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Forest Litter Interception Model for a Sessile Oak Forest

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Abstract – Models that describe hydrological processes in forests may help to estimate the consequences of forestry interventions or of climate change. The authors employed a hydrologic model for estimation of forest litter interception of a middle-aged sessile oak (*Quercus petraea*) stand. Antecedent water content and the storage capacity of the forest litter were the main parameters of the model. The antecedent water content of the litter was estimated by the daily precipitation and temperature data, collected in Hidegvíz Valley research catchment in a three year measurement period (2006–2008). The measurements were done by an instrument of own development, where the undisturbed forest litter samples were enclosed in frames and measured in daily time steps.

interception model / forest litter / forest hydrology

Kivonat – **Avarintercepció modellezése egy kocsánytalan tölgyesben.** Az erdőben lezajló hidrológiai folyamatokat leíró modellek segítenek megbecsülni az erdészeti beavatkozások, és a klímaváltozás következményeit. Jelen munka egy hidrológiai modellel foglalkozik, ami egy középkorú kocsánytalan tölgy (*Quercus petraea*) állomány avarintercepcióját becsüli. Az avar megelőző víztartalma és tározási kapacitása a modell fő paraméterei. Az avar megelőző víztartalmát a napi csapadék és hőmérséklet adatokból becsültük, melyek a Hidegvíz-völgyi kísérleti vízgyűjtőből származnak a három éves mérési periódus időtartamára (2006–2008). Az adatgyűjtést saját fejlesztésű eszközzel végeztük úgy, hogy a bolygatatlan avarminták tömegét zárt keretekben napi gyakorisággal mértük.

intercepciós modell / avar / erdészeti hidrológia

1 INTRODUCTION

Forest litter interception is an important element of the water balance of the forest and can be an important parameter of the rainfall runoff models in a forested area. Forest litter interception has been dealt with since the middle of the last century but it has been the focus of research only in recent decades.

Ijjász (1936) examined the role of forest litter in the water balance of a forest in Hungary. He focused on the volumetric water content proportion of the three litter sub-layers (litter, fermentation and humus layers). Helvey (1964) investigated the forest litter interception in a southern Appalachian hardwood stand. Monthly values of litter interception and water content

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of litter after rainfall were measured. According to Helvey (1964), litter interception depends mainly on the annual quantity of forest litter.

Führer (1994) calculated litter interception values for the growing and dormant seasons using data of small lysimeters, for determination of water retention of tree stands in Hungary. In their forest litter interception research, Putuhena and Cordery (1996) did not made a distinction between parts of the living and dead plants. All of the organic materials were involved in the study which was a maximum 50 cm above the soil surface. Wang and Weng (2002) analysed the role of litter, the water retaining capacity of litter and the influencing factors (amount of litter, decomposition stage, tree species, amount of rainfall, and topography) were evaluated related to soil protection and erosion. Sitkey (2006) dealt with the full interception loss in connection with water balance investigations in forest climate zones (from forest beech climate to forest-steppe zones) in Hungary. Gerrits et al. (2006) continuously measured litter interception as a parameter of runoff models using a new technique of measurement in a beech (Fagus *sylvatica*) stand. Bulcock and Jewitt (2012) gave canopy and litter interception values as components of a forest hydrologic cycle in three different tree species in Africa: flooded gum (*Eucalyptus grandis*), spreading leaved pine (*Pinus patula*) and Australian acacia (*Acacia mearnsii*). For forest litter interception, there are different results (usually 2–12%) in proportion to the gross precipitation due to the different climate (rainfall and evaporation conditions), measurement methodology, litter weight and tree species.

2 DEFINITION OF INTERCEPTION

A part of the gross precipitation (*P*) falls through the canopy (*T*) and reaches the forest litter. After saturation of the leaf storage capacity, another part of the precipitation, drips down from the canopy (*D*), adsorbs on leaves and partly evaporates during and after the rain event (*E*) or flows down the trunk (stemflow: *SF*) (Horton 1919; Delfs 1955). That can be symbolized by with the next equation:

$$P = T + D + SF + S + E \tag{1}$$

The interception loss (I) is that part of precipitation which does not reach the soil (Leonard 1967):

$$I = S + E \tag{2}$$

Interception in a forest has two main parts: canopy and litter interception. Forest litter interception is the difference between the stand and effective precipitation:

$$E_S = P_{atot} - P_{eff} \tag{3}$$

where $P_{atot} = T+D+SF$, P_{eff} is the effective precipitation which can infiltrate into the soil (Lee 1980).

The canopy and also the litter interception processes can be described by the saturation function, because leaves cannot store more moisture after reaching their storage capacity. Drying of the canopy is faster due to the less saturated and more turbulent environment of the leaves than the litter, where the air is much closer to saturation and the stratified leaves keep the moisture longer. There is an additional difference between the two processes that the canopy leaves characteristically are wetted only on the surface, but the leaves of the litter store the water inside of them due to their composited structure.

However, due to the similarity of the two processes, canopy interception models can be a good starting point for employing litter interception functions. As an example, the Merriam (1960) formula for canopy interception can be a good basis for a litter interception model:

$$E_{su} = S \cdot \left(1 - e^{-c \cdot P}\right) + K \cdot P \tag{4}$$

where E_{su} is the canopy interception (mm), S is the storage capacity (mm), c is a constant (without dimension), P is the gross precipitation (mm) and K is the rate of the evaporation under the precipitation and the gross precipitation. The first component of the equation is the wetting up of canopy and the second component is the evaporation.

There is an essential difference between the forest litter and canopy interception. The quantity of the water storage of the leaves (the amount of adsorbed water, not on the surface of the leaves) can be disregarded in the canopy interception. In the forest litter interception, litter stores water not only on its surface but precipitation also can infiltrate into the body of the litter layer. Forest litter rarely dries out entirely during the rainless period between two precipitation events. Therefore the stored volume of water in the litter layer is never zero. This means that the actual storage capacity never reaches the total storage capacity. Thus, if the water content is high, the current storage capacity is low. This relation is described by the equation which is developed in this paper *(Eq. 5)*:

$$E_S = (S - w_{(i-1)}) \cdot \left(1 - e^{-\left(\frac{Th}{(S - w_{i-1})}\right)}\right) \tag{5}$$

where $w_{(i-1)}$ is the antecedent water content (mm).

Therefore Eq. 5 is the Merriam equation completed with the antecedent water content, which reduces the maximum storage capacity to the current storage capacity. The second evaporation term from the original equation is neglected, because the evaporation can be disregarded under the canopy near the soil surface during the rainfall event in those closely saturated conditions of air.

3 MATERIAL AND METHODS

A new instrument has been developed for measurement of forest litter interception. This method supports the data collection, eliminating the subjectivity of the observer compared to traditional methods (Helvey 1964) Thus consecutive data can be compared with each other. Ten frames (50 cm wide and 50 cm long, 0.25 m2 in area) were settled in the forest stand following the contour lines and slopes (5–5 pieces). The frames are covered with fly screen on each side (and also on the top) so the movement of any insect, snail, etc. does not disturb the measurement. Quasi-undisturbed litter was placed into these frames from the same area as the frames. Before starting the measurements, the frames were uncovered for 1 or 2 weeks in the field to allow precipitation to settle the litter leaves.

We applied an UWE HS-7500 digital hanging scale with 5 g accuracy (www.uwe.com) for weighing the forest litter.

Measurements provided data each day, from May to November/December in every study year (05/05/2006-14/12/2006, 10/05/2007-14/12/2007, and 28/05/2008-29/08/2008).

At the end of each study year, the dry weight can be determined in each frame. Dry weight values support the calculation of the litter water content at each time. After the measurement period (according to the dates above, usually one growing season), the frames were emptied. The next measurement period was started with new litter samples. A measuring period is represented by *Figure 1*.

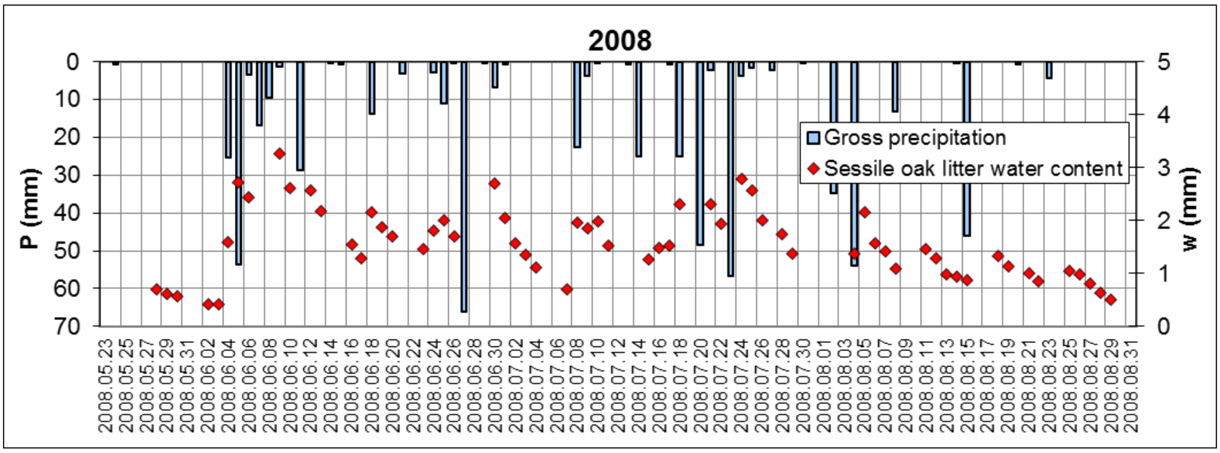

Figure 1. Gross precipitation and water content of the forest litter in the sessile oak stand during the year 2008

4 THE STUDY SITE

The study site (Hidegvíz Valley, *Figure 2.*) is located in Sopron Hills at the eastern border of the Alps. (Lat: 47-35-08 - 47-39-06, Lon: 16-25-31 - 16-28-15 above WGS 84 datum.)

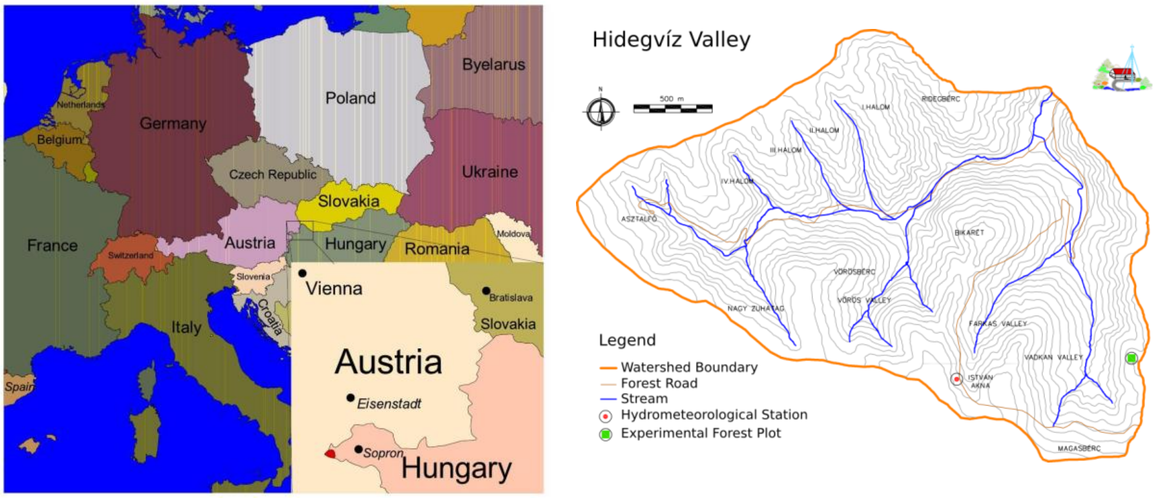

Figure 2. The study site in Hidegvíz Valley

The area enjoys a sub-alpine climate, with daily mean temperatures of 19 °C in July, and -2 °C in January, and with an annual precipitation of 750 mm. Late spring and early summer are the wettest and fall is the driest season (Marosi and Somogyi, 1990; Dövényi, 2010).

The slope of the sessile oak stand is 3–6%, located on the west side at an altitude of 500 m above sea level. The soil is classified as Cutanic Luvisol (Epidystric). The stand forming tree species is sessile oak (*Quercus Petraea*). The average height of the middle-aged stand (40 years old at the start of these measurements) was 14–15 m, canopy closure was 87%, and the average diameter at breast height of the stand was 14–16 cm. The undergrowth of sessile oak stand was sparse.

Gross precipitation values were registered by an automatic rain gauge located about 1 km from the oak interception garden (N: 47°39'21, 16", E: 16°27'16, 28", m ASL: 515 m, WGS84). Temperatures were measured by an automatic thermometer located next to the automatic rain gauge.

5 CALCULATION OF THROUGHFALL

Since no continuous throughfall records are available, throughfall data (*Th*=*T*+*D* from *Eq. 1*) applied for the interception analyses have been determined with iteration using the gross precipitation data with the following equation:

$$P = S' \cdot \left(1 - e^{-\frac{Th}{S'}}\right) + K' \cdot Th \qquad (6)$$

In the *Eq. 6 P* is the gross precipitation; *S'* is the parameter depending on the water storage capacity of forest canopy; *K'* is the multiplicator factor which describes the slope of the line approximating the relation between gross precipitation and throughfall data above the limit of storage capacity. In our case *K'*=1 and *Th* is the throughfall (*Figure 3*). According to the literature (Kucsara, 1996), rainfall with low intensity and rainfall depth can be almost entirely stored on the surface of leaves, while almost the total amount (i.e. the amount reduced by the evaporation) of precipitation falls through the canopy at heavy rainfalls when the storage capacity is exceeded. *Eq. 6* represents this process.

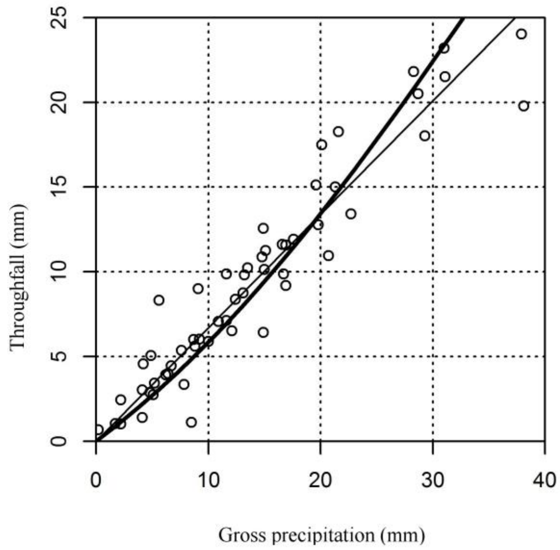

Figure 3. Connection of throughfall with gross precipitation

The iteration has been performed with the script using the R free software (R Core Team 2012). Throughfall data calculated with this method served as basis for the further analyses.

6 CALCULATION OF THE FOREST LITTER INTERCEPTION CONSIDERING THE WATER STORAGE

Litter weight in the frames changes year by year; thus maximum storage capacity changes as well. To apply the selected data from the 3 years in one combined estimation, data from the given year have been divided by the average weight of forest litter in the same year and multiplied by the 3-year average litter weight. Results of the estimation (*Eq. 7*) related to the normalised data are shown in *Table 1*. Statistical analysis utilized nonlinear regression by the least-squares method performed with R software.

$$E_S = (1.799 - w_{(i-1)}) \cdot \left(1 - e^{-\left(\frac{Th}{(1.799 - w_{(i-1)})} \right)} \right) \tag{7}$$

Due to the spatial heterogeneity of the throughfall, there can be greater differences in the moisture changes of the 10 frames. The previous estimation was made using the average values based on the measurement of 10 frames. One extreme value can greatly offset the average values, thus distorting the estimation. Therefore, the approximation has also been made with weights. A reciprocal of the standard deviation for the ten data at the same time has been applied as a weight at that time. Results of this estimation (*Eq. 8*) are summarized in *Table 1*.

$$E_S = (1.702 - w_{(i-1)}) \cdot \left(1 - e^{-\left(\frac{Th}{(1.702 - w_{(i-1)})} \right)} \right) \tag{8}$$

Table 1. Results of the forest litter interception calculation based on the three-year dataset

	S	p-values	Standard residual error
Sessile oak	1.799	< 2e–16	0.4199
Sessile oak, weighted	1.702	< 2e–16	1.599

No significant deviation (< 0.1 mm) has been obtained between the storage capacities estimated with the two formulas (*Eq. 7–8*). *Figure 4* demonstrates the results of the weighted estimation.

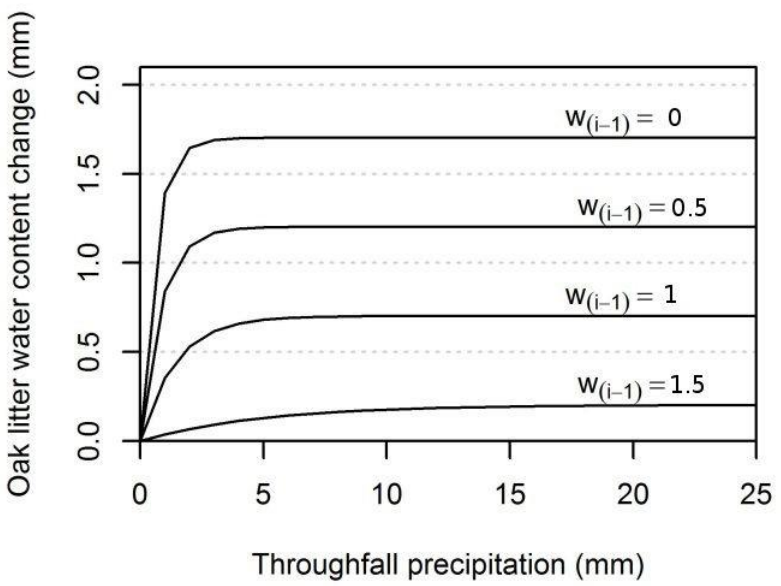

Figure 4. Water content change of the forest litter in a sessile oak stand with different antecedent water content (weighted estimation)

7 CALCULATION OF THE ANTECEDENT WATER CONTENT OF THE FOREST LITTER

The antecedent water content of the forest litter is an important question in terms of the litter interception. If the forest litter is not entirely dry, the maximum value of the storage capacity will be lower. Antecedent precipitation (API) has been calculated by the estimation of the effective storage.

According to the literature (Kontur et al. 2001), one method of the API calculation is based on a weighting process using linearly decreasing weights.

Water content of the forest litter decreases faster at the beginning of the desiccation process, and decreases more slowly to the end of the process. As the forest litter desiccation is non-linear, application of linear weights in the API calculation is incorrect. The speed of desiccation of the forest litter depends on the ambient temperature as well. In conclusion, a reliable equation to determine the API uses weights which regard the real desiccation and which are corrected with the temperature. We adapted the soil moisture relation of Jakeman and Hornberger (1993) for calculation of the antecedent water content of the forest litter:

$$w_i = c \cdot \left[P_1 + \left(1 - \frac{1}{\tau}\right) \cdot P_2 + \left(1 - \frac{1}{\tau}\right)^2 \cdot P_3 + \left(1 - \frac{1}{\tau}\right)^3 \cdot P_4 + \ldots \right], \tag{9}$$

where c is the normalising parameter, P_1, P_2, … is the rainfall depth which has fallen 1, 2… days before the rainfall event inducing the water content recharge of the forest litter. The current τ detention time has been computed using the *Eq. 10*:

$$\tau_i = \tau_0 \cdot \exp\left[g \cdot (T_0 - T_i)\right], \text{ where } \tau \geq 1, \tag{10}$$

where g is the factor of temperature-change (it shows how the τ changes as a function of the temperature), τ_0 is the reference detention time, T_0 is the reference-temperature, T_i is the temperature at the current time.

Parameters from the equations above have been calculated on the basis of our field observations. As the first step, we selected the desiccation periods according to the measurements, which lasted at least 5 days. Variables describing the speed of recession (desiccation process) have been determined using the equation of the exponential fitting based on the data of the observed periods:

$$w_i = w_0 \cdot e^{-\alpha \cdot t}, \tag{11}$$

where w_i is the water content related to the current day (mm)
w_0 is the initial water content (mm)
α speed of recession ($^1/_{\text{day}}$)
t is the elapsed days (day).

The τ detention times can be obtained as the reciprocals of the α rates of the decrease of water content. Average temperature values have also been computed for the desiccation periods.

Taking 0 °C for the reference temperature, parameters of the *Eq. 10* were estimated by applying a linear regression model with a logarithmic transformation. Results of the estimation are the followings in the sessile oak (*Figure 5, Table 2*):

Table 2. τ_0 and g values for the observed desiccation periods, the determination coefficient (R^2) and p-value of the estimation

	τ_0	g	R^2	p-value
Sessile oak	21.926	0.088	0.80	7.047 e^{-06}

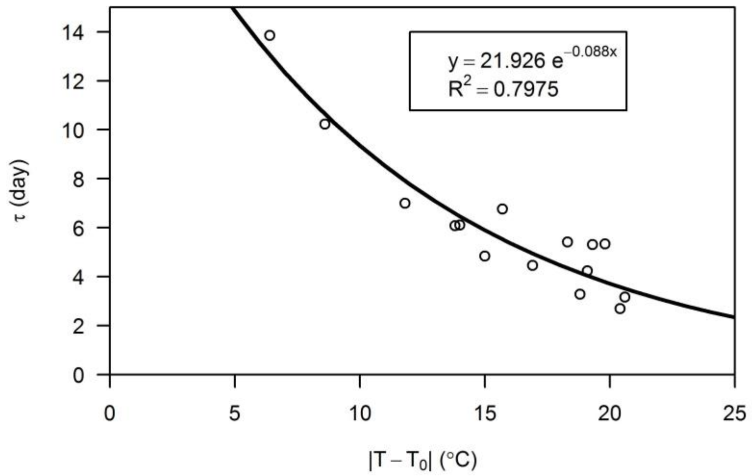

Figure 5. The τ detention time against the difference between the temperature of the desiccation period and the reference-temperature of sessile oak

Estimated parameters are the basis for calculating the antecedent water content (w_i). The determination coefficients were examined between the water content of the forest litter and the API (Jakeman-Hornberger 1993). The strength of the relation is moderate in the years 2007 and 2008, while a weak relation was obtained in 2006. In general, according to the Jakeman-Hornberger (1993) model, the API_{30} shows the strongest correlation with the water content of the forest litter, and the second strongest correlation was with the API_{20}. *Figure 6* demonstrates the strength of relations between the API according to the Jakeman-Hornberger (1993) model and the water content of the sessile oak litter in the year 2008. The strength of the relation increases from 0.56 to 0.69 neglecting only two outliers (*Figure 6*). After appropriate reordering, the equations of fitted lines provide the *c* parameters (*Eq. 9*) related to the given time periods in the given years. Considering the values of the *c* parameters, similar values were recorded in the years 2007 and 2008, while c parameters are the half of the values from 2007 and 2008 in the year 2006. The reason of this phenomenon is not yet known.

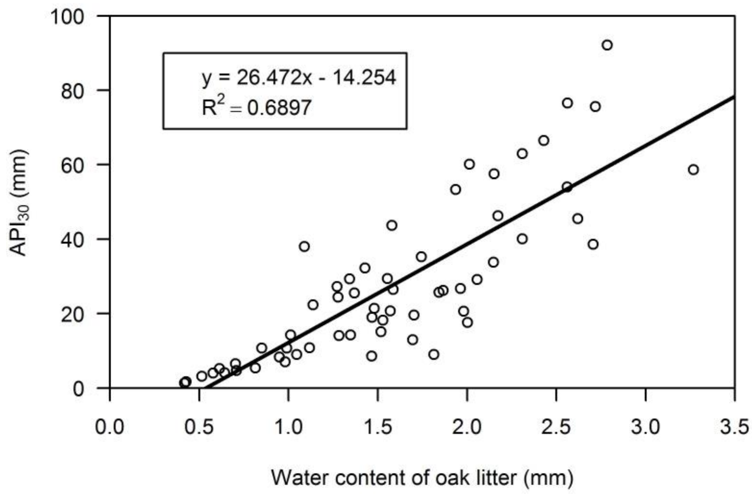

Figure 6. Relation between the API_{30} (according to the Jakeman-Hornberger (1993) model) and the water content of the sessile oak litter in 2008 after neglecting outliers.

8 APPLICATION OF THE MODEL

The model developed for estimating the forest litter interception can be used under changing environmental (different climate and litter mass, etc.) conditions. Reliable adaptation of the model depends on having information about the litter mass of the forest stand which can be determined from the maximum storage capacity of the litter in the given stand. The throughfall from the gross precipitation can be estimated on the basis of the leaf area index. The antecedent moisture content of the litter can be calculated with the Jakeman – Hornberger model (1993) using the daily temperature and precipitation data, and as a result, litter interception can be estimated. However, for the universal model application, a multi-year data set is required. Using different input climate data, the impact of the climate change can be forecast, e.g. the effect of different temperatures (change in speed of recession) or precipitation amount and distribution (changes in the length of the drying period). If the litter production is changing due to climate change (Black 2009), further modifications of the model should be made regarding the storage capacity. The impact of forestry interventions can be also estimated with this model, such as the hydrological aspects of litter interception related to clear cuts or gaps.

The effect of climate change was estimated by the model. It was found that the rate of litter interception is decreased (*Table 3*) due to the change of the distribution of precipitation. Rainfall less than 2 mm does not reach the forest litter (Kucsara 1996). Under the impact of climate change, precipitation becomes more extreme. In our estimations, the sequentially 2–4 rainfall events were merged, and the maximum rainfall decrease (30 mm over 10 years in the summer half-year) predicted by Gaál (2007) was validated with a linear equation. Iterating the new predicted data series, a throughfall dataset was calculated which serves as a basis for further estimations (*Th* for 2016–2018). An assumed increase in temperature and changes in litter mass (Kotroczó et al. 2012) were not taken into account. *Table 3* shows the calculated data for the growing season.

Table 3. Forest litter interception estimation for three years by the model we developed (growing season

Year	E_s (mm)	E_s (%)
2006	23.70	4.74
2007	43.29	7.32
2008	42.63	6.01

Year	E_s (mm)	E_s (%)
2016	12.87	2.74
2017	25.13	4.48
2018	25.12	3.70

The impact of climate change on litter interception is a complex process. Due to a lower rate of small rainfall events (less than 2 mm) more precipitation can reach the litter. An extreme rainfall event does not increase the water content of the litter after the saturation of the storage capacity. Heavy rains show a proportionately lower impact on the litter. Forest litter interception was reduced about 2–3% in the proportion of gross precipitation over 10 years according to this hypothesis (*Table 3*). Taking into account the effect of higher temperature, this reduction would be smaller, because the litter can dry out between two rainfall events. Therefore, the current storage capacity would be larger.

9 DISCUSSION

According to our model estimation, the litter interception was 5–7% of the gross precipitation. Other authors also published data about litter interception of gross precipitation or annual value (*Table 4*). Litter interception data of the net precipitation (throughfall) was 8–12% in mixed oak stands (Pathak et al. 1985), and 34% for November 2004 in beech forests (Gerrits et al. 2006).

Table 4. Forest litter interception values according some authors

	Study site	Tree species	Litter interception (%) of gross precipitation
Pathak et al. (1985)	India (Kumaun Himalaya)	*mixed oak forest*	8–12
Führer (1994)	Central Europe	*(Quercus petraea)*	8 (summer) 16 (winter)
	South Africa	*(Pinus patula)*	12.1
Bulcock és Jewitt (2012)		*(Eucalyptus grandis)*	8.5
		(Acacia mearnsii)	6.6

The comparison of our data is uncertain because of different climatic conditions and tree species (mainly due to the weight of litter) and different methods of measurement.

10 SUMMARY

A simple formula was developed to describe the water retention properties of litter using daily gross precipitation and forest litter mass measurement data series. This equation takes into account the moisture content of the forest litter before rainfall events, thus considering the current storage capacity. To determine the antecedent moisture content, the Jakeman – Hornberger (1993) model has been adapted which refers to the soil moisture. It has been found that the antecedent precipitation index, which applies exponential weights (taking temperature into account), are suitable to estimate the antecedent moisture content of the litter. The model we developed provide an opportunity to estimate litter interception under changing climatic conditions and thus the effects of climate change can be detected.

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