Premises for the construction of balance equations of water reserves in the saturation zone of forest soil

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Abstract: Premises for the construction of balance equations of water reserves in the saturation zone of forest soil are presented in this paper. Changes of soil water reserves are dealt with as an effect of the atmosphere-tree stand-soil balance at the assumption of constant ground water flow and negligibly small losses for infiltration down the soil profile below saturation zone. These assumptions are met in permeable lowland forest soils, particularly in areas where the aquifer is situated on relatively shallow impermeable substratum. Then, for snow-free periods, it is possible to: 1) combine the increment of soil water reserves with precipitation above tree crowns and with plant and litter interception and 2) combine the losses of soil water reserves with plant transpiration and evaporation from the soil surface. The periods of increments and losses of soil water reserves are determined from limnigraph records of ground water table depth in piesometers. Examples are given in the paper of equations identified by long term data from 13 soil profiles localised in pine forests on Pleistocene floodplain of the Dunajec River. The data included: ground water table depth, physical properties of grounds in soil profiles, and hydro-climatic conditions. The equations combine increments and losses of water reserves in the saturation zone with rainfall and deficits of air humidity measured on a mid-forest meadow.

Key words: *forestry, forest hydrology, mathematical modelling, soil water reserve, water budget in a forest*

INTRODUCTION

The dynamics of water reserve in forest soils is an effect of water balance in the atmosphere – tree stand – soil system; hence its analysis may deliver important information for both diagnosis of moisture in forest habitats and balance of water resources in a catchment. It has been underlined in this context that any economic activity in forests and interactions of biotic and abiotic factors may significantly affect water relations in a forest (SULIŃSKI and JAWORSKI, 1998) and detailed water budget of a catchment (SULIŃSKI, 1989b).

Most comprehensive data for the balance of water reserve in soil may be obtained from measurements of water amount in both aeration and saturation zones. Adopting some necessary assumptions it is possible to precisely calculate water reserve in a given soil profile and then to construct balance equation combining its values with biometric features of tree stand (SULIŃSKI, 1993; 1995). Measurement of water reserves in the aeration zone providing the results useful for balance calculations is feasible but still poses some methodical and organisational difficulties (KUCZA, 2005). It is easier to measure ground water table depth which informs on changes in water reserves in the aeration zone. The depth is equal to present thickness of aeration zone situated above. Noteworthy, there might be a linear relationship between water reserve in the whole soil profile and the depth of free ground water table (KUCZA and SULIŃSKI, 1987).

The problem of factors affecting the dynamics of ground water table has long been present in hydrologic and forest studies (e.g. BENECKE, 1976; BIELECKI, 1968; KOWALKOWSKI, 1961; KOSTURKIEWICZ, 1963; KUŹNIAR, 1938; MILER and PRZYBYŁA, 1997; MOLCHANOV, 1953; PLECZYŃSKI, 1983; SOMOROWSKI, 1964; SULIŃSKI, 1981; URIE, 1967). Nevertheless, there are still no necessary quantitative approaches. The problem is crucial for forest practice because the occurrence and dynamics of ground water table, estimated together with their visible effects in soil profile, are the basis for diagnosis of moisture in lowland forest habitats (Siedliskowe…, 2004). Balance equations of water reserve in soil are constructed in relation to assumed target and to available data necessary for their identification. Balance equations set up separately for recharge phases following rainfalls and loss phases associated with transpiration and evaporation enable studying the factors affecting the dynamics of water reserve in soil (SULIŃSKI, 1993; 1995). This methodical approach has been developed in the present paper.

The object of this study was the reserve of water in aeration zone and factors affecting its dynamics. The aim of the study was to present premises explaining this dynamics and being a basis for the construction of balance equations adjusted to their destination and possessed data for identification. It was attempted to make the usefulness of proposed premises credible by examples of equation constructions describing the dynamics of water reserve in the saturation zones of 13 soil profiles localised in pine tree stands of the same age. In particular, an attempt was undertaken to check, whether the increments and losses of water reserves in the saturation zone manifesting themselves in the dynamics of free ground water table could be described by the amount of rainfall and deficits of air humidity measured in mid-forest meadow and by the characteristics of soil water properties.

MAIN FACTORS AFFECTING THE DYNAMICS OF SOIL WATER RESERVE IN THE SATURATION ZONE

Pondering factors that affect water reserve in forest soil needs to distinguish them into external factors and those associated with tree stand (SULIŃSKI and JA-WORSKI, 1998). The former include rainfall, potential evapotranspiration (drying ability of the air – CZARNOWSKI, 1978) above tree crowns and hydro-geologic conditions affecting the occurrence of saturation zone in the soil profile. The latter factors include mainly the processes of space fulfilment by plant biomass (SULIŃSKI, 1997) manifesting themselves i.a. by the values of biometric features of trees and other plants forming forest community whose variability is the reason of differentiated components of water balance in the atmosphere – tree stand – soil system (SU-LIŃSKI, 1993).

Most useful for identification of balance equations would be the parameters measured in a definite vertical cross-section through a tree stand from the root system to tree tops (Fig. 1). Such studies are, however, difficult to perform on a wider
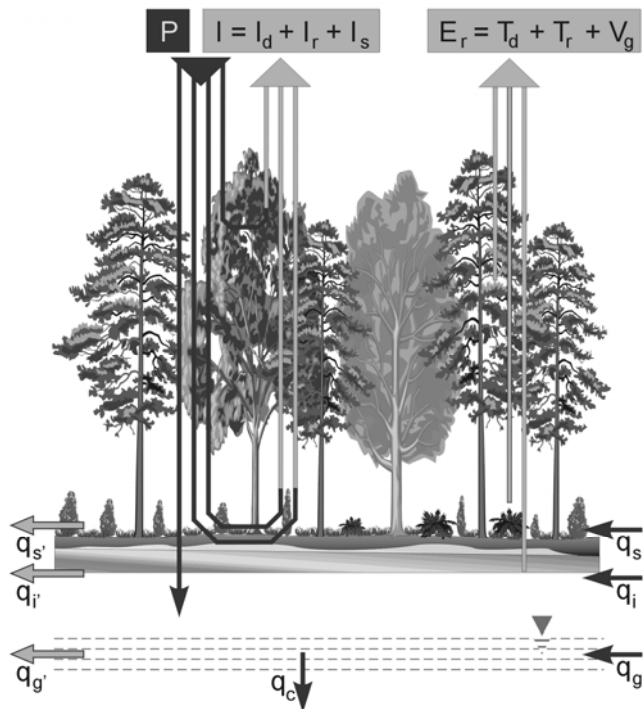

Fig. 1. A scheme of water balance between atmosphere, tree stand and soil in lowland forest ecosystem (SULIŃSKI, 1995) *P* – precipitation above tree crowns, *I* – interception of: *d* – trees, *r* – undergrowth, *s* – litter; E_r – actual evapotranspiration, *T* – transpiration of: *d* – trees, *r* – undergrowth; V_g – evaporation from the soil surface; *q* – intensity of water flow: *s, s'* – on surface, *i, i'* – subsurface, *g, g'* – in the ground, q_c – "vertical" ground water outflow

scale, hence some simplifications. Conditions prevailing above tree crowns are usually referred to measurements in an open area. For example, atmospheric pre-cipitation or the amount of solar energy measured in mid-forest meadow near the study profiles might be considered equivalent to values obtained above tree crowns. The same is true for the measurements of wind velocity – in a flat area it is sufficient to consider a gradient resulting from the height of trees (CZARNOWSKI, 1978). There are many possibilities of designing such studies, current measurement methods and calculation techniques provide a wide range of possibilities in that aspect. It should be, however, underlined that precision of calculations is always associated with the precision of input data and with adopted time step of measure-ments.

Recognition of hydro-geologic conditions in view of water budget in the at-mosphere – tree stand – soil system requires first of all estimating the occurrence of aquifers with water available for plant rhisosphere and their recharge with rainfall and melting snow. Geo-morphologic processes affecting the system of aquifers very often exert an effect on their lithologic structure i.e. also water relations in soils. Understanding vertical arrangement and range of aquifers is also very useful in the assessment as to how selected soil profiles are representative for the whole forest complex (SULIŃSKI, 1981). Water properties of forest soils are modified by the presence of organic horizons, tree roots and the activity of soil fauna. This is a specific of forest soils often hard to observe and describe since the effects of modifying factors are prolonged in time. Noteworthy is also often underestimated fact that water properties analysed in soil samples do not often characterise pre-cisely enough the properties of soil profile as a whole. The reason of such discrep-ancy is already mentioned specific of forest soils.

Studying the influence of factors associated with tree stand on the dynamics of soil water reserve and resulting effects on plant habitat conditions may be accom-plished in two ways. The first consists in analysing the results of measurements made in one soil profile for the time period long enough to reveal changes in bio-metric features of tree stand. The changes proceed faster in young tree stands and slower in older ones; in every case it is a period of several or a dozen or so years. Such databases are rather rare. The second way consists in collecting data simulta-neously from different tree stands and then, observing the principle *ceteris paribus*, analysing the effect of definite features of tree stands on the occurrence and dy-namics of ground water (SULIŃSKI, 1981) and particular components of water bal-ance in the atmosphere – tree stand – soil system (KUCZA and SULIŃSKI, 1987; SU-LIŃSKI, 1993).

Remarkably useful for this purpose are methical recommendations and ex-amples of construction of mathematical models with the use of ecological criteria of CZARNOWSKI (1978). Both ways were used in this paper. The influence of cli-matic conditions and water properties of soils on the dynamics of water reserve in the saturation zone were studied using three-year long measurement series (Fig. 2).
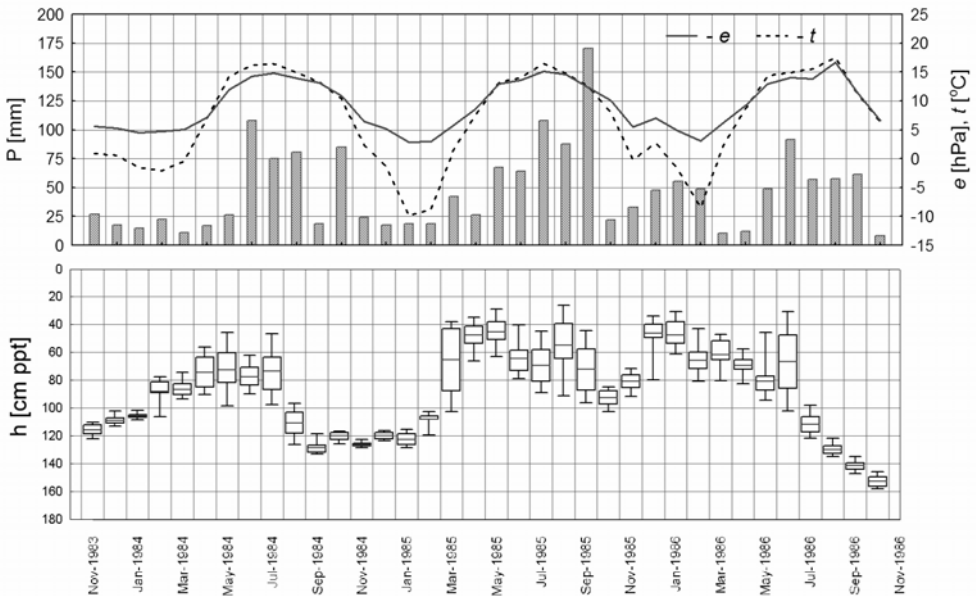
Fig. 2. Free ground water table depths in the study profile 3 compared to climatic conditions measured on a nearby mid-forest meadow. *h* – free ground water table depth measured with limnigraph in a piesometer; *P* – monthly sum of atmospheric precipitation measured with a rain gauge 1 m above ground; *e* – mean deficit of air humidity; *t* –monthly mean air temperature calculated from thermo-hygrograph records measured in Stevenson screen 2 m above ground

To study the reasons of differentiation of the components of water budget in the atmosphere – tree stand – soil system in 13 analysed soil profiles the equations of multiple regressions were constructed.

Water balance in soil profile (Fig. 1) in the phase of water increments and losses in aeration and saturation zone together may be expressed with the following general equation (SULIŃSKI, 1993):

$$Z_p = P - \left(I_d + I_r + I_s\right) - \left(\left(q_s - q_{s'}\right) + \left(q_g - q_{g'}\right) + q_c\right) \tag{1}$$

where:

Z_p – increment of water reserve in soil;
P – precipitation (above tree crowns);
I – interception of: *d* – trees, *r* – plants of forest undergrowth; *s* – litter;
q – inflow and outflow of: *s, s´* – surface water, *g, g´* – ground water, q_c – outflow to deeper soil layers.

The element expressing the contribution of water flow in horizontal direction had to be introduced to eq. (1) for the completeness of theoretical assumptions. In

practical applications, it is less important for "vertical components" of the balance in the atmosphere – tree stand – soil system (Fig. 1). In flat areas and on slopes with continuous forest cover the surface runoff does not exist or is small, hence the assumption that $(q_{s'} - q_s) = 0$ is acceptable. The ground water movement is usually continuous or quasi-continuous; therefore one may accept $(q_{g'} - q_g) = 0$. If soil profiles with saturation zone are considered, water outflow to deeper, non-balanced layers is negligibly small, thus $q_c \approx 0$. The rightness of these assumptions is most distinctly evidenced by comparison of water losses from the saturation zone between winter and vegetation periods which might be read from the limnigraph of free ground water table (Fig. 2).

After adopting these assumptions, the increments of soil water reserve can be expressed as a difference between atmospheric precipitation above tree crowns and interception of trees, plants of undergrowth and forest litter (Fig. 1). In the presence of lower tree storey or abundant shrub layer, eq. (1) may be appropriately supplemented.

Considering in further deliberations three layers (main tree stand, undergrowth vegetation and forest litter) one has to involve two factors associated with tree stand in the phase of water reserve increments in the saturation zone. The first is plant surface area which is an equivalent to potential evapotranspiration (maximally possible at unlimited rainfall). The second factor is the mass of forest litter which in turn is an equivalent of its potential interception. This course of reasoning is to be continued in chapter "Balance equation for the phase of increments of water resources in the saturation zone".

General equation for the phase of losses of water reserves from soil profile in relation to aeration and saturation zones taken together has a form:

$$Z_u = (T_d + T_r) + V_g + ((q_s - q_{s'}) + (q_g - q_{g'}) + q_c) \tag{2}$$

where:

  Z_u – the loss of water reserve from soil;
  T – transpiration of: d – trees, r – undergrowth plants;
  V_g – evaporation from the soil surface;
  q – inflow and outflow of: s, s' – surface water, g, g' – ground water, q_c – outflow to deeper layers.

Reasons for omitting „horizontal" ground water flow in eq. (1) are also valid for eq. (2). Therefore, losses of water reserve from soil profile may be associated with the transpiration of trees and undergrowth vegetation and with evaporation from the soil surface. Plant transpiration is proportional to produced biomass – with respect to forest ecosystem it is proportional to habitat productivity. Evaporation from the soil surface is determined by its exposition considered in the context of solar energy transfer from above tree crowns to the level of forest litter and of

hampering wind velocity within tree stand in relation to the velocity above tree crowns (SULIŃSKI, 1993; 1995). These factors change in relation to biometric features of a tree stand. The features may change naturally in subsequent phases of tree stand development due to biotic and abiotic factors or as a result of cultivation procedures. These determinants were considered when constructing detailed balance equations for the phase of water losses from the saturation zone described in chapter "Balance equation for the phase of losses of water reserve from the saturation zone of forest soils".

THE WAY OF DETERMINING THE PHASES OF INCREMENTS AND LOSSES AND CALCULATING WATER RESERVE IN THE SATURATION ZONE OF SOIL PROFILES

Considered below detailed balance equations (4) and (6) were constructed as applications adjusting general formulas (1) and (2) to the study aim and to possessed results of measurements that were useful in their identification.

Archive data documenting hydrologic-forest studies in the Pleistocene floodplain of the Dunajec River (western section of the Vistula River Valley) were used in the study. Study profiles were localised in the Forest District Wierzchosławice, Forest Commission Dąbrowa Tarnowska (SULIŃSKI, 1989a). The floodplain is composed of fluvio-glacial formations of the Carpathian origin deposited in the Mid-Polish and Baltic glacial periods. Quaternary formations in the study region are from several to dozen or so metres deep, locally even more, and are underlined by the Tertiary siltstone formations creating essentially one aquifer. On the surface there are numerous dune fields of relative height of several metres and lenses of impermeable formations remained after river floods in the Holocene. Studies were performed in the years 1979–1986 by research team of the Department of Forest Engineering, Faculty of Forestry, Hugo Kołłątaj Agricultural University in Cracow.

All selected soil profiles are permeable from the surface with free ground water table. Limnigraph records of the ground water table depth from 13 piesometers localised in pine tree stands (Tab. 1) and measurements of hydro-climatic factors on mid-forest meadow (Fig. 2) were used in particular. Uninterrupted measurements were performed since November 1983 till October 1986. Complete analyses of water properties of soils including laboratory determination of the coefficient of gravitational drainage (OWSIAK, 2005) were made for every soil profile. Tree stands in the surrounding of piesometers were measured in circle plots of a diameter of 5 or 10 m (Tab. 1).

Phases of increments and losses of water reserves in the saturation zone during vegetation periods were estimated on limnigraph curves for each of 13 study profiles. Then, the increments of ground water table depth were calculated and reduced

Table 1. Description of soil profiles

No. of profile	Forest division	Habitat type	Dominating species	Tree stand characteristic						Properties of soil profiles					
												ground water table depths			
				A	D	H	N	W_o	M	L_s	μ_{sr}	h_c	h_{sr}	h_{min}	h_{max}
1	80a	BMw	pine	53	22.2	18.6	750	0.162	13.3	0.810	0.051	58	60	–10	137
2	66a	LMśw	pine	67	29.0	21.5	525	0.140	13.4	1.168	0.038	103	104	29	160
3	41g	BMśw	pine	51	23.5	20.3	800	0.184	14.2	1.440	0.050	89	93	27	158
4	7a	BMw	pine	65	28.8	22.5	400	0.087	13.9	1.050	0.053	93	97	41	140
5	1i	BMśw	pine	20	10.7	7.7	1625	0.280	12.9	1.395	0.043	184	188	136	227
6	2a	BMw	pine	83	32.0	21.1	350	0.093	12.1	1.242	0.046	125	128	71	163
7	4d	BMw	pine	75	31.0	25.4	425	0.099	14.3	2.232	0.042	132	133	73	186
13	83d	meadow	–	–	–	–	–	0.025	12.0	2.012	0.027	38	48	–3	113
14	84d	LMśw	pine	30	15.7	13.4	1450	0.302	13.8	0.858	0.042	131	128	49	190
15	71b	LMśw	pine	40	20.6	17.8	900	0.192	14.3	0.990	0.037	150	148	79	214
16	71a	LMśw	pine	75	32.8	24.9	250	0.050	14.2	0.980	0.039	196	194	129	250
19	20Af	LMśw	pine	53	21.8	20.6	800	0.157	14.1	1.275	0.054	85	87	23	114
20	19b	LMśw	pine	95	34.8	26.0	350	0.091	13.4	1.217	0.033	133	134	83	180

Explanations: A – age (years); D – mean diameter at breast height (cm); H – mean height (m) N – number of trees (pieces·ha⁻¹); W_o – coefficient of soil exposition within tree stand (SULIŃSKI, 1993; 1995); M – habitat quality expressed by annual biomass production (t fresh weight of above ground plant parts·year⁻¹·ha⁻¹) calculated acc. to methods given in SULIŃSKI (2007); L_s – litter mass (g·cm⁻²); μ_{sr} – coefficient of gravitational drainage, mean for the profile; h – free ground water table depth (cm); c – mean for the period XI 84–X 86; sr – min – max – mean, minimum, maximum for summer months of the period XI 84–X 86; BMw – mixed wet coniferous forest; LMśw – fresh mixed deciduous forest; BMśw – mixed fresh coniferous forest.

through multiplying them by the coefficient of gravitational drainage. The way of determining phases and calculating changes in water reserves in the saturation zones during these phases is illustrated in Fig. 3. For every phase the rainfalls and deficits of air humidity measured in mid-forest meadow were summed up (Fig. 3). Demonstration fragment of database is given in Table 2.
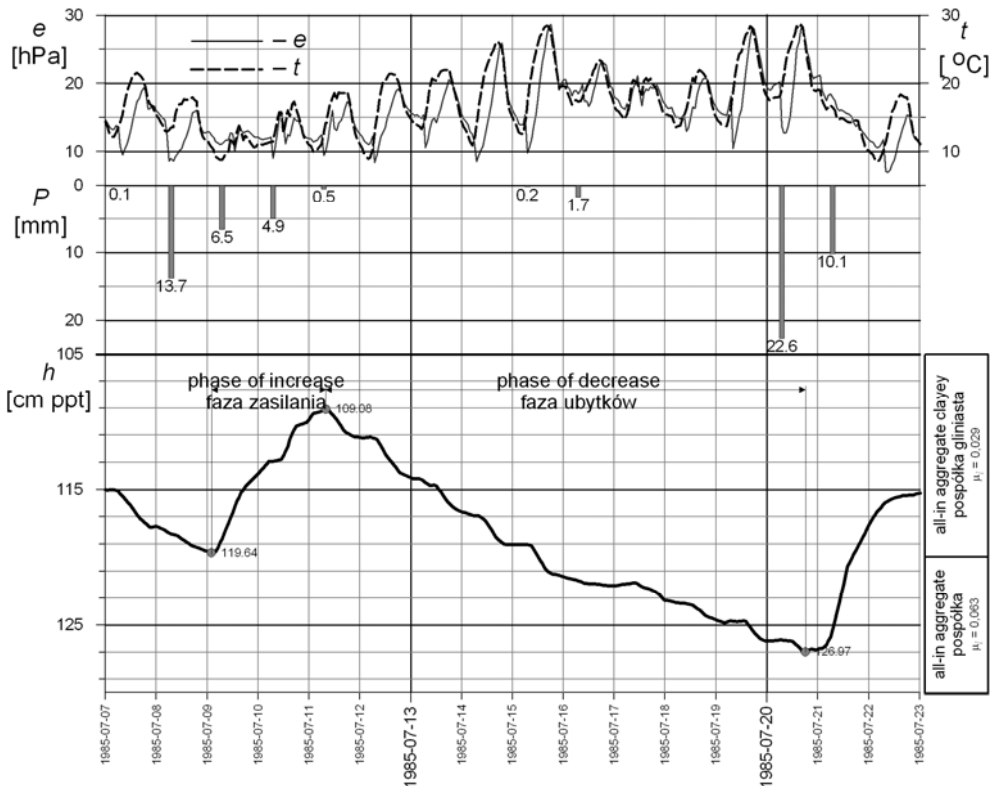

Fig. 3. An example of distinguishing phases of ground water movement from the limnigraph curve; *h* – ground water table depth, *P* – daily sum of atmospheric precipitation, *e* – deficit of air humidity, *t* – air temperature, μ_l – coefficient of gravitational drainage

BALANCE EQUATION FOR THE PHASE OF INCREMENTS OF WATER RESOURCES IN THE SATURATION ZONE

For a single soil profile the adjustment of general equation (1) to a form suitable for studying the relationship between rainfall above tree crowns and the amount of water enlarging the saturation zone is associated with the necessity of construction an element that would express interception of plants and forest litter and the amount of water remaining in the aeration zone of a soil profile (Fig. 1).

Table 2. Demonstration values from the database describing the phases of water increments and losses in the saturation zone distinguished based on limnigraph of free ground water table for profile no. 20

Phase of increments									Phase of losses								
Data	godz.	czas	h_{pp}	h_{pk}	h_{rpp}	h_{rpk}	ΔZ_{ps}	P_p	Data	godz.	czas	h_{up}	h_{uk}	h_{rup}	h_{ruk}	ΔZ_{us}	d_u
1985.04.25	12:00	278	124	102	54.4	48.0	6.51	51.8	1985.05.07	02:00	140	102	107	48.0	49.5	1.69	66.2
1985.05.12	22:00	61	107	102	49.5	48.1	1.39	4.5	1985.05.15	11:00	84	102	108	48.1	49.7	1.66	57.9
1985.05.18	23:00	66	108	103	49.7	48.3	1.47	13.9	1985.05.21	17:00	33	103	104	48.3	48.6	0.24	20.1
1985.05.23	02:00	13	104	103	48.6	48.4	0.16	13.1	1985.05.23	15:00	456	103	123	48.4	54.2	6.79	239.0
1985.06.11	15:00	14	123	122	54.2	54.0	0.21	9.7	1985.06.12	05:00	156	122	126	54.0	55.1	1.34	73.3
1985.06.18	17:00	22	126	124	55.1	54.7	0.47	20.1	1985.06.19	15:00	136	124	129	54.7	56.0	1.52	85.1
1985.06.25	07:00	104	129	116	56.0	52.2	3.81	41.4	1985.06.29	15:00	72	116	117	52.2	52.6	0.58	43.6
1985.07.02	15:00	41	117	116	52.6	52.1	0.51	26.2	1985.07.04	08:00	149	116	121	52.1	53.8	1.78	78.5
1985.07.10	13:00	45	121	119	53.8	53.2	0.63	26.2	1985.07.12	10:00	208	119	128	53.2	55.7	2.66	157.0
1985.07.21	02:00	126	128	126	55.7	55.1	1.02	34.5	1985.07.26	08:00	307	126	135	55.1	57.9	3.43	195.7
1985.08.08	03:00	95	135	100	57.9	47.5	10.53	69.4	1985.08.12	02:00	156	100	109	47.5	50.0	2.86	121.0
1985.08.18	14:00	81	109	97	50.0	46.6	3.47	32.7	1985.08.21	23:00	121	97	105	46.6	48.9	2.57	72.9
1985.08.27	00:00	42	105	83	48.9	42.4	6.43	44.3	1985.08.28	18:00	1103	83	134	42.4	57.5	16.24	579.6
1985.10.13	17:00	107	134	129	57.5	56.1	2.06	18.3	1985.10.18	04:00	79	129	133	56.1	57.2	1.09	30.5

Explanations: Data, godz. – date and hour of the start and end of a given phase; czas – duration of a given phase (hours); h – ground water table depth (cm); pp, pk – in the beginning and at the end of increment phase; up, uk – in the beginning and at the end of loss phase; h_r – ground water table depth reduced by the coefficient of gravitational drainage (mm); pp, pk and up, uk – as before; ΔZ_{ps} – increment of water reserve in the saturation zone (mm); ΔZ_{us} – loss of water reserve from the saturation zone (mm); P_p – sum of rainfall in the phase of water increment (mm); d_u – sum of daily mean deficit of air humidity (hPa).

Plant interception may be expressed by the formula given by CZARNOWSKI (1978) and generalised by SULIŃSKI (1993):

$$i_{rz} = \beta F i_0 w_p = \beta F i_0 \left(1 - e^{-\alpha s}\right)\left(1 - e^{-\gamma t}\right) \tag{3}$$

where:

i_{rz} − actual plant interception;

i_0 − coefficient of initial interception (for dry surface of plants $i_0 = 1$, for maximally wetted $i_0 = 0$);

F − index of surface areas of all plants in forest community;

w_p − coefficient of utilisation of potential interception by single rainfall, dependent on its characteristics;

s − rainfall intensity;

t − rainfall duration;

β, α, γ − coefficients to be calculated during identification of the equation.

Plant interception described by eq. (3) was called "fulfilment of leaky reservoir" (SULIŃSKI, 1993; 1995). Verbalizing its content one may say that plant interception is a product of potential interception and coefficient of its utilisation which, according to results of up-to-date studies may be expressed by a function of duration and intensity of rainfall. Considering recharge of the saturation zone in a single soil profile, eq. (3) can be simplified by assuming $i_0 = 1$ and $F = $ const. The second assumption is justified by the fact that even in the beginning and at the end of vegetation season, when plants' surface area F is reduced, rainfalls of high intensity and lasting long enough to fully utilise potential interception are rare in our climatic conditions. Therefore, parameter α expressing combined potential interception of plants and forest litter and calculated during identification was introduced to eq. (4). Further simplification of eq. (3) consists in replacement of two elements that express the effect of rainfall intensity and duration by one element with the amount of rainfall. This simplification is justified inasmuch as the amount of single rainfall and its intensity are mutually interrelated (EAGLESON, 1978; LAMBOR, 1971).

Ground water table depth measured in a point ending the phase of water increments was adopted as an equivalent of water remaining in the aeration zone after rainfall (Fig. 3). The depth was recalculated for water reserve by multiplying it by coefficients of gravitational drainage appropriate for a given part of soil profile (Fig. 3). It was thus assumed that the increment of water reserve in the saturation zone starts not before capillary porosity of the aeration zone is exhausted. One has to keep in mind, however, that cases departing from this assumption are often observed in research practice. Top forest soil layer is not a continuous medium even if built of hardly permeable ground. As already mentioned, this is a result of dead plant roots present there, tunnels dug out by soil fauna and other specific properties

associated with the presence of organic matter (KUCZA, 2007). These are the problems poorly understood and hard to quantitative presentation.

Considering the described assumptions adjusting eq. (1) to a form suitable for solving the study aim and for possessed database of field measurements, the formula describing water reserve increments in the saturation zone may be presented in a form:

$$\Delta Z_{ps} = P_p - \left(\alpha + \delta h_{rpk}\right)\left(1 - e^{-\gamma P_p}\right) \tag{4}$$

where:

ΔZ_{ps} – increment of water reserve in the saturation zone (mm);

P_p – atmospheric precipitation that initiated the phase of increment (mm);

h_{rpk} – the depth of free ground water table at the end of increment phase reduced by the coefficient of gravitational drainage (mm);

α – equivalent of combined potential interception of plants and litter calculated together with coefficients δ and γ in the process of identification (Tab. 3).

Table 3. Results of identification of eq. (4)

No. of profile	Coefficients			Assessment of agreement between calculated and measured values					
	α	δ	γ	n	$100R^2$	σ	v	quartiles	
								lower	upper
1	316.3	8.71		65	94.4	1.71	22.0	–14.8	23.2
2	435.8	11.72		56	99.0	1.24	7.8	–3.9	4.2
3	468.3	8.32		74	98.3	1.39	12.3	–9.0	8.6
4	447.3	8.08		44	99.3	1.40	7.7	–3.9	5.8
5	487.5	7.26		44	99.7	0.74	4.1	–1.9	3.6
6	451.3	8.41		68	99.2	1.03	8.2	–4.7	6.0
7	765.9	4.47	0.00081	47	99.4	1.03	6.5	–2.9	6.4
13	710.8	11.17		102	86.2	3.26	41.3	–41.9	16.2
14	362.0	11.96		50	99.3	1.02	7.0	–6.9	4.1
15	415.3	13.59		33	99.1	1.87	8.1	–4.2	4.8
16	397.9	9.01		42	99.6	1.03	5.5	–5.1	4.6
19	483.2	8.10		58	97.1	1.83	14.2	–12.1	10.3
20	459.3	13.40		40	99.7	1.03	4.9	–9.0	2.5

Explanations: n – number of cases used to identify the equation, $100R^2$ – coefficient of determination (%). σ – standard deviation of differences between measured and calculated values; v – variability coefficient calculated as a quotient of σ and the mean of measured dependent variable (%); quartiles calculated for the error of single cases expressed in percent.

    Parameters obtained during identification of eq. (4) performed based on data described in chapter 3 are set up in Table 3. The table presents also a comparison of increments of water reserves calculated from eq. (4) with those measured in piesometers. Obtained data demonstrate that identification of the formula gave very good results in both explaining the variability of water increments in the saturation zone ($100R^2$) and in the error of single cases (Table 3, mean error of estimate ν and quartiles). Result of identification for profile no. 13 localised in mid-forest meadow differ from the others in mean error of estimate ν, though the values of quartiles are already acceptable. Noteworthy, ground water table in this meadow was often on soil surface or several cm beneath.

    Positive result of identification of eq. (4) confirms the rightness of adopted assumptions as to the factors affecting the dynamics of water reserves in the saturation zone in particular soil profiles during a three-year long period. It is thus legitimate to check the assumptions on the components of soil water balance between profiles. This pertains to the coefficient α (Tab. 3) regarded equivalent to potential interception or maximum amount of water that would have been retained on plants' surface or in litter if rainfall intensity were large enough and its duration sufficiently long.

    If it is true that the total surface area of all plants forest habitat is independent on tree species but is proportional to habitat quality (SULIŃSKI, 1993), then the values of α should be proportional to habitat productivity M and to the mass of forest litter L_s (Tab. 1) according to the formula:

$$\alpha_i = \delta M_i + \varepsilon L_{s,i} \tag{5}$$

where:
- α – equivalent of combined potential interception of plants and forest litter calculated during identification of eq. (4) for i-th soil profile (Tab. 3);
- M_i – habitat productivity (Tab. 1);
- $L_{s,i}$ – litter mass (Tab. 1);
- δ, ε – coefficients to be calculated during identification of the equation (Tab. 4).

    Results of identification of eq. (5) set up in table 4 fully confirm described assumptions on α, and hence the rightness of premises adopted to construct and interpret eq. (4). Nevertheless, application of demonstrated relationships in further studies or for solving practical problems in balancing water resources in forest soils requires far advanced caution. One should keep in mind that apart from assumptions simplifying the construction of eq. (4), results of its identification could have been affected by other factors not taken into account here.

Table 4. Results of identification of eqs (5), (7), and (8)

Equation number	Coefficients		Assessment of the agreement between measured and calculated values from eq. (6)					
			n	$100R^2$	σ	ν	quartiles	
							lower	upper
(5)	$\delta = 7.02$	$\varepsilon = 297.7$	13	0.963	24.2	5.1	−1	3
(7)	$\gamma = 0.273$	$\eta = 0.243$	13	0.960	0.126	17.0	−8	16
(8)	$\lambda = 76.5$	$\varphi = 1.503$	13	0.857	1.21	23.3	−23	18

Explanations: see Table 3.

BALANCE EQUATION FOR THE PHASE OF LOSSES OF WATER RESERVE FROM THE SATURATION ZONE OF FOREST SOILS

Water losses from soil profile are mainly associated with plants' transpiration and evaporation from the soil surface. At deep ground water table depths the losses of water reserve from the saturation zone are mainly caused by the former. Plant roots take water just from the saturation zone or from the zone of active capillary rising. Water consumption for evaporation from the soil surface decreases water reserves in the saturation zone only if ground water table is so shallow that active capillary rising wets evaporating surface. This happens only in extreme and momentary situations. For most of the time the exchange of water between aeration and saturation zones in the context of evaporation from the soil surface is more complex (KOWALIK, 2007). A thorough recognition of these processes is crucial for diagnosing and predicting the dynamics of moisture in forest habitats and for proper calculating water budget for the whole catchment, for example for estimating ground retention with the method of selected wells. This substantiates the search for solutions with simplified equations – possible to identify based on data from field measurements.

At the construction of balance equations separately for the phases of increments and losses of water reserve one faces the problem of appropriate perspective of litter interception. The definition of forest litter itself and separation it from humus horizon in the soil poses substantial problems in many practical applications (KUCZA, 2007; SULIŃSKI, 1993). Evaporation of water stored in litter during the water increment phase is not directly included into balance equation for the phase of water losses from the saturation zone; nevertheless, together with plant interception it is a kind of competition with evaporation from the soil surface for the utilisation of potential evapotranspiration above tree crowns. There are many signs that evaporation of water from plant interception takes place still in the increment phase lasting usually from several to several dozen hours. Evaporation of water from forest litter is probably more prolonged; hence, still in the phase of water losses it may have significant limiting effect on the possibility of evaporation from the soil sur-

face. During drought the problem is less important but in the periods of positive water balance in the atmosphere its significance tends to increase. Adjusting eq. (2) to achieve the goal of present paper it was assumed that possible evaporation from litter does not substantially change evaporation from the soil surface in subsequent phases of water losses. When studying the variability of components of water balance in the atmosphere – tree stand – soil system among soil profiles this issue may have greater importance.

Apart from the two already discussed factors, water reserve in the aeration zone is important for the amount of water taken during the phase of water losses from the saturation zone. In view of missing direct measurements it was assumed that this reserve in the beginning of the loss phase is expressed by the ground water table depth reduced by the coefficient of gravitational drainage i.e. the same as for the phase of water increments. Such assumption may, however, lead to inaccuracies. The reasons for one of them have already been mentioned – due to leakages in the ground medium the increments of water reserve in the saturation zone may appear before capillary porosity of soil in the aeration zone is fulfilled. The second inaccuracy results from the fact that water reserves in the aeration zone are dynamic. Water reserve may be recharged by rainfall which admittedly does not change the turn of ground water table movement but may increase the amount of water in the aeration zone which is beyond balance calculations.

Actual evapotranspiration of forest community (Fig. 1) is usually not measured. Therefore, in the constructed balance equation it was expressed by the equivalent value of deficit of air humidity measured on mid-forest meadow. These values measured every hour and summed up for the periods of particular phases of losses of water reserve in the saturation zone were introduced to eq. (6). According to adopted scheme, water losses from the saturation zone are mainly associated with water uptake by plant roots for transpiration and with possible active capillary rising of water to near-top layer of soil profile where "evaporation from the soil surface" might occur. The sum of transpiration and evaporation from the soil may thus not overcome the sum of actual evapotranspiration calculated for a given phase. Presented assumptions in reference to eq. (2) lead to the equation of water losses from the saturation zone of a form:

$$\Delta Z_{us} = \alpha \, D_{su}{}^{\beta} \left(1 - \chi \sqrt[3]{h_{rup}} \right) \tag{6}$$

where:

ΔZ_{us} – the loss of water reserve from saturation zone calculated as a sum of values measured every hour in the period of loss phase (mm);

D_{su} – the sum of deficits of air humidity in the phase of water losses, measured on mid-forest meadow with an hourly time step (10^{-3} hPa);

h_{rup} — ground water table depth in the beginning of the phase of water losses, reduced by the coefficient of gravitational drainage (cm);

α, β, χ — coefficients to be calculated in the process of identification of equation (Tab. 5).

Table 5. Results of identification of eq. (6)

No. of profile	Coefficients			Assessment of the agreement between measured and calculated values from eq. (6)					
	α	β	χ	n	$100R^2$	σ	ν	quartiles	
								lower	upper
1	47.41	0.667	0.517	58	0.932	2.81	25.5	–40	16
2	35.41	0.586	0.526	55	0.880	1.28	36.9	–54	28
3	31.12	0.695	0.492	73	0.912	1.25	28.2	–58	16
4	31.82	0.715	0.467	43	0.824	1.32	42.1	–76	7
5	24.27	0.741	0.459	44	0.932	0.80	25.6	–34	8
6	20.41	0.859	0.469	68	0.905	1.06	31.4	–51	17
7	19.04	0.719	0.469	47	0.900	1.07	29.7	–77	8
13	9.02	0.916	0.466	99	0.715	2.86	52.2	–72	30
14	23.95	0.696	0.500	47	0.920	0.99	27.4	–65	16
15	10.06	0.734	0.461	33	0.927	1.22	25.0	–71	8
16	11.82	0.782	0.436	42	0.962	0.88	28.6	–54	11
19	49.46	0.650	0.512	53	0.924	1.15	27.5	–73	8
20	6.92	0.946	0.501	40	0.936	0.73	28.0	–26	21

Explanations: see Table 3.

In the sense of tests used to analyse the significance of explanation of variability of measured water losses ΔZ_{us} (Tab. 5) and the significance of partial regression coefficients, results of identification of eq. (6) are positive for all 13 soil profiles. One may thus accept that premises adopted for its construction are suitable to direct further studies onto processes determining water budget in the atmosphere – tree stand – soil system based on measurements of ground water table. Relatively high are, however, the values of mean error ν and the values of error quartiles for single cases (Tab. 5). Therefore, application of eq. (6) in presented form for predicting the dynamics of ground water table is limited. For the sake of assessment of the efficiency of eq. (6) it is worth mentioning that significant errors of single cases occurred most frequently for ΔZ_{us} values smaller than or close to one millimetre. Identification was performed at the assumption that all phases distinguishable from limnigraph records are considered. Therefore, the number of cases with minimum increments ΔZ_{us} was relatively high.

To make the legitimateness of the construction of eq. (6) credible, an attempt was undertaken to demonstrate that the variability of components of water balance in soil calculated singly for 13 studied soil profiles may be associated with the properties of forest communities: water losses from the saturation zone with habitat productivity and equivalent of evaporation from the soil surface (possible to calculate from eq. (6)) – with the degree of its exposition. To do this, appropriate sums of water losses $\Delta Z_{us,i}$ and evaporation equivalent $V_{g,i}$ (Tab. 6) were calculated for every profile and two regression equations were written. The first equation pertains to the relation between losses of water reserve from the saturation zone and habitat productivity with the consideration of ground water table depth:

$$\Delta Z_{us,i} = \frac{\gamma M_i}{\eta + h_{\min i}} \tag{7}$$

where:

$\Delta Z_{us,i}$ – losses of water reserve in the saturation zone of *i*-th soil profile, daily means (mm);

M_i – productivity of forest habitat (t fresh wt. of above ground plant parts·ha⁻¹year⁻¹; Tab. 1);

$h_{\min,i}$ – depth of free ground water table (m), minimum for summer months (Tab. 1);

γ, η – coefficients to be calculated during identification of the equation (Tab. 4).

Table 6. Sums of measured losses of water reserve from the saturation zone $\Delta Z_{us,i}$ and equivalent evaporation from the soil surface $V_{g,i}$ calculated from eq. (6) for 13 study profiles

No. of profile	1	2	3	4	5	6	7	13	14	15	16	19	20
$\Delta Z_{us,i}$	2.47	0.49	0.88	0.36	0.33	0.56	0.38	1.59	0.63	0.37	0.30	0.84	0.25
$V_{g,i}$	10.06	6.82	7.00	6.51	5.08	5.22	3.59	1.21	5.26	1.57	2.19	11.51	1.79

Results of identification of eq. (7) set up in Table 4 agree with expectations and confirm the correctness of the construction of equation (6). Indicating linear relationship between water losses from saturation zone $\Delta Z_{us,i}$ and habitat productivity M_i it should be underlined that the losses are mainly associated with water taken from the saturation zone for plant transpiration. Having in mind that studied pine tree stands contain a large percent of other tree species and undergrowth vegetation (OWSIAK, 2005), the relationship given in eq. (7) is the next confirmation of a hypothesis (SULIŃSKI, 1993; 1995), according to which unit water consumption for transpiration in forest ecosystems is a habitat and not species-specific feature as it is the case at an individual or population level (CZARNOWSKI, 1978) of e.g. an ag-

rocoenosis. The importance of obtained result is, however, weakened by the fact that the variability of M_i among studied profiles was relatively small (Tab. 1). Moreover, an additional reasoning for dealing losses $\Delta Z_{us,i}$ as equivalent to plant transpiration is the already mentioned linear relationship between water reserves measured at the same time in the aeration and saturation zones (KUCZA and SULIŃSKI, 1987).

The second equation making premises adopted when constructing eq. (6) credible pertains to similarity of calculated values of evaporation from the soil surface V_g, and the degree of its exposition W_o:

$$V_{g,i} = \frac{\lambda \left(1 - e^{-4W_{o,i}}\right)}{\varphi + h_{\max,i}} \tag{8}$$

where:

$V_{g,i}$ – equivalent of evaporation from the soil surface for i-th soil profile, daily means from the periods of water losses from soil (Tab. 6);

$W_{o,i}$ – coefficient of soil exposition in a tree stand (Tab. 1);

$h_{\max,i}$ – the depth of free ground water table (m), maximum for summer months (Tab. 1);

λ, φ – coefficients to be calculated in the process of identification of equation (Tab. 4).

Results of identification of eq. (8) are given in Table 4. Expression in the numerator of eq. (8) allows comparing the degree of soil exposition in a tree stand with totally exposed soil. Similarity of the two independently calculated variables – equivalent of evaporation $V_{g,i}$ calculated separately from eq. (6) for each of 13 soil profiles and coefficient of soil exposition W_o for tree stands in which the profiles were localised (Tab. 1) – fully confirms the legitimateness of construction of eq. (6). The equation may thus be considered a successful attempt of quantitative description of the dynamics or water reserve in the saturation zone of forest soils which gives a foundation for its association with biometric features of tree stand. Coefficient W_o is calculated with the use of these features according to the concept based on integration of factors affecting energy transfer and hampering wind velocity within tree stand theoretically formulated by SULIŃSKI (1993) and confirmed by the results of measurements (SULIŃSKI and SYPKA, 1997; 2000).

SUMMARY AND CONCLUSIONS

Water reserve in the saturation zone of forest soils was the subject of this paper. The study was aimed at presenting premises for the construction of balance equations of water in the saturation zone of forest soil profiles and verifying their

usefulness. Equations (4) and (6) combining respectively the increments and losses of water reserve in the saturation zone with atmospheric precipitation and deficits of air humidity measured in mid-forest meadow are the results of the study. The equations pertaining to single soil profiles were identified based on results of limnigraph measurements in 13 piesometers (Figs 2 and 3) localised in pine tree stands in Pleistocene floodplain of the Dunajec River (Tab. 1).

In order to make the results of identification of eq. (4) and (6) shown in tables 3 and 4 credible, it was demonstrated that the variability of components of water balance in the saturation zone – calculated from these equations for 13 soil profiles (Tab. 6) – may be with high statistical significance explained by the variability of habitat productivity and biometric features of tree stands. Verification was made acc. to equations (5), (7) and (8) and its results were given in Table 4.

Positive verification of premises used to construct balance equations of water reserve in the saturation zone of forest soils allows, in the context of the paper's goal, for formulating the following conclusions.

1. Premises and balance equations presented in this paper may be applicable for all forest soils with free ground water table. Coefficients calculated in the process of identification are, however, valid for areas from where the measured data were acquired. For other areas the process of identification should be repeated based on results of measurements performed there. Properly constructed balance equations should be dealt with as a tool useful for diagnosing and predicting the changes in water reserve of forest ecosystems taking place under the effect of varying tree stand features.

2. Balance equations of water reserve in soil are still one of the main methods of calculating the balance components in the atmosphere – tree stand – soil system. Ordinates of the free ground water table, if measured with sufficiently short time interval, may be useful for quantitative analysis of the factors affecting these components. Localisation of soil profiles should be preceded by a thorough recognition of the properties of a tree stand within the scope that should be primarily established in the context of detailed aim of balance calculations and logistic possibilities of performing field and laboratory measurements.

3. Interpretation of biological meaning of the coefficients from balance equations given in the paper was focussed on the needs of further methodical research in studies of water budget in forest ecosystems. The importance of balanced values calculated from these equations is the matter of other papers.

4. At present conditions of performing hydrologic – forest studies, restriction of measurements of soil water reserves to the saturation zone enables elongation of measurement series and increasing the number of sampling points. In order not to restrict interpretation possibilities, it is necessary to advance the knowledge on relationships between water reserve in the saturation and aeration zones.

5. Determination of the coefficient of gravitational drainage in particular layers of soil medium in soil profiles is the most crucial part of calculation of the in-

crements and losses of water in the saturation zone. Presently available methods are insufficient. This is true for both empirical formula and determinations made directly in soil samples.

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STRESZCZENIE

**Przesłanki do konstrukcji równań bilansowych zapasu wody
w strefie saturacji gleb leśnych**

Słowa kluczowe: *bilans wodny lasu, hydrologia leśna, leśnictwo, modelowanie
matematyczne, zapas wody w glebie*

W pracy przedstawiono przesłanki do konstrukcji równań bilansu wody w strefie saturacji gleb leśnych. Zmiany zapasu wody w glebie są traktowane jako wynik bilansu atmosfera–drzewostan–gleba, z założeniem ruchu ciągłego wody gruntowej, oraz zaniedbywalnie małych strat na infiltrację w głąb profilu, poniżej strefy saturacji. Założenia te są spełnione w wysokim stopniu w nizinnych glebach

leśnych, przepuszczalnych od powierzchni, szczególnie na tych obszarach, na których warstwa wodonośna znajduje się na stosunkowo płytko położonym stropie utworów nieprzepuszczalnych. Wówczas w okresach bez pokrywy śniegowej możliwe jest: (1) związanie przyrostu zapasu wody glebowej z opadem nad koronami drzew i intercepcją roślin oraz ściółki, (2) związanie ubytków zapasu wody glebowej z transpiracją roślin i parowaniem z powierzchni gleby. Okresy przyrostów i ubytków zapasu wody glebowej są wyznaczane na podstawie zapisu limnigraficznego głębokości zwierciadła wody gruntowej w piezometrach. W pracy podano przykłady równań opracowanych na podstawie danych z wieloletnich pomiarów w 13 profilach glebowych zlokalizowanych w lasach sosnowych na plejstoceńskiej terasie Dunajca, tj.: 1) głębokości zwierciadła wody gruntowej, 2) właściwości fizycznych gruntów budujących profile glebowe, 3) warunków hydroklimatycznych. Równania te wiążą przyrosty i ubytki zapasu wody w strefie saturacji z opadami deszczu i niedosytami wilgotności powietrza, pomierzonymi na śródleśnej łące.

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