UDC 581.151 (571.1/5)

ALTITUDINAL-BELT VARIABILITY OF EVAPOTRANSPIRATION OF FOREST ECOSYSTEMS IN THE MOUNTAINS OF SOUTHERN SIBERIA

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Received 01.02.2023

This work is devoted to the study of evapotranspiration in the landscape complexes of the northern macroslope of the Western Sayan. Article summarizes literature and authors' data on evapotranspiration obtained at experimental watersheds in the basin of the river Kebezh, on one of which in the 70s, as an experiment, 50 % of the forest area in the watershed has been cut down. Calculations of the total evaporation of phytocenoses at the basin level has been made, taking into account the altitudinal zonality. To calculate evapotranspiration at the study sites, field data obtained as a result of silvicultural and geobotanical studies and hydrological observations were used. Based on interpretation of remote sensing images and the use of digital elevation model, classification of landscape-hydrological complexes for the basins of the Kebezh and Taigish rivers was carried out, for which the components of evapotranspiration were calculated. The results showed that evapotranspiration in the dark coniferous taiga of the Western Sayan is an important component of the water balance and a significant proportion is the unproductive consumption of moisture for the evaporation of precipitation intercepted by tree crowns. It has also been established that the structure of evapotranspiration changes along the altitudinal zones in accordance with the vertical differentiation of climatic parameters and vegetation productivity. Estimated evapotranspiration data for various landscape-hydrological complexes made it possible to an indirect estimates of their contribution to the formation of runoff in river basins. This study can serve as a theoretical guide for landscape hydrological studies in the temperate cool zone.

Keywords: *precipitation, evapotranspiration, river basins, watersheds, altitudinal zonality of landscape, Western Sayan.*

DOI: 10.15372/SJFS20230403

INTRODUCTION

Evaporation is one of the most important components of a moisture cycle. In the water balance of forest ecosystems the evapotranspiration includes evaporation of intercepted precipitation, transpiration and physical evaporation from soil and snow. A. R. Konstantinov (1968) made generalization of data on evaporation in the Russian regions with different climatic and soil conditions.

In summer, transpiration of vegetation is one of the main elements of the water regime in forest ecosystems. It accounts for a significant part (until 50–70 %) of the total moisture spending for evaporation (Rakhmanov, 1962; Antipova, 1990, et al.). The values of physical evaporation and transpiration in the water balance of forest ecosystems for different regions of Russia were calculated by Yu. L. Rauner (1974), V. N. Pautova (1975), A. N. Antipov and N. D. Antipova (1975), A. V. Lebedev (1977, 1982), L. N. Kas'yanova and N. N. Pogodaeva (1979), I. N. Beideman (1983), and other authors.

Along with transpiration, an important element in the evapotranspiration of forest ecosystems is the evaporation of intercepted precipitation by tree crowns. Studies conducted under various geographical conditions indicate that precipitation interception depends on the tree density, composi-

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tion and age of stands, precipitation time on crowns, wind regime, temperature and amount of precipitation (Pomeroy et al., 1998; Onuchin, 2001; Chang, 2003; Onuchin, Burenina, 2008).

Evaporation of moisture from snow under forest canopy is significantly different from physical evaporation in open areas. It is known that transporting snow by wind is an important factor in the process of snow accumulation. Blizzards contribute to increased evaporation from the snow surface and the spatial redistribution of solid precipitation (Dyunin, 1961; Grudinin, 1981). Forest ecosystems significantly transform the type of the wind speed profile and create a special microclimate that helps reduce physical evaporation from snow. In the works of V. I. Rutkovsky (1956), E. D. Sabo (1956), S. F. Fedorov (1977), G. V. Grudinin (1981), A. A. Onuchin (2001, 2008) the role of forest vegetation in reducing moisture consumption for evaporation from snow cover is shown.

Physical evaporation from soil in forest ecosystems makes an insignificant contribution to evapotranspiration. It mainly depends on soil moisture. Maxima evaporation from soil is associated with precipitation; minimal – occur in dry periods of the year (Antipov, 1979). According to the results of hydrological studies in the dark coniferous forests of Southern Siberia (Lebedev, Uskova, 1975; Protopopov, 1975; Lebedev, 1982), in the summer months, the moisture evaporates in a forest 8 times less than from the soil in open sites.

Evaluation of total evaporation in the forest is a complex and not always solvable with the required accuracy problem. There are three approaches to evapotranspiration estimating: direct field measurement methods, computational methods, and empirical relationships. A number of calculation methods for determining the total evaporation are based on empirical dependencies (Budyko, 1956, 1971; Budagovsky, 1989; Bondarik, Karpechko 1999). In foreign countries, mainly computational methods were developed (Morton, 1984; Klaassen, 2001; Zhang et al., 2001). Within the framework of the model proposed by M. I. Budyko (1971), various variations of computational methods of evapotranspiration in a river basin are developed taking into account orography and vegetation cover (Donohue et al., 2012; Hou et al., 2022). One of the most common models for studying total evapotranspiration is the Penman-Monteith formula (Monteith, 1965) due to the convenience of calculation and the ease of obtaining the necessary meteorological data. It is modified by many researchers taking into account the factors affecting the evapotranspiration process (Yang et al., 2007; Zhang et al., 2016). The energy balance method is used to estimate the actual evapotranspiration. Estimation of evaporation from the land surface according to Earth remote sensing data SEBS (Surface Energy Balance Systems), SEBAL and METRIC (Gibson et al., 2013; Leng, 2017) has been repeatedly tested in sub-satellite experiments of various scales and directions, including Russian researchers' studies (Muzylev et al., 2019).

NASA uses the Penman-Monteith method to estimate evapotranspiration from remote sensing data, the source of which is the MODIS medium spatial resolution spectrometer. The climatic characteristics of the studied territory, the types of the underlying surface, as well as the diversity of vegetation cover are taken into account (Mu et al., 2007, 2011; Rasulova, 2021).

Based on the concept of the connection between evapotranspiration and biometric indicators of forest stands, we tried to answer the question: what are the differences between evapotranspiration for dark coniferous stands and secondary forests of the Western Sayan? The aim of the study is to show the role of evapotranspiration in the structure of the water balance of dark coniferous taiga and evaluate its effect on runoff formation in various altitudinal zones.

This work is of scientific and practical interest, because for a specific territory, an analysis of all components of the water balance obtained both as a result of field measurements and as by calculation methods has been performed. Combining the approaches and the results of previous studies we considered the contribution of the components of evapotranspiration: vegetation transpiration (woody plants, grass-shrub layer), interception of precipitation by tree crowns, evaporation of moisture from the soil and snow. The values of these components will differ significantly in the dark coniferous and deciduous forests of the study area, for each altitudinal zone.

To implement such a methodological approach a considerable volume of data is needed. These data were accumulated for the forest ecosystems of the Western Sayan by the researchers of V. N. Sukachev Institute of Forest Siberian Branch of the Russian Academy of Sciences in the course of many years of field studies. The results of field studies on vegetation transpiration in experimental catchments obtained by the authors were supplemented with literature data on the components of total evaporation (Antipov, Antipova, 1975, 1979; Antipov, 1979; Kozlova, 1979; Burenina, 1981, 1982; Lebedev, 1982; Antipova, 1990). In addition, in the mountain forests of the Western Sayan, on permanent test areas, observations were made on the dynamics of reforestation in logging areas of the 60s of the last century. All these conditions determined the choice of the study area – the northern macroslope of the Western Sayan.

In a changing climate, the assessment of the contribution of evapotranspiration to the water balance of river basins makes it possible to consider the effects of both natural and anthropogenic factors on the water content of rivers in the region, which is important not only theoretically, but also practically.

STADY AREA, INITIAL DATA AND METHODS

The investigations were conducted in the mountain coniferous taiga of the northern macro slope in the Western Sayan (Fig. 1).

Western Sayan Mountain Ridge, a wide strip of mountains with elevations above sea level (a. s. l.) of up to 2500 m at South Siberia, stretches from west to east for a distance of 650 km. Western Sayan borders on vast hilly Minusinsk Hollow covered by forest-steppe vegetation. Central Tuvan Hollow occupied by dry steppe is adjacent to this mountain ridge in the south. This region is in moderately continental climate characterized by mild winter and warm summer seasons. Average annual air temperature is minus 1 °C and precipitation ranges 600 mm to 1200 mm depending on elevation a. s. l. In foothills, snow pack is 60–80 cm deep, whereas snow depth increases to 100–180 cm, depending on slope aspect, at high (Srednesibirskoe upravlenie…, 2023).

All the altitudinal vegetation zones, from forest-steppe to mountain tundra, common in the mountains of southern Siberia can be found on the northern macro slope of Western Sayan. In the lower part of macro slope the light coniferous and coniferous-deciduous forests, dominated by pine (*Pinus* L.), birch (*Betula* L.) and aspen (*Populus tremula* L.) are presented. The zone of dark coniferous taiga (chern taiga) is located between 300 m and 700 m a. s. l. Higher it is replaced by the mountain taiga zone. At 1200–1300 m a. s. l. mountain taiga is replaced by subalpine zone – Siberian pine (*Pinus sibirica* Du Tour) / Siberian fir (*Abies sibirica* Ledeb.) open woodlands and alpine meadows. Between 1400 m and 1500 m a. s. l., these open woodlands are replaced by tundra vegetation (Smagin et. al, 1980).

Evapotranspiration was estimated at objects belonging to territorial units of various ranks ranging from elementary catchment (by which we mean the smallest catchment area with a distinct channel, having an unbranched hydrological network and

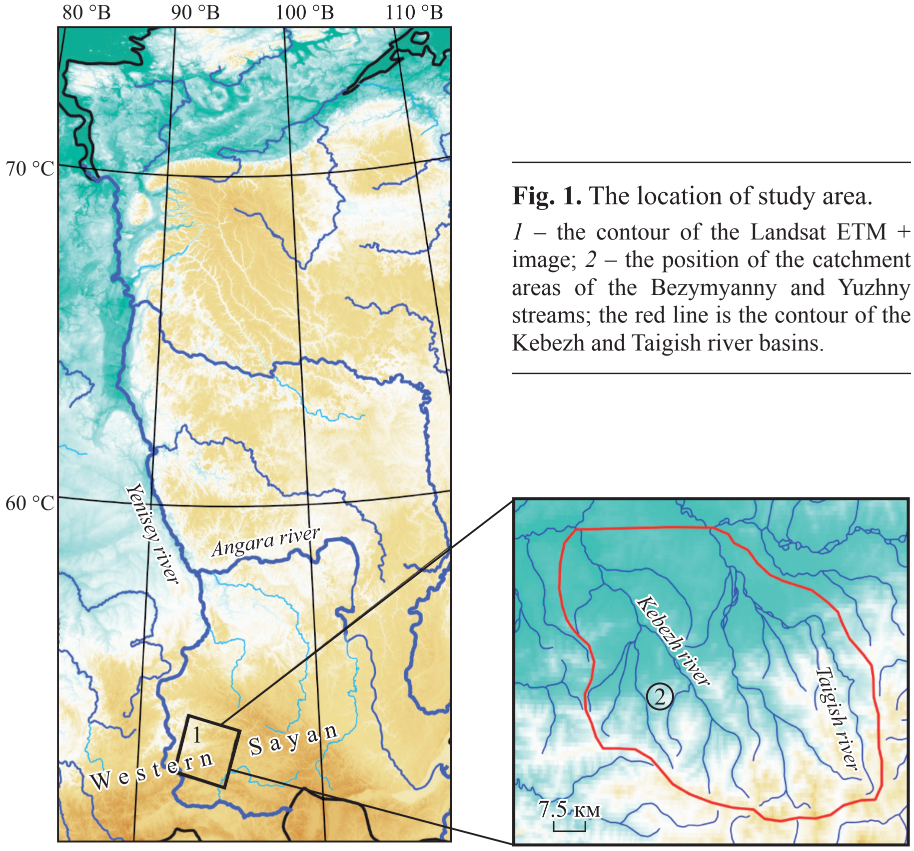

Fig. 1. The location of study area.

1 – the contour of the Landsat ETM + image; *2* – the position of the catchment areas of the Bezymyanny and Yuzhny streams; the red line is the contour of the Kebezh and Taigish river basins.

Table 1. Forestry and inventory characteristics of the sample plots

Test site number	Type of forest stand	Composition	Tree species	Age, years	Growing stock volume, m³/ha	Needles phytomass	Shrub and grass phytomass
						t/ha	
1	Siberian pine stand with fern and green moss	9Ps1F + B	Ps F	220 110	364	11.9	4.24
2	Fir stand with fern and green moss	7F3Ps + B	Ps F	150 130	170	13.5	2.30
3	Siberian pine stand with tall grass and fern	9Ps1F	Ps F	190 130	300	12.8	2.92
4	Siberian pine stand with tall grass and fern	9Ps1F	Ps F	230 130	494	13.4	3.30
5	Siberian pine stand with cowberry (*Vaccinium vitis-idaea* L.) and green moss	7Ps3F + B	Ps F	200 110	320	19.3	3.70
6	Siberian pine stand with cowberry, sedge (*Carex* L.) and green moss	10Ps	Ps	40	16.8	7.7	4.11

Footnote. B – Birch; Ps – Siberian pine; F – Siberian fir.

characterized by uniform surface structure, soil, vegetation) to river basins with dissected hydrographic network and complex terrain. The authors analyzed the results in separate blocks. The first block presents the results obtained in the field at test sites located on the catchments basins of the Southern and Nameless streams. In the second block, the results of calculation of evapotranspiration for the Kebezh and Taigish river basins are presented. The catchments of the Kebezh and Taigish rivers belong to the Yenisei River basin in Southern Siberia and are located at the northern slope of the Western Sayan ridge. The basin areas of these rivers are somewhat equal: Kebezh – 1000 km², Taigish – 750 km².

The observations were carried out at six test sites, which are located within these catchments (Table 1).

In the basin of the Southern Stream Siberian pine forests of II class bonitet are dominated, growing stock volume 320–400 m³/ha, in the upper part of the catchment they are replaced by fir stands, growing stock volume 170–200 m³/ha. At the catchment of the Nameless Stream, Siberian pine forests of II class bonitet, with growing stock volume 300 m³/ha are prevalent.

Hydrological monitoring was accomplished at V. N. Sukachev Institute of Forest Sib. Br. USSR Acad. Sci. field experimental station from 1966 to 1980. All components of the evapotranspiration were calculated using the field data. The moisture consumption for transpiration was calculated by the formula (1) (Lebedev, 1982):

$$T = N\,\Sigma_k I_k P_\mathrm{k} + \Sigma_k i_k m_k/10^4, \qquad (1)$$

where T – transpiration for a season, mm; N – number of transpiration hours for the season; I_k, i_k – average transpiration intensity of the trees and of the grass-shrub layer for season, mg/g × hour; P_k – phytomass of needles and leaves of trees, t/ha; m_k – phytomass of the grass-shrub layer, t/ha; k – index of phytocenosis.

In the field, to determine the transpiration rate of vegetation we used the modification of L. A. Ivanov (1951) method. This is a quick way to weigh a cut of a leaf or shoot detached from a plant. The first weighting is carried out immediately after cutting, and the second after 3–5 minutes, which makes it possible to measure transpiration in the state of saturation of the leaf with water in which it was on the plant.

Data on the phytomass of needles and foliage of tree species were obtained by calculation methods (Zamolodchikov et al., 2005; Usoltsev, 2007), using inventory parameters of the forest stands of test sites. The phytomass of the grass-shrub layer was determined according to the methods used in geobotanical studies (Programma…, 1974). The number of transpiration hours was calculated using the dependence of the frequency of precipitation on their total amount (Lebedev, 1982).

The interception of liquid atmospheric precipitation by the canopy was carried out according to the methods (Molchanov, 1970; Protopopov, 1975), with standard precipitation gauges used in the hydro meteorological service of Russia. Two methods were used to assess the interception of winter precipitation by the canopy: comparing precipitation in precipitation buckets in the forest and in the open area and comparing snow storage in the open site and under the forest canopy.

To estimate accumulation of snow in the forest, we used relative values, so-called snow storage coefficient or snow accumulation coefficient, which is the ratio of snow storage in the forest to that on relatively small open sites in the forest or in deciduous forest (Rutkovsky, 1956; Kolomyts, 1975; Protopopov, 1975; Fedorov, 1977; Golding, Swanson, 1978). This coefficient characterizes capability of forest stand to snow accumulation and enables estimate the amount of solid precipitation intercepted by tree crowns. This coefficient can be expressed in units from zero to one or in percent. Snow measurement was carried out by conventional methods in hydrology (Sabo, 1962) using some amendments to ensure the accuracy of the measurement of snow storage.

Physical evaporation from the soil was determined by the weight method using soil evaporators (Rekomendatsii…, 1976). To assess the physical evaporation from the snow cover, the calculated and experimental methods were used (Kuzmin, 1974). To account for the evaporation of snow moisture by experimental method, snow evaporators with an area of 500 cm^2 were used. The monoliths of snow in the evaporators were renewing when they began to thaw. The reiteration of determination of moisture evaporation from soil and snow was 5–10 days per month.

For Kebezh and Taigish river basins, quantitative characteristics of evapotranspiration were obtained using calculations taking into account the landscape differentiation of catchments (Burenina et al., 2012*a*, *b*). In order to take into account the altitude zonality and landscape differentiation of the Kebezh and Taigish river basins, a satellite image of the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) radiometer and a digital elevation model of the Shuttle Radar Topography Mission (SRTM) were used. A Landsat 7 ETM+ image acquisition date was 6 July, 1999. Spatial resolution is 30 m, spectral channels in the visible, near and mid-IR region of the electromagnetic spectrum. Detection of training samples for the classes of forest vegetation was carried out with the involvement of long-term field observation data and inventory data of the Ermakovskiy forestry district. Classification was made using maximum likelihood classification method, as a result, the following types of land cover were identified: dark coniferous (mature primary stands) forests, coniferous-deciduous (secondary stands) forests, clear cuts and burned areas, grass-marsh complexes, dark coniferous open woodlands, shrubs, mountain meadows, yernicks, rocks, water surfaces, roads, built areas.

The digital elevation model SRTM, widely used in scientific research, was obtained as a result of processing radar topographic survey data for most of the globe between 60° N. and 54° S in 2000. Interferometric data processing made it possible to obtain a digital elevation model with a resolution of 1 arc second for the entire covered area. With the help of this DEM, the territories of the Kebezh and Taigish river basins were identified and their altitude differentiation was carried out according to zoning (Smagin et al., 1980). For each high-altitude zone from the classification results of the Landsat 7 ETM+ image, plant classes of dark coniferous, coniferous-deciduous forests, cuttings and burnes, grass-marsh complexes were identified and their area was estimated.

Based on the concept of the interdependence of landscape and hydrologic spatial structure (Glushkov, 1961) we consider that every landscape complex has a certain hydrological content. We thought it possible to use the term «landscape hydrological complexes» (LHC) for our selected classes of the earth's surface.

The components of the evapotranspiration were calculated for each selected type of LHC, and then the average value of these components was determined for the high-altitude zone. Moisture consumption for transpiration along altitudinal belts for each LHC was determined by the formula (Lebedev, 1982), using the long-term average indicators of the intensity of plant transpiration in Siberia and the actual phytomass values of LHC and the number of transpiration hours for year.

For calculation of moisture transpiration, data were used on the transpiration intensity of woody and grass-shrub vegetation obtained for the virgin, secondary stands and logged sites in the forests of Western Sayan. To calculate the moisture consumption for transpiration in the chern taiga, we used the results of our own observations (Burenina, 1981, 1982). For other altitudinal zones – forest-steppe, subtaiga, mountain taiga and tundra – were involved from literature data on the transpiration intensity (Sudachkova, 1963; Pautova, 1975; Antipov, Antipova, 1979, 1980; Kozlova, 1979; Beideman, 1983; Antipova, 1990). The number of transpiration hours was determined by the dependence of the precipitation frequency on total quantity of rains (Lebedev, 1982) during the season for the year 1999.

The stock of phytomass was determined by a calculation based on the forest survey characteristics of sample plots, which were used in determining the training samples of the appropriate vegetation classes. Calculations were made according to forming the stand species through the determination of conversion coefficients by the three-parameter equation:

$$Kf = a \times D^{b} \times H^{c}, \qquad (2)$$

where D and H are the average diameter and height of the stand or element of the forest, and a, b, and c are parameters for the main forest-forming species (Zamolodchikov, 2005). The phytomass was determined through the stem volume per 1 ha and Kf of the strata. In the calculations of moisture transpiration with grass-shrub cover, data were used on phytomass of the grass-shrub layer and undergrowth in logged sites and in secondary and virgin forests (Babintseva, 1965; Burenina, 1981, 1982).

In assessing the interception of precipitation by the forest canopy, we used computational methods based on the dependences of precipitation retention on the taxation and biometric characteristics of forest stands (Onuchin, 1985, 2001; Onuchin, Burenina, 2008). To determine the amount of evaporation from the soil and snow we used the results of experimental studies on the natural evaporation on forest and treeless watersheds (Burenina, 1981, 1982; Lebedev, 1982) and data from scientific reports on field research in mountain taiga of Siberia.

RESULTS AND DISCUSSION

Field studies at the test sites. The interception of liquid atmospheric precipitation by the canopy and grass cover is important for the formation of surface runoff in the summer. Table 2 presents data from field observations of the interception of rainfall by forest vegetation over nine years (1975–1983).

Interception of liquid atmospheric precipitation by a canopy of fir stands at experimental catchments amounts to 20–38 % of the total precipitation during the season.

The formation of spring runoff is determined, first, by the accumulation of snow during the winter, which in turn depends on the interception of solid precipitation by tree crowns. The interception of solid precipitation by the forest canopy and their subsequent evaporation (sublimation) are a more complex process than the evaporation of liquid precipitation.

Not all precipitation evaporates into the atmosphere; part is blown off the crowns and replenishes snow storage under the forest canopy. The evaporation from tree crowns depends on many factors: by how long snow remains in crowns (i. e. its residence time) and by how much snow drops to the ground. Interception of snow by tree crowns increases with increasing air temperature, because the warm and moist snow becomes more adhesive to the crowns (Miller, 1964; Onuchin, 2001). At the same time, metamorphism of the intercepted snow may increase and the snow may become less solid (Kobayashi, 1987; Gubler, Rychetnik, 1991). Some researchers (Bunnell, 1985; Wheeler, 1987; Schmidt, Gluns, 1991) note that low air temperature-induced wind speed and low snow density contribute to snow interception by the forest canopy, and a warm spell following a snowfall enhances the amount of intercepted snow falling to the ground.

According to the results of study in the dark coniferous forests of the Western Sayan, precipitation interception by the canopy of the forest stands for cold period ranged from 14 to 39 %. Our data

Table 2. Interception of liquid atmospheric precipitation by the forest canopy (ground truth data for1975–1983 years)

Precipitation of the warm period, mm	Test plot											
	1		2		3		4		5		6	
	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
754	205	27.2	240	31.8	243	32.2	252	33.4	202	26.8	228	30.3
803	189	23.5	201	25.0	217	27.0	291	36.2	219	27.3	223	27.8
662	162	24.5	137	20.7	116	26.6	175	26.4	187	28.2	167	25.3
1081	277	25.6	270	25.0	313	29.0	299	27.7	291	26.9	290	26.8
714	213	29.8	208	29.1	192	26.9	193	27.0	211	29.6	203	28.5
617	165	26.7	214	34.7	179	29.0	239	38.7	216	35.0	202	32.8
559	181	32.4	170	30.4	193	34.5	195	34.9	247	44.2	197	35.3
776	253	32.6	194	25.0	243	31.3	274	35.3	243	31.3	241	31.1
769	239	31.1	252	32.8	263	34.2	291	37.8	238	30.9	257	33.4

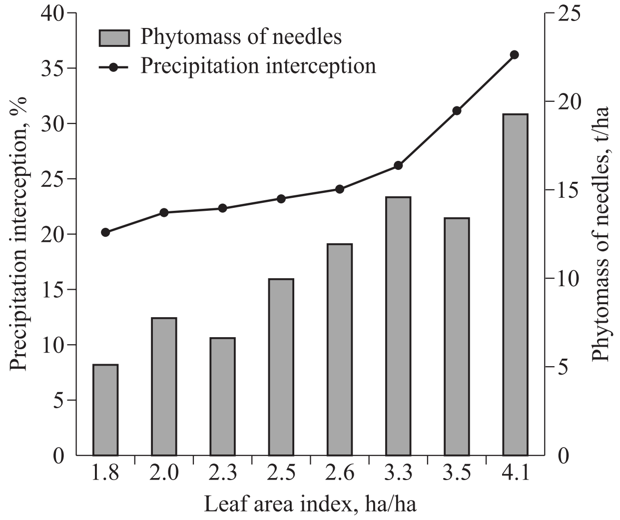

Fig. 2. Precipitation interception dependence on biometric characteristics of forest stands.

are consistent with the results obtained previously A. V. Lebedev (1974) on precipitation gauges installed in the forest and in the open site. Based on our observations and literature data (Protopopov, 1975; Lebedev, 1982), the relationship between the total precipitation interception by the canopy and inventory and biometric characteristics of stands was analyzed. With an increase in the density of the canopy from 0.4 to 0.6, the average value of intercepted precipitation increases by 3–5 %. Precipitation interception by forest canopy is highly dependent on foliage biomass, leaf area index and other easily measurable biometric characteristics of forest stands (Fig. 2).

During the summer transpiration of vegetation is one of the important expendable elements of the water balance in forest ecosystems.

The study results showed that the intensity of transpiration of the main tree species (Siberian pine and Siberian fir) is changeable, and depends on the daily temperature and air humidity. The average values of the transpiration rate of fir and Siberian pine differ both in years and in locality of study objects (Table 3).

A comparative analysis of our own research and literature data (Sudachkova, 1963; Antipov, Antipova, 1979, 1980; Kozlova, 1979) showed that even for one region the transpiration rate of tree species depends on their age, the absolute height of the terrain and the temperature regime of a concreate season.

The moisture consumption for transpiration by vegetation in the summer is determined not only by the transpiration intensity. Largely, it depends on the productivity of the forest stands. Using the phytomass data for test plots and field data on transpiration intensity in stands, calculations of moisture consumption for transpiration by dark-needle forest stands for five vegetation seasons were made (Fig. 3).

Figure 3 shows that the moisture consumption for transpiration varies significantly for stands of different ages and species composition. In fir forests, moisture consumption for transpiration is higher than in Siberian pine forests. Values of moisture consumption for transpiration vary by year, which is associated with the length of the growing season and weather conditions, on which transpiration intensity depends.

Physical evaporation from soil and snow is a small part of the evapotranspiration in forest phytocenoses. This is especially true for coniferous forests. Experiments of A. V. Lebedev (1982) on the study of physical evaporation from soil under a canopy of dark coniferous forest and from soil monoliths without grass in a glade (open area) showed that under the tree crowns soil evapora-

Table 3. The intensity of transpiration of tree species (average for the growing season) in various stands of the Western Sayan, mg/g hour

Test plot	Composition of stand	Species	1977	1978	1979	1980	Mean
1	9Ps1F + B	Ps F	112 250	128 282	147 199	139 254	132 246
2	7F3Ps + B	Ps F	124 231	139 291	130 236	142 267	109 256
3	9Ps1F	Ps F	129 244	119 193	116 148	112 189	119 194
4	9Ps1F	Ps F	131 253	136 230	114 168	121 183	126 209
5	7Ps3F + B	Ps F	94 163	118 207	124 197	132 196	117 191
6	10Ps	Ps	112	152	187	162	153

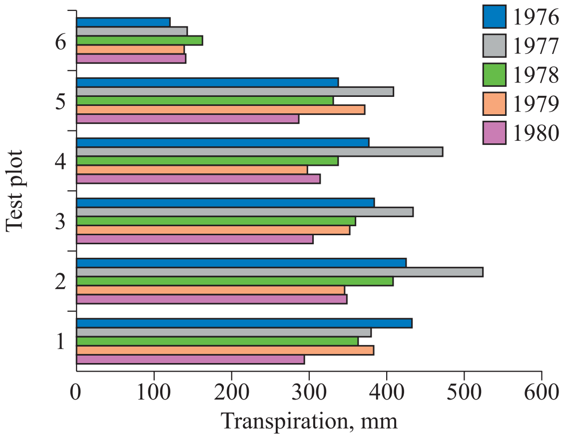

Fig. 3. The change in moisture consumption for transpiration by years.

tion is 8–10 times less than in an open place. Our own data on the evaporation from the soil for each month are based on a series of daily observations (8–10 times for month). The averaged data for all the test plots for the warm period of the year are shown in Table 4.

Observations of evaporation from the snow under the canopy at the test plots showed that from the date of the beginning of the stable snow cover to the end of February, the average daily evaporation was 0.06–0.08 mm per day. Over the years of observations during this period, the evaporation from the snow ranged from 4 to 9 mm, while during the first two months of spring, from 7 to 20 mm evaporated in the test areas. The obtained field data on the components of the evapotranspiration at the test sites were used for water-balance calculations at the experimental catchments (Table 5).

According to table 5, up to 48 % of the evapotranspiration in dark-needle stands is spent on transpiration and almost the same on evaporation of intercepted precipitations by crowns. Less than 10 % of the total consumption of evaporated moisture by the forest phytocenoses is evaporation from the soil and the surface of the snow cover.

At the same time, the transpiration and evaporation of intercepted precipitation vary significantly from year to year (Fig. 4a, b) depending on the amount of annual precipitation. In years with abundant rainfall, transpiration is 22–30 %, and the evaporation of intercepted precipitation is 65–70 % of the evapotranspiration. In years with a small amount of precipitation, the moisture consumption for transpiration increases to 60–65 %, the evaporation of intercepted precipitation 30–35 %.

A close correlation was established between the amount of rainfall intercepted by the forest canopy

Table 4. Average evaporation from soil in the forest

Years	Physical evaporation from soil, mm					
	May	June	July	August	September	Total
1977	2	12	13	4	2	33
1978	3	6	8	6	1	24
1979	2	4	4	3	2	15
1980	1	2	4	3	2	12
Average	2	6	7	4	2	21

Table 5. Elements of the water balance at the catchment of Nameless stream and Southern stream, mm

Years	Annual precipitation	Transpiration	Precipitation interception	Evaporation from soil	Evaporation from snow	Evapotranspiration
Nameless stream						
1966*	1147	243	298	10	24	575
1967	1094	175	339	11	25	550
1968	758	290	258	20	22	590
1969	998	281	284	14	20	598
1970	1089	248	311	12	24	595
1971	779	258	276	20	23	577
1972	1254	226	369	12	18	625
1973	998	253	299	18	24	594
1974	823	370	208	21	19	618
1975**	740	356	199	17	23	595
1976	982	235	304	16	20	575
1977	978	310	277	14	19	620
1978	823	263	290	12	20	585
1979	1009	383	371	10	21	784
1980	1052	294	336	12	21	663
Southern stream						
1966*	1147	232	243	10	35	520
1967	1091	175	339	10	11	535
1968	757	290	220	20	20	550
1969	1004	271	226	10	30	537
1970	1096	248	236	10	36	530
1971	803	248	243	10	15	516
1972	1224	126	398	10	19	553
1973	1026	253	231	10	35	529
1974	837	370	158	10	22	560
1975**	761	335	137	13	20	505
1976	984	262	239	10	25	536
1977	967	288	206	10	20	524
1978	1173	235	275	10	30	550
1979	990	255	242	11	24	532

Footnote. * Literature data (Lebedev, 1974, 1982). ** Authors' data.

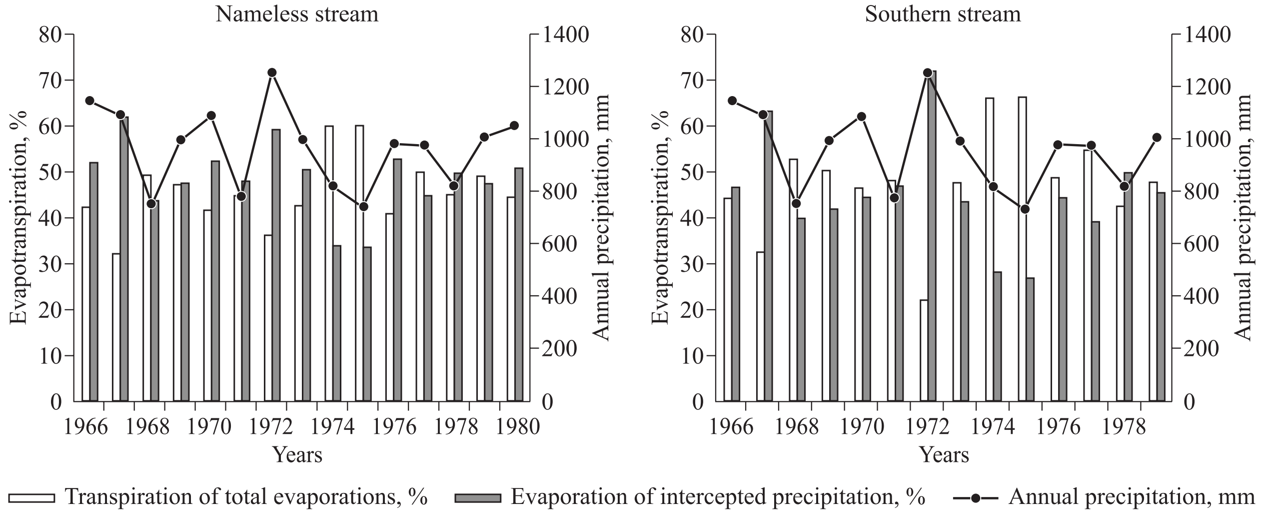

Fig. 4. Correlation of transpiration and evaporation of intercepted precipitation with annual precipitation.

and the annual amount of rainfall. For the basin of the Nameless stream the correlation coefficient is 0.77, for the basin of the Southern stream – 0.72. To compare the evapotranspiration at the experimental catchments, an evaporation coefficient was used that reflects the ratio of evapotranspiration to precipitation.

At the forest watersheds in the mountain taiga from 44 to 80 % of the precipitation is spent for evapotranspiration. The relatively small differences between evapotranspiration in the experimental basins can be explained by the fact that the catchments are in the same climatic conditions with a similar stand in terms of productivity. It should be noted that under the canopy of a dark coniferous forest, a similar microclimate is formed, on which the transpiration of the under crown vegetation largely depends.

Calculations of evapotranspiration for the Kebezh and Taigish river basins. For Kebezh and Taigish river catchments following LHC were allocated: 1 – rock outcrops; 2 – dwarf birch (*Betula nana* L.) sites (yerniks); 3 – bog-grass communities; 4 – grass/small shrub communities; 5 – open dark-needled conifer woodlands; 6 – alpine meadows; 7 – tall and small shrubs sites; 8 – virgin dark-needled conifer forest; 9 – secondary mixed conifer/deciduous stands; 10 – logged sites and fire scars.

Calculations of the evapotranspiration were made taking into account the altitudinal zonality of the vegetation cover in these catchments. Changes in evapotranspiration according to high altitude zones is due to radiation balance of the territories, but within every zone, the evaporation rate depends on the ratio of forest and treeless territories and the productivity of plant communities (Table 6).

The altitudinal zonality of LHC affects the structure of evapotranspiration (Fig. 5). In areas not covered with vegetation, i. e., rock outcrops, moisture evaporation includes only physical evaporation from the snow cover and soil. In the mountain tundra, physical evaporation from snow and soil exceeds the transpiration rate of tundra vegetation.

According to the published data and previous studies (Lebedev, 1982; Burenina, 1982; Burenina et al., 2012*a*, *b*), from the snow and soil surface, from 40 to 60 mm evaporate, which is 30 to 60 % of the evapotranspiration in these LHC.

In the forest areas of studied watersheds in the mountain-taiga and chern taiga zones, the moisture expenditure on evaporation from the soil and snow in the stands does not exceed 30–45 mm, which is a small fraction in the overall balance of moisture (6–12 %). In logged sites, burned areas, and other treeless lands, this value reaches 30 % of the evapotranspiration.

In the mountains, especially in the high-altitude part, the loss of snow moisture to unproductive evaporation occurs owing to wind activity. The magnitude of evaporation in the rock outcrops deposits on the northern slope of the Western Sayan was calculated as the difference between the background of solid precipitation (Olen’ya River weather station) and snow pack in open areas. The long-term average rate of moisture for evaporation obtained from the data of LHC is equal to 110 mm, which is consistent with published data for the mountains of the southeastern Baikal region (Onuchin, Burenina, 2008).

In the subalpine zone, the share of transpiration of plant communities and evaporation of intercepted precipitation in evapotranspiration increases.

Table 6. Differentiation of evaporation according to zonality

Landscape-hydrological complex	Evapotranspiration, mm				
	Transpiration		Evaporation of precipitation intercepted by tree crowns	Evaporation from soil and snow	Total
	Forest stands	Grass and shrubs			
	Mountain tundra				
Rock outcrops	–	–	–	110	110
Dwarf birch sites (yerniks)	–	63	–	60	123
Grass-bog sites	–	65	–	60	125
	Subalpine zone				
Tall and small shrubs	0	79	60	60	199
Dark-needled conifer open woodlands	36	98	102	40	276
Alpine meadows	–	142	–	60	202
	Mountain taiga				
Dark-needled conifer open woodlands	–	76	74	60	210
Virgin dark conifer forest	98	85	250	30	463
Secondary mixed conifer / deciduous stands	84	110	148	45	387
Logged land and fire scars	–	143	–	60	203
Grass-bog sites	–	98	–	60	158
	*Chern taiga**				
Open woodlands and shrubs	–	86	84	60	230
Virgin dark-needled conifer stands	97	120	230	30	477
Secondary mixed conifer / deciduous forest	87	138	130	45	400
Logged land and fire scars	–	148	–	60	208
Grass-bog sites	–	103	–	60	163

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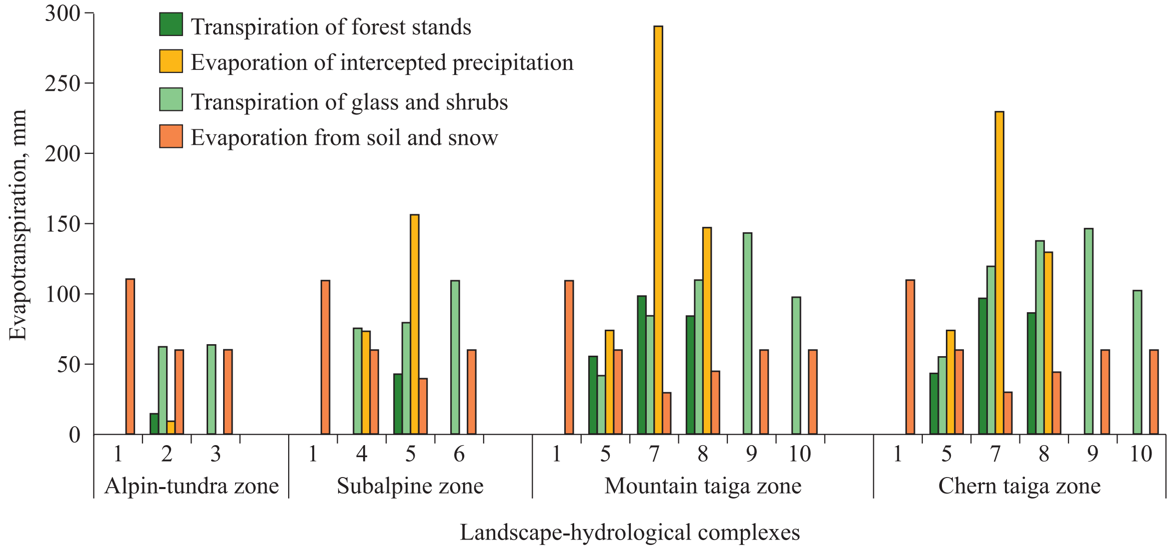
* Chern taiga is a dark coniferous taiga with aspen in the low mountain zone, which is characterized by a softer and more humid climate than mountain taiga of Siberia and a large variety of herbaceous vegetation.



1 – rock outcrops
2 –dwarf birch (*Betula nana*) sites (yerniks)
3 – grass-bog sites
4 – tall and small shrubs
5 – dark-needled conifer open woodlands
6 – alpine meadows
7 –virgin dark coniferous forest
8 – secondary mixed conifer/deciduous stands
9 – logged land and fire scars
10 – grass-bog sites

Fig. 5. Structure of evapotranspiration according to vertical differentiation of landscape-hydrological complexes.

The main components of the evapotranspiration in the mountain and chern taiga, as shown by calculations, are the transpiration of phytocenoses and the evaporation of intercepted precipitation by tree crowns. In mountain and chern taiga, plant transpiration and evaporation of intercepted precipitation are the major processes accounting for 80–95 % of the total moisture evaporation. The ratio of moisture transpiration and evaporation of intercepted precipitation varies considerably for dark coniferous stands and secondary coniferous-deciduous forests. The highest values of intercepted precipitation are characteristic for plantations of the mountain taiga zone, where dark coniferous forests predominate. In the chern taiga, significant areas are occupied by secondary deciduous forests, which affects the evaporation of precipitation intercepted by the crowns of trees.

The study showed the possibility to obtain quantitative characteristics of evapotranspiration using of landscape-hydrological analysis in conjunction with satellite images and a digital elevation model. The calculated data on the evapotranspiration for different landscape-hydrological complexes allowed us to indirectly estimate their contribution to the formation of runoff in river basins, since the formation of river flow is the integration of various water-balance ratios characteristic of the landscape complexes of the catchment.

This work is of some scientific interest, because it is based on factual data (ground truth data), but has territorial limitations. The use of GIS technology and remote sensing data of the Earth's surface in the last three decades allows us to move to the study of evapotranspiration at a new level. It is known that the evapotranspiration indicators obtained from the remote sensing data of the Earth MODIS Global Evapotranspiration Project (MOD16 ET) take into account the climatic characteristics of the studied area, the types of the underlying surface, as well as the diversity of vegetation cover (Mu, 2007, 2011; Rasulova, 2021). The use of evapotranspiration time series obtained on the basis of data from the Terra MODIS satellite (MOD16A2) for the territory of the river basin makes it possible to consider the spatial-temporal dynamics of evapotranspiration, taking into account the disturbance of forest cover by logging and fires.

CONCLUSION

Forest hydrological studies at test sites in the experimental catchments have shown that moisture consumption for transpiration of vegetation and evaporation of intercepted precipitation by tree crowns depends on the species composition and age of the stand, as well as on the phytomass of tree crowns. Fir forest evaporates more moisture than Siberian pine stands.

Evaporation from snow and soil surface makes up a small fraction of the evapotranspiration in both fir and Siberian pine stands. The variability of evapotranspiration by the years is determined by weather conditions: the more rainy days during the growing season, the lower the moisture consumption for transpiration. In years with a rainy summers, transpiration is 22–30 % of the evapotranspiration, and in dry seasons it reaches 65 %. The evaporation of intercepted precipitation depends on the amount of snow and winter air temperatures.

Comparison of evapotranspiration for different landscape-hydrological complexes showed that it varies in accordance with altitudinal differentiation. In high mountainous landscapes, plant communities spend less moisture on transpiration than similar phytocenoses in mountain and chern taiga. Physical evaporation in treeless areas of highlands and mountain tundra exceeds evaporation from soil and snow in forest phytocenoses of mountain and chern taiga due to wind activity.

Thus, evapotranspiration in the dark coniferous taiga of the Western Sayan is an important component of the water balance. At the same time, a significant share in the moisture circulation of forest ecosystems is the unproductive consumption of moisture for the evaporation of rainfall intercepted by tree crowns. The spatial variability of moisture consumption for transpiration is determined primarily by differences in the productivity of phytocenoses, while the variability of moisture consumption for transpiration in the temporal aspect is the effect of weather and climate conditions of each years.

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УДК 581.151 (571.1/5)

ВЫСОТНО-ПОЯСНАЯ ИЗМЕНЧИВОСТЬ ЭВАПОТРАНСПИРАЦИИ ЛЕСНЫХ ЭКОСИСТЕМ В ГОРАХ ЮЖНОЙ СИБИРИ

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Поступила в редакцию 01.02.2023 г.

Статья посвящена изучению эвапотранспирации в ландшафтных комплексах северного макросклона Западного Саяна. Обобщены литературные и авторские данные по эвапотранспирации, полученные на экспериментальных водосборах в бассейне р. Малый Кебеж, на одном из которых в 70-е годы в качестве эксперимента 50 % площади водосбора было пройдено рубкой. Выполнены расчеты суммарного испарения фитоценозов на бассейновом уровне с учетом высотной поясности. Расчет эвапотранспирации на объектах исследования проведен по натурным данным, полученным в результате лесоводственных и геоботанических исследований и гидрологических наблюдений. На основе дешифрирования космических снимков и использования цифровых моделей рельефа проведена классификация ландшафтно-гидрологических комплексов для бассейнов рек Кебеж и Тайгиш, для которых рассчитаны составляющие эвапотранспирации. Показано, что эвапотранспирация в темнохвойной тайге Западного Саяна является важной составляющей водного баланса, значительная доля обеспечивает непроизводительный расход влаги на испарение осадков, перехватываемых кронами деревьев. Установлено, что структура эвапотранспирации изменяется по высотным поясам в соответствии с вертикальной дифференциацией климатических параметров и продуктивности растительности. Расчетные данные эвапотранспирации для различных ландшафтно-гидрологических комплексов позволили косвенно оценить их вклад в формирование стока речных бассейнов. Представленные материалы могут служить теоретическим ориентиром для ландшафтно-гидрологических исследований в умеренно-холодной зоне.

Ключевые слова: *осадки, сток, речные бассейны, водосборные бассейны, высотная зональность ландшафта, Западный Саян.*

Буренина Т. А., Федотова Е. В., Занг Ч. Ф. Высотно-поясная изменчивость эвапотранспирации лесных экосистем в горах Южной Сибири (*Burenina T. A., Fedotova E. V., Zang C. F.* Altitudinal-belt variability of evapotranspiration of forest ecosystems in the mountains of Southern Siberia) // Сибирский лесной журнал. 2023. № 4. С. 26–40 (на английском языке, реферат на русском).