \( t \) is the time coordinate (s) and

\[
c(h_w) = \frac{\partial \theta}{\partial h_w}
\]

where \( \theta \) is the volumetric water content (cm\(^3\) cm\(^{-3} \)). To calculate the water distribution in the soil profile, van Genuchten’s [23] parameters were used. They allow the expression of unsaturated hydraulic conductivity (\( h_w \)), depending on the water content or water potential.

The boundary condition at the upper boundary of the unsaturated soil is based on meteorological data and stand characteristics. The transport of water towards the soil profile takes place via precipitation or irrigation. It is possible to run daily simulations, which are useful for evaluating the current water content in soil profiles during its interactions with the root zone and vegetation, respectively [22,24]. Since the water table was located far below the domain of interest and did not affect the flow in the transport domain, the bottom boundary condition was characterised as a free drainage. A summary of the input data is shown in Table 1.

**Table 1. Summary of the inputs to the GLOBAL model.**

| Meteorology ¹ | Precipitation (mm\( \cdot \)day\(^{-1} \)) |
|---------------|------------------------------------------|
|               | Mean Air Temperature (°C)                |
|               | Sunshine (h)                             |
|               | Vapor Pressure (hPa)                     |
|               | Wind Speed (m\( \cdot \)s\(^{-1} \))     |
| Vegetation Canopy Parameters | Leaf area index (LAI) (m\(^2\)\( \cdot \)m\(^{-2} \)) ¹ |
|               | Albedo (-) ¹                             |
|               | Surface roughness (m\(^2\)) ¹           |
|               | Root depth (cm) ¹                        |
|               | Potential root water uptake factor (0,1) |
|               | Feddes parameters                       |
| Hydrophysical parameters ² | \( \theta_r \) residual water content (cm\(^3\)\( \cdot \)cm\(^{-3} \)) |
|               | \( \theta_s \) saturated water content (cm\(^3\)\( \cdot \)cm\(^{-3} \)) |
|               | \( K_s \) saturated hydraulic conductivity (cm\( \cdot \)day\(^{-1} \)) |
|               | \( \alpha, n \) parameters of van Genuchten’s soil hydraulic functions |
| Initial condition within the soil profile ² | Initial water content (cm\(^3\)\( \cdot \)cm\(^{-3} \)) |
| Bottom boundary condition | Free Drainage |

¹ Daily data. ² Set for each soil horizon.

2.3. Hydrophysical Characteristics

The soil profile was not vertically homogenous, and the horizons had different properties and compositions (described in Section 2.1 Study area). For this reason, three soil
samples from each horizon of the representative soil profile were taken. A pressure plate apparatus (NTE 5 produced by TLAKON SK, s.r.o. Žilina. Manufacturing No. 14521/2012) was applied to measure the points of a drying branch on the soil water retention curve for each horizon, approximated using van Genuchten’s method [23] (3) considering Mualem’s model (4) below:

\[
\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha h)^n]^m}
\]

\[
m = 1 - \frac{1}{n}
\]

where \(\theta\) is the volumetric water content (cm\(^3\)·cm\(^{-3}\)), \(\theta_r\) is the residual water content, \(\theta_s\) is the saturated water content and \(h\) is the pressure (kPa). Hysteresis can be assumed, but for this study, only drying soil hydraulic functions were measured. To fit values of the retention curve, the RETC program [25] was used from PC-PROGRESS (version 6.02/2009).

Values of saturated hydraulic conductivity (\(K_s\)) were intended according to Orfánus & Sitková [26], while there was a strong decreasing tendency with the depth [5]. A summary of the hydrophysical characteristic inputs is displayed in Table 2.

Table 2. Hydrophysical characteristics of each horizon of the soil profile.

| Soil Horizon | Saturated Water Content \(\theta_s\) (cm\(^3\)·cm\(^{-3}\)) | Residual Water Content \(\theta_r\) (cm\(^3\)·cm\(^{-3}\)) | Parameter \(\alpha\) (cm\(^{-1}\)) | Parameter \(n\) (-) | Saturated Hydraulic Conductivity \(K_s\) (cm·day\(^{-1}\)) |
|--------------|---------------------------------|---------------------------------|-----------------|-----------------|---------------------------------|
| A (0–4 cm)   | 0.517                           | 0.094                           | 0.014           | 1.284           | 76.85                           |
| B (5–22 cm)  | 0.512                           | 0.089                           | 0.016           | 1.264           | 66.52                           |
| B/C1 (23–40 cm) | 0.563                        | 0.086                           | 0.009           | 1.311           | 56.43                           |
| B/C2 (41–66 cm) | 0.595                        | 0.088                           | 0.047           | 1.202           | 25.72                           |

Besides this, the soil moisture profile was measured from samples using the gravimetric method for each horizon. It was needed for the model to set the initial water content (IWC) at precise observation nodes (depths) to calculate the initial amount of water in the soil profile at the beginning of the simulation. The IWC in the A horizon was 0.383 cm\(^3\)·cm\(^{-3}\), in the B horizon, 0.397 cm\(^3\)·cm\(^{-3}\), in B/C1, 0.390 cm\(^3\)·cm\(^{-3}\), and in the B/C2 horizon, 0.382 cm\(^3\)·cm\(^{-3}\).

2.4. Meteorological Data

Meteorological data were used from an automatic weather station (EMS Brno, Brno, Czech Republic) situated in an open field close to the research stand. The air temperature (°C) and relative humidity (%) were measured at the height of 2 m. Global radiation (W·m\(^{-2}\)) was measured at 5-min intervals, and precipitation was recorded continuously at 1 m above the ground. The measured data were stored as 20-min averages in a data logger (EMS Brno, Brno, Czech Republic) [5]. The potential evapotranspiration (PET) was calculated using the Penman equation [27]. It represents theoretical atmospheric evaporative demands when the soil water deficiency is not considered:

\[
\text{PET} = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} \frac{6.43(1 + 0.536u_2)D}{\lambda}
\]

where \(\Delta\) is the slope of the saturation vapour pressure curve, and \(R_n\) is the net radiation (W·m\(^{-2}\)) estimated as 80% of the global incoming solar radiation. The psychometric constant \(\gamma\) was set at 66 Pa·K\(^{-1}\), and the latent heat of vaporisation \(\lambda\) was set at 2.45 MJ·kg\(^{-1}\) [18]. \(D\) is the vapour pressure deficit defined as \(e_v - e_a\) (kPa), where \(e_v\) is the saturated vapour pressure at a given air temperature, and \(e_a\) is the vapour pressure of the free-flowing air. For this calculation, a constant wind speed of 1.5 m·s\(^{-1}\) at the height of 2 m was used.
The information about wind speed (m·s$^{-1}$) and vapour partial pressure (hPa) needed for GLOBAL were collected from a nearby meteorological station of the Slovak Hydrometeorological Institute situated in Sliač. The station is at an altitude of 313 m a.s.l., and the comparability of the meteorological data from these two stations was confirmed [21].

2.5. Root System Data

Since the model puts emphasis on the root zone, root distribution functions (RDF) are considered, as well as the Feddes water stress model for the water uptake under limited conditions [28,29]. The depth of the root zone was set as a constant with consideration of the length of the modelled period. From in situ observations, the root zone termination was found at a depth of 40 cm, while a decrease in the root density was significant from a depth of 22 cm. Therefore, considering the beech root system [30,31], the potential root water uptake factor was assumed to be 1 in the uppermost 22 cm. From this depth, the potential root water uptake decreased to 0 in a depth of 40 cm. For water uptake under limited conditions, the Feddes water stress model [28] was implemented while, in view of the site conditions of the research area, as well as the results of previous studies [5,32], aeration stress was neglected. According to Šípek et al. [33], this was defined as the pressure head below which roots start to extract water from the soil ($P_0 = -10$ cm), the pressure head below which roots extract water at the maximum possible rate ($P_1 = -10$ cm) and the pressure head below which roots can no longer extract water at the maximum possible rate ($P_2 = -800$ cm). The value of the pressure head below which the root water uptake ceases was defined at the wilting point ($P_3 = -$ cm) [28].

2.6. Leaf Area Index Measurement

Seasonal changes in the LAI were measured during the vegetation season of 2019 via a non-destructive optical method using a LAI-2200 Plant Canopy Analyzer (LI-COR Biosciences, Lincoln, NE, USA). The Plant Canopy Analyzer measures the fraction of diffuse sky radiation that passes through the canopy (gap fraction) as a function of the zenith angle. It requires an above-canopy reading for reference. Sunlit leaves are problematic, but LAI-2200 provides post-measurement corrections for direct sunlight. During the vegetation season, 20 in situ measurements were carried out (Table 3). Approximate daily data were gained by linear interpolation between the measured values, which is in correspondence with a chart of seasonal changes in the stand characteristics, according to Allen et al. [18]. These data were used as typical seasonal LAI changes for both hydrological years.

| Date     | LAI       | Date     | LAI       | Date     | LAI       | Date     | LAI       |
|----------|-----------|----------|-----------|----------|-----------|----------|-----------|
| 12 March | 1.027 ± 0.07 | 13.04    | 1.461 ± 0.04 | 29.04    | 4.526 ± 0.08 | 01.08    | 5.920 ± 0.08 |
| 20 March | 1.821 ± 0.04 | 15.04    | 1.780 ± 0.03 | 06.05    | 5.393 ± 0.08 | 01.09    | 4.540 ± 0.08 |
| 1 April  | 1.787 ± 0.02 | 17.04    | 2.097 ± 0.05 | 15.05    | 5.693 ± 0.09 | 01.10    | 3.900 ± 0.08 |
| 8 April  | 1.658 ± 0.15 | 21.04    | 2.745 ± 0.04 | 21.06    | 5.931 ± 0.07 | 23.10    | 3.757 ± 0.07 |
| 9 April  | 1.649 ± 0.08 | 25.04    | 3.950 ± 0.08 | 01.07    | 6.100 ± 0.08 | 30.10    | 3.142 ± 0.10 |

2.7. Albedo and Surface Roughness

The methodology of indirectly estimating the albedo and surface roughness for the Slovak conditions was developed by Novák [34] based on publications by Doorenboos & Pruitt [35] and Allen et al. [18]. It is based on the four stages of stand development and the five thresholds separating them. Changes in the albedo and surface roughness can be calculated indirectly if the LAI is known [34]. First, it is necessary to set the relative LAI ($\omega_r$), which is defined as:

$$\omega_r = \omega / \omega_{0,m}$$ (6)
where $\omega$ is the LAI, and $\omega_{0,m}$ is the maximum value of the LAI during the vegetation season. The relationship between the $\omega_r$ and albedo ($a$) is:

$$a = (a_m - a_s) \cdot \omega_r + a_s$$

(7)

where $a_m$ is the maximum value of albedo during the vegetation season, and $a_s$ is the albedo of bare soil without vegetation. The relationship between the $\omega_r$ and surface roughness ($z_0$) is:

$$z_0 = (z_{0,m} - z_{0,s}) \cdot \omega_r + z_{0,s}$$

(8)

where $z_{0,m}$ is the maximum value of surface roughness during the vegetation season, and $z_{0,s}$ is the surface roughness of the bare soil without vegetation. The maximum values of the albedo and surface roughness were estimated for deciduous forests according to the stage of the stand development, as well as the albedo and surface roughness of bare soil without vegetation [34,35].

2.8. Climatic Index of Irrigation and Hydrolimits

To evaluate drought occurrence, two approaches were applied. First, from a meteorological point of view, the CII was used, which is defined as the difference in water that could evaporate from sufficiently moistened soil profiles and plants (PET) and water that an ecosystem obtains from precipitation (P). Positive values represent water deficits in soil profiles, and negative values indicate a surplus of water supply [14,15]. Based on the daily values of the CII, we summarised the water deficiency days (WDD) for each month as days when there was a positive value of the CII. Secondly, the hydrolimits FC, PDA and WP were used. According to convention, the FC was defined at the water potential of $pF = 2.2$, PDA at $pF = 3.3$ and WP hydrolimit at $pF = 4.18$ [16]. After the drying branch of the soil water retention curve was measured, the critical water content of the hydrolimits for each horizon of the soil profile was calculated (Table 4). The PDA was used as the critical threshold of the onset of soil drought and the FC and WP as the range of water availability (extractable water) [16,17].

Table 4. Mean values of the critical soil water content ($cm^3 \cdot cm^{-3}$) of the FC, PDA and WP hydrolimits (calculated) for each horizon of the soil profile.

| Soil Horizon | A   | B   | B/C1 | B/C2 |
|--------------|-----|-----|------|------|
| FC ($pF$ 2.5)| 0.366| 0.367| 0.417| 0.424|
| PDA ($pF$ 3.3)| 0.258| 0.262| 0.279| 0.284|
| WP ($pF$ 4.18)| 0.185| 0.189| 0.188| 0.191|

2.9. Data Analysis

To assess the water balance in the forest ecosystem, it is important to take into account not only the growing season but also the winter period, which is hydrologically important for the creation of water reserves for the following year. Therefore, data based on the hydrological year, which begins on 1 November and lasts until 31 October of the following year, were evaluated [36].

GLOBAL provides raw data about the water content at each cm of depth in the soil profile. Since the soil profile was not vertically homogenous, it was divided into four horizons of different depths. The information about water changes was calculated as an average per cm of depth for each horizon, which made them comparable. Basic statistical analyses of the daily values and monthly averages were provided using R (R Core Team 2013). The variability in the changes in the water content was evaluated using the monthly coefficient of variance. The Pearson correlation coefficient (PCC) was also calculated to evaluate the relationship between the results of GLOBAL and the CII in different soil horizons.
3. Results

3.1. Analysis of Meteorological Conditions

The seasonal dynamics in precipitation and air temperature and their comparison with the long-term mean in Bienska Valley (450 a.s.l.) are shown in Figure 1. The total precipitation in the hydrological year 2015 was 612.8 mm, which was 88.5% normal. The winter months were below the long-term mean (roughly 30% less); therefore, the water supplies for the upcoming growing season were insufficient. The temperatures during the winter and early spring were significantly above normal; thus, the snow cover was depleted. The greatest positive temperature deviation from normal was recorded in January (+3.02 °C). The distribution of rainfall during the growing season was uneven; long periods without rain were intermitted by acute rainfall (May and July). In June, a precipitation of only 15.2 mm was recorded, and there was a period of 15 days without any rain that began at the end of this month. The maximum mean daily temperature for all growing seasons was recorded during this time (25.8 °C on 7 July). July was dry, except for enormous rain over three days when the precipitation reached 67.2 mm in total. In August, there was no rain for 20 days, but the duration of rainless episodes was three days on average. September had 16 days without rain, with an average rainless duration of two days. During the entire growing season (April–September), the precipitation was 15% less than the long-term mean. October, as the last month of the hydrological year, had a total precipitation of 188% compared to the normal.

| Year | June | July | August | September |
|------|------|------|--------|-----------|
| 2015 | 15.2 | 0.0  | 87.5   | 0.0  |
| 2016 | 15.0 | 0.0  | 72.3   | 0.0  |

The hydrological year 2016 had a precipitation level of 782.4 mm (113% of the long-term mean). In February, 41 mm of precipitation was recorded in one day. The distribution of precipitation during the growing season was uneasy. The first long, rainless period began on 17 March and lasted 22 days. The following months were similar to the long-term mean, except for August and October, which had more precipitation. In August, we recorded 127.6 mm of precipitation, with the maximum being 47 mm over two days. The mean temperature during these two days was 15 °C, which was 3 °C less than normal. Afterwards, no rain fell over the following 13 days, which confirms the uneasy distribution of the precipitation. During the autumn, the distribution of rain was more equable, while September was slightly warmer and drier than normal (Figure 1).
3.2. Climatological Drought

To evaluate the drought risk from a climatological perspective, the climate irrigation index (CII) was used. The results showed that both growing seasons lacked the precipitation needed to meet the demands of the ecosystem, even though, during the growing season of 2016, the precipitation was above average (Figure 2). The growing season of 2015 was significantly dry, with reduced water supplies during the winter and spring months. The driest month was July, when the WDD were recorded for 25 days, and the total missing water reached 129 mm (Table 5). Cumulative values showed a fast-growing water deficit during the summer and its accumulation until the end of October with a 212.6 mm water deficit (Figure 3a).

![Figure 2. Monthly totals of the CII and its components (P and PET).](image)

Table 5. Sum of the occurrences of days with water deficiencies during the hydrological years 2015 and 2016.

| Month | HY 2015 | HY 2016 |
|-------|---------|---------|
|       | Water Deficiency Days (WDD) | Precipitation in WDD (mm) | PET in WDD (mm) | CII in WDD (mm) | Water Deficiency Days (WDD) | Precipitation in WDD (mm) | PET in WDD (mm) | CII in WDD (mm) |
| XI    | 21      | 0.6     | 11.4  | 10.8  | *       | *       | *       | *       |
| XII   | 16      | 0.6     | 5.6   | 5     | 19      | 0.4     | 4.7     | 4.3     |
| I     | 18      | 1       | 6.1   | 5.1   | 23      | 1       | 6.48    | 5.48    |
| II    | *       | *       | *     | *     | 11      | 1.4     | 8.95    | 7.55    |
| III   | 24      | 3.2     | 48.9  | 45.7  | 25      | 1       | 48.3    | 47.3    |
| IV    | 25      | 2.8     | 89.4  | 86.6  | 24      | 1       | 80.9    | 79.9    |
| V     | 21      | 5.2     | 84.4  | 79.2  | 25      | 5.4     | 94.9    | 89.5    |
| VI    | 28      | 4.6     | 125.7 | 121.1 | 23      | 10.4    | 109     | 98.3    |
| VII   | 25      | 6.6     | 136.5 | 129.9 | 23      | 6.8     | 108     | 101.6   |
| VIII  | 26      | 3       | 109.5 | 106.5 | 22      | 4.4     | 91.1    | 86.7    |
| IX    | 24      | 5       | 67.5  | 62.5  | 26      | 1.8     | 74.3    | 72.5    |
| X     | 18      | 0.4     | 24.4  | 24    | *       | *       | *       | *       |

* Indicates no data.
During growing season 2016, the water supplies were larger, but an uneven distribution of precipitation created a lack of water for more than 20 days of each month from March to September (Table 5). The monthly precipitation exceeded the demands of the ecosystem only in August. However, the distribution of precipitation must be considered. The daily measurements showed that August had 18 rainless days, and 127.6 mm of precipitation was recorded in the remaining 13 days. However, relatively sufficient water supplies from the spring months contributed to the delay of drought onset. The maximum value of the cumulative water deficit (62 mm) was recorded in the middle of August. At the end of October, there was only 6.9 mm of missing water (Figure 3b), which was 206 mm less than the previous year. Thus, sufficient spring water supplies were essential to mitigate the effects of drought on the ecosystem during the summer months.

3.3. Seasonal Changes in Water Content (Results from GLOBAL)

The drought risk was evaluated in terms of the PDA hydrolimit. A summary of the drought episodes in hydrological years 2015 and 2016 with the water content under the PDA lasting longer than 10 days is shown in Table 6. From November 2014 until the end of February 2015, significant variations in the soil moisture were not observed, and the volumetric water content in the A horizon was, most of the time (85/120 days), above the field capacity (0.366 cm\(^3\)·cm\(^{-3}\)), with an average water content of 0.375 cm\(^3\)·cm\(^{-3}\). Since then, the upper horizon of the soil profile became more dynamic, which persisted throughout the growing season (Table 7). During March, two episodes with reduced water contents were modelled, but they lasted only 5 days on average in the A horizon (Figure 4a). In the B horizon, an episode of drought began 2 days after the second drought episode in the A horizon and lasted 6 days longer (Figure 4c). The subsequent precipitation enhanced the water supply in these upper layers. In mid-April, a 16-day dry episode began in the A horizon with an average water content of 0.233 cm\(^3\)·cm\(^{-3}\). In the B horizon, the water content was below the PDA 5 days later and lasted 6 days longer. In the B/C1 horizon, the situation was different (Figure 5a). The dry episode started 17 days later than the first drought episode in the A horizon but lasted 38 days until the beginning of May. During this month, there was another episode of drought significant in the A and B horizons, which was caused by the suction of water in the root zone. A noteworthy situation was in the B/C2 horizon, where the water content was below the PDA hydrolimit from 10 March until the beginning of May (57 days) (Figure 5c). We assumed it was related to a lower initial water content (0.382 cm\(^3\)·cm\(^{-3}\)) and because of the water suction in the main root zone concentrated above this horizon. Increases in the water supply were caused by six days of continuous rain (75.6 mm in total) that started on 20 May. In June began the greatest drought episode, which was specific in each horizon. The water content dropped below the PDA hydrolimit firstly in the B/C2 horizon and lasted until the second half of July.
(50 days), because water from precipitation was gained in the upper layers. In the main root zone, which terminated at a depth of 40 cm, drought started in the bottom layers (35–40 cm) 6 to 7 days earlier and lasted 5–9 days longer. The water supplies from precipitation came from the soil surface with a time delay that grew along with the depth, while the activity of the root zone was continuous in the whole root zone. According to the CII, there was a water deficit of more than 200 mm for the ecosystem from the beginning of June until the second half of July, when an improvement towards a relatively optimal water status in the soil profile was indicated. There was an increase in precipitation, as well as a decrease in extreme temperatures. At the end of August, another drought episode began, which lasted under the PDA for 20 days in the A horizon. In the B horizon, the soil water content fell below the PDA for 25 days until the second half of September, with a time delay of 3 days (Figure 4a,c). In the B/C1 horizon, a dry episode began 4 days after the B horizon and lasted 40 days. The most unfavourable situation was in the B/C2 horizon, where a drought episode lasted 57 days, with an average water content of 0.246 cm$^3$·cm$^{-3}$ (Figure 5a,c and Table 6).

Table 6. Summary of the occurrences of days with water contents under the PDA hydrolimit.

| Layer  | Date                        | Duration (Days) | Precipitation (mm) | PET (mm) | CII (mm) | Average Water Content (cm$^3$·cm$^{-3}$) |
|--------|-----------------------------|-----------------|--------------------|----------|----------|------------------------------------------|
| A (0–4 cm) | 12–27 April 2015            | 16              | 1.6                | 61.0     | 59.4     | 0.233                                    |
|        | 5–19 May 2015               | 15              | 6.0                | 60.0     | 54.0     | 0.237                                    |
|        | 19 June–7 July 2015         | 19              | 1.1                | 85.8     | 84.7     | 0.228                                    |
|        | 30 August–18 September 2015 | 20              | 11.8               | 62.2     | 50.4     | 0.248                                    |
|        | 22 March–7 April 2016       | 17              | 0.0                | 47.5     | 47.5     | 0.231                                    |
| B (5–22 cm) | 21–31 March 2015            | 11              | 27.6               | 19.8     | −7.9     | 0.255                                    |
|        | 17 April–3 May 2015         | 17              | 14.2               | 54.1     | 39.9     | 0.246                                    |
|        | 7–24 May 2015               | 18              | 44.2               | 65.3     | 21.1     | 0.253                                    |
|        | 13 June–12 July 2015        | 30              | 14.2               | 139.9    | 125.7    | 0.253                                    |
|        | 2–25 September 2015         | 24              | 39.4               | 63.3     | 23.9     | 0.238                                    |
|        | 1–14 October 2015           | 14              | 21.6               | 15.7     | −5.9     | 0.253                                    |
|        | 25 March–26 April 2016      | 33              | 21.6               | 91.7     | 70.1     | 0.24                                     |
| B/C1 (23–40 cm) | 28 March–4 May 2015         | 38              | 64.2               | 108.8    | 44.6     | 0.266                                    |
|        | 12 June–16 July 2015        | 35              | 14.4               | 164.0    | 149.6    | 0.272                                    |
|        | 6 September–15 October 2015 | 40              | 77.2               | 74.5     | −2.7     | 0.257                                    |
|        | 1–29 April 2016             | 29              | 39.8               | 82.9     | 43.1     | 0.262                                    |
|        | 2–22 June 2016              | 21              | 54.2               | 86.8     | 32.6     | 0.270                                    |
|        | 30 September–9 October 2016 | 10              | 0.6                | 12.3     | 11.7     | 0.269                                    |
| B/C2 (41–66 cm) | 10 March–5 May 2015         | 57              | 86.0               | 145.2    | 59.2     | 0.264                                    |
|        | 1 June–21 July 2015         | 50              | 28.8               | 245.9    | 217.1    | 0.276                                    |
|        | 23 August–18 October 2015   | 57              | 120.8              | 127.6    | 6.8      | 0.246                                    |
|        | 26 March–2 May 2016         | 38              | 40.8               | 105.3    | 64.5     | 0.258                                    |
|        | 23 May–27 June 2016         | 36              | 79.8               | 156.1    | 76.3     | 0.261                                    |
|        | 19 September–21 October 2016| 33              | 73.4               | 44.2     | −29.2    | 0.244                                    |
status in the soil profile was indicated. There was an increase in precipitation, as well as a decrease in extreme temperatures. At the end of August, another drought episode began, which lasted under the PDA for 20 days in the A horizon. In the B horizon, the soil water content fell below the PDA for 25 days until the second half of September, with a time delay of 3 days (Figure 4a, c). In the B/C1 horizon, a dry episode began 4 days after the B horizon and lasted 40 days. The most unfavorable situation was in the B/C2 horizon, where a drought episode lasted 57 days, with an average water content of 0.246 cm$^3$·cm$^{-3}$ (Figure 5a, c and Table 6).

Figure 4. Seasonal changes in the volumetric water content (cm$^3$·cm$^{-3}$) (a) in the A horizon in HY 2015 and (b) in HY 2016, (c) in the B horizon in HY 2015 and (d) in HY 2016 and their relation to the PDA hydrolimit (dashed line). The sum of the days under the PDA is stated in the box under the dashed line.
In HY 2016, the model exposed a sufficient water supply during the winter and early spring. A significant decrease in the water content began in March, when a continuous decline from 0.402 cm³·cm⁻³ to 0.252 cm³·cm⁻³ was recorded in the A horizon over 16 days. In this horizon, the volumetric water content was continuously under the PDA for 17 days, which was the longest drought episode in HY 2016 (Figure 4b). It was an absolutely rainless episode, and according to the CII, the ecosystem missed 47.5 mm of water. In the B horizon, the episode under the WP started 4 days later but lasted until the end of April (33 days) (Figure 4d). In the B/C1 and B/C2 horizons, the drought episodes started later but lasted longer (Figure 5b,d). Later, at the end of May, another dry episode began. In the upper horizon, it was not marked because of the early supplement of water from precipitation. We identified two drought episodes in the B horizon, with an average length of 7 days. In the B/C1 horizon, a water content under the PDA hydrolimit was recorded for 21 days and, in the B/C2 horizon, for 36 days. Since July and August had higher than average precipitation (219.4 mm in total) (Figure 1), there was a significant supply of water in the soil profile. That caused an increase in the water content nearly to the winter status and later mitigated the impacts of a lack of precipitation in September, which was below the long-term mean. The autumn dry episode was not very pronounced, since the vegetation season was terminated, and the transpiration demands were reduced to a minimum value.

Overall, HY 2015 was dry, with more than 110 days under the PDA hydrolimit in the main root zone (B and B/C1 horizons), while the most significant drought was during the autumn (Figures 4c and 5a). The number of drought episodes, as well as their average duration, was higher than in HY 2016 (Table 6). HY 2016 was more sufficiently supplied
by precipitation. One larger drought episode in the spring was identified, but since then, the ecosystem was in a relatively optimal state. Especially beneficial was August with a higher precipitation, which returned the soil moisture to the optimal state until the end of the growing season.

### 3.4. Dynamics of the Water Content in Different Soil Horizons

The results of the model showed several trends in the dynamics of the water content in Bienska Valley related to the soil depth and the individual characteristics of the soil horizons. The upper horizons of the soil profile were recognised to be more dynamic during changes of the water contents during the growing season, which confirmed the higher coefficient of variance in the upper horizons (Tables 7 and 8). These horizons responded almost immediately to meteorological changes. The PCC between the daily deviations from the PDA hydrolimit and the CII was 0.56 in the A horizon and 0.35 in the B horizon. The water supplies run out faster in those layers, which was most likely related to the activity of the root zone concentrated there. Drought episodes began earlier in the upper layers, but after the precipitation events, these layers tended to become saturated faster. Drought episodes in the upper horizons had shorter average durations, and the total number of days under the PDA hydrolimit was smaller than in the deeper horizons (Table 9).

### Table 8. Monthly means of the soil water content (cm$^3$·cm$^{-3}$) and coefficients of variance (CV) in HY 2016.

| Soil Horizon | Indicator | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct |
|--------------|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|-----|
| A            | MEAN      | 0.387 | 0.371 | 0.380 | 0.398 | 0.310 | 0.272 | 0.314 | 0.312 | 0.323 | 0.387 | 0.322 | 0.367 |
|              | CV        | 2.254 | 2.361 | 1.973 | 6.083 | 22.232 | 19.441 | 12.680 | 11.588 | 20.588 | 10.185 | 10.161 | 7.156 |
| B            | MEAN      | 0.383 | 0.379 | 0.366 | 0.378 | 0.319 | 0.242 | 0.291 | 0.270 | 0.316 | 0.355 | 0.278 | 0.331 |
|              | CV        | 0.866 | 1.849 | 2.127 | 2.014 | 16.762 | 6.126 | 5.986 | 7.938 | 5.548 | 9.105 | 11.081 | 16.145 |
| BC1          | MEAN      | 0.380 | 0.374 | 0.375 | 0.375 | 0.323 | 0.264 | 0.322 | 0.286 | 0.353 | 0.364 | 0.287 | 0.326 |
|              | CV        | 1.283 | 2.457 | 1.128 | 3.288 | 10.562 | 3.916 | 7.734 | 9.908 | 4.821 | 3.865 | 13.923 | 13.923 |
| BC2          | MEAN      | 0.369 | 0.365 | 0.373 | 0.380 | 0.299 | 0.252 | 0.312 | 0.264 | 0.347 | 0.330 | 0.268 | 0.272 |
|              | CV        | 1.775 | 2.714 | 2.938 | 4.200 | 8.997 | 7.890 | 12.573 | 8.911 | 2.604 | 6.545 | 8.066 | 15.631 |

### Table 9. Summary of the days with water contents ($\theta$) within certain hydrolimits (FC—field capacity and PDA—point of decreased availability) and characteristics of a drought.

| Hydrological Year | Soil Layer | 2015 | | 2016 | | | | | | | | |
|-------------------|------------|------|------|------|------|------|------|------|------|------|------|------|
|                   | $\theta > FC$ | A    | B    | B/C1 | B/C2 | A    | B    | B/C1 | B/C2 | | | |
| $\Sigma$ days     | 134        | 135  | 0    | 0    | 175  | 145  | 0    | 0    | 0    | | | |
| $FC > \theta > PDA$ | 142       | 116  | 252  | 201  | 159  | 165  | 301  | 259  | | | |
| $PDA > \theta$    | 89         | 114  | 113  | 164  | 32   | 56   | 65   | 107  | | | |
| Average Length of Drought Episode (PDA > $\theta$) | 13 | 19 | 38 | 55 | 11 | 11 | 16 | 36 | | | |
| Number of Drought Episodes | 7 | 6 | 3 | 3 | 3 | 5 | 4 | 3 | | | |

The soil water contents in the bottom horizons of the soil profile were less dynamic, which was evident from the lower CV values. These layers had a delayed response to changes in the meteorological parameters. Drought in the bottom horizons began later, lasted much longer and receded slowly. After precipitation started again, most water supplies were frequently absorbed in the upper few centimetres of the root zone, while the main root zone and bottom layers persisted in a suboptimal state for a long time. The
PCC of the daily values between deviations from the PDA hydrolimit and the CII was 0.22 in the B/C1 horizon and 0.18 in the B/C2 horizon. It is necessary to consider that we recorded a higher proportion of sand and coarse fragments in the deeper horizons, which are associated with a lower water retention rate. In addition, the IWC values were under the FC hydrolimit, which caused a lower initial amount of water. That could have contributed to the unfavourable humidity at these depths. However, since the root zone terminated above the B/C2 horizon, the direct impact on the root water uptake was not relevant.

4. Discussion

Over large areas of Europe, climate change causes an increasing risk of drought in forest ecosystems [11,37]. Climate models predict an increased frequency of unfavourable dry years in Central Europe, resulting in changes to the soil climate and interference in the soil water regime [12]. In this research, the response of climatological drought (CII) in soil hydrology was emphasised. The mathematical simulation indicated during which periods of the year and in which depths of the soil profile the droughts were most pronounced. Hydrological years 2015 and 2016 varied significantly in their mean precipitation amounts and precipitation distribution throughout both years. Very dry conditions were observed during HY 2015 throughout Europe [38–40], as well as regionally, which was highlighted by local hydrometeorological reports [41]. In North Slovakia, 2015 was considered the driest summer of the last 50 years [38]. In Bienska, visible damage to beech seedlings was confirmed by local foresters [42]. Based on the modelled soil water content in the root zone and the CII, we identified three episodes of drought when significant water stress (under the PDA) persisted in the B horizon and the B/C1 horizon for 100 days. In the B/C2 horizon, the water content remained below the PDA for 164 days. The water requirements for evapotranspiration were higher than the water supply that the ecosystem effectively received from precipitation, which was confirmed by the cumulative value of the CII of 212 mm at the end of the growing season (Figure 3a). The water balance in hydrological year 2016 was completely different. At the beginning of the year, there were several records in the temperature and precipitation measured in February [43,44]. During the growing season, higher precipitation was recorded when compared to 2015 [45]. Therefore, the water supplies for the ecosystem were higher. At the end of July, an intensive storm formation developed over Slovakia when a cold front from Poland passed through. This formation also hit the Kremnica Mountains, and the nearest meteorological station in Kremnické Bane recorded a daily precipitation of 122 mm [46]. Nevertheless, at the research plot, which was just several kilometres southwest, a daily precipitation of only 13.4 mm was recorded. That could be clearly explained by the impact of the rain shadow that resulted from the locations of the two stations. Kremnické Bane Station is located northwest of the Kremnica Mountains, while Bienska Station is southeast of the mountains. Thus, this could impact the amount of precipitation in Bienska in general, which means a higher risk of drought for beech forests could occur in this location, as well as comparable rain shadows of the mountain range. Despite the relatively rich precipitation during the growing season of 2016, the modelled water content remained under the PDA for 56 days in the B horizon and 65 days in the B/C1 horizon. Not negligible is the fact that the precipitation was very unevenly distributed during that year. There were more than 22 days with water deficiencies according to the CII in each month of the growing season (Table 5). In the context of future climate conditions, the predictions draw attention to the increasingly uneven nature of precipitation in the future [47]. Gennaretti et al. [48] emphasised that beech forests are sensitive to the timing of drought onset over the growing season, while a higher risk is in fast drought onsets during the early growing season, which was, according to the GLOBAL results, evident in Bienska Valley during both growing seasons. In addition, since beech stands have a high ability to extract water from deeper horizons [33,49], it is essential to take into account the bottom parts of the root zone, which demand longer-lasting precipitation to obtain full saturation. When assessing the drought risk based on the model GLOBAL, it is necessary to consider that the model assumes a uniform water
distribution in each soil horizon. That is therefore a considerable simplification, because if
the rock and coarse fragments are taken into account, there may be a sudden decrease in
humidity after the water has been extracted from the areas between those particles [50]. In
our study, we also did not consider the possible occurrence of soil water repellence, which
may significantly affect the infiltration of water into the deeper layers of the soil profile and
result in nonuniform drainage [51,52].

5. Conclusions

Soil water modelling seems to be an appropriate and precise method to predict and
analyse drought occurrence and its characteristics in beech ecosystems compared to the
classical approach of climatological indices. Although this brief overview of the potential
drought impacts could be carried out using simple indices, such as the CII, to understand
the complexity of droughts, it is necessary to obtain information about drought evolution
in specific soil horizons, because the simple application of drought indices does not provide
the required accuracy. As shown in the Results, drought episodes (soil water content under
the PDA) persisted despite the improved climatological conditions (as indicated by the
CII) in the relatively humid growing season of 2016. The higher soil horizons showed
greater variability in the available water content, which implies another contrariety to using
climatological indices. It is necessary to understand rain time distribution patterns, as
well as what amounts of rain are effective in specific ecosystems. Under the context of the
predicted climate change, this information will be incorporated into drought monitoring
systems. Future research should focus on modelling the soil moisture in beech ecosystems
occurring in different soil types and in different habitat conditions.

Author Contributions: Conceptualisation, Z.O. and J.V.; methodology, Z.O.; software, Z.O. and
J.V.; validation, Z.O.; formal analysis, Z.O.; investigation, Z.O. and J.V; resources, Z.O. and J.V; data
curation, J.V. and Z.O.; writing—original draft preparation, Z.O.; writing—review and editing, J.V.
and Z.O.; visualisation, Z.O.; supervision, J.V.; project administration, J.V. and Z.O. and funding
acquisition, J.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science Grant Agency of the Ministry of Education,
Science, Research and Sport of the Slovak Republic VEGA No. 1/0392/22 and KEGA No. 011TUZ-
4/2021 and by the Slovak Research and Development Agency under contract no. APVV-18-0390 and
contract no. APVV-19-0340.

Acknowledgments: The authors thank Peter Fleischer, Jr. for his help with sharing the measured
LAI data used in the study and Marián Homolák, for his help with the laboratory analyses of the soil
samples.

Conflicts of Interest: The authors declare no conflict of interest.

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