ОБЗОРНЫЕ СТАТЬИ

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NEW LOOK AT UNDERSTANDING HYDROLOGICAL ROLE OF FOREST

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The article is concerned with the discussion of the reasons for the contradictions existing in the assessment of the hydrological role of forests. The authors believe that the accumulation of new information related to seemingly well-studied processes and phenomena necessitates revisions of traditional views and leads to new knowledge of the hydrological role of forests. Various conceptual approaches to assessing the hydrological role of forests in different geographic conditions are considered. System analysis of the materials obtained by the authors and literature data made it possible to identify the features of the hydrological cycle depending on the structure of forests and climatic conditions. The data of 460 snow surveys in the period of maximum snow reserves in 212 forest stands growing in different climatic and ecological conditions were used. The comparison of the features of snow moisture balance of the forest and treeless ecosystems in different climatic conditions contributed to understanding the reasons for the contradictory assessments of the hydrological role of forests. The authors showed that in the conditions of mild and warm winters, forests are more powerful evaporators of snow moisture than treeless sites and in conditions of severe winters with frequent snowstorms, they are the accumulators of snow moisture and sources of river flow. The paper presents a conceptual model describing the mechanisms of water cycle in the forests of the boreal zone, which determine the features of the influence of forest ecosystems on the river runoff depending on the geophysical background.

Keywords: *boreal forests, forest hydrology, hydrological cycles, snow moisture balance, geographical determinism.*

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INTRODUCTION

The accumulation of new information in relation to the seemingly well-studied processes and phenomena often requires the revisions of the traditional views and results in obtaining new knowledge about the world. New concepts and understanding of the processes taking place in the global ecosystem, i.e., the Earth's biosphere, should allow us to approach the problems connected with the global climate changes and increasing anthropogenic pressure on biosphere components. It is believed that many of today's environmental problems are to be considered on a space-time scale as the problems of complex systems (Proctor, Larson, 2005), which is true in relation to forest hydrology.

The discussion of the hydrological role of the forest has recently been focused on the influence of boreal forest vegetation on the water cycle, from river basin to global scales. Starting from the end of the 19th century to the 1960s, forest policy makers of some the countries of North America and Eurasia developed a simplified view on the hydrological role of forests. They believed that forest cover increases water resources, regulates seasonal water dynamics, and maintains high water quality, regardless of hydrological and ecological conditions (Kittredzh, 1951; Rutkovskiy, 1956).

At present, interest in assessing the hydrological role of forests is associated with global climate change and the transformation of terrestrial ecosystems, caused by a complex of factors related to vegetation disturbances, such as forest fires, insect infestations, industrial pollution, etc. The influence of these factors can cause serious problems in near future for water use, which will require new approaches to water, land and forest resources management, as well as a combination of direct and indirect responses to the functioning of the catchment areas (Sun, Vose, 2016; Wei et al., 2016).

Some researchers generalize the conclusions made for tropical and mid-latitude forests and believe that these conclusions could be applied to all types of forests. Their viewpoint is based on the facts that forest ecosystems, as water consumers, reduce groundwater level and reduce river runoff through evaporation of intercepted precipitation and transpiration. The prevailing opinion among forest hydrologists that forests are important evaporators of moisture is partly due to the fact, that main forest hydrological studies were concentrated on tropical and mid-latitude zones. The boreal zone has a low population density with less than 10 % of the world's population, but boreal forests, having an area of 1.7 billion ha represent almost 30 % of the global area of forests (Global Forest Resources Assessment, 2010). Accordingly, boreal forests make a significant contribution to the ecological balance of the Earth ecosystems. The aim of our study is to analyze the causes of the contradictions in the assessment of the hydrological role of the boreal forest and to seek an agreement by developing a concept of the geographically determined hydrological role of boreal forests.

CONCEPT OF GEOGRAPHICAL DETERMINISM IN ASSESSMENT OF HYDROLOGICAL ROLE OF FOREST

Many aspects of the hydrological role of forests are described in detail in scientific literature. The acquisition of field data to estimate the hydrological role of forests of the Northern Hemisphere most often requires a network of the observations of runoff from paired catchments. The influence of forests on runoff was first studied in the late nineteenth century in Switzerland, where the suggestion of Professor Buller of monitoring the runoff at the two-paired catchments differing in forest cover was realized (Engler, 1919). In 1910, a similar experiment was developed in Colorado (US) in two small, fully forested watersheds, on one of which the forest was cut down. Coweeta Hydrologic Laboratory, Southeastern Forest Experiment Station from 1939 to 1960, carried out a large-scale experiment in the United States. Detailed reviews of the literature on this issue were presented in several publications (Bosch, Hewlett, 1982; Gu et al., 2013).

Many researchers have observed that river discharge decreases with forest cover; other investigators state that forests contribute to the total runoff by reducing evapotranspiration. The assessment of the causes of this ambiguous forest impact on the structure of water balance has been and continues to be the subject of heated discussions (Hewlett, 1970; Voronkov, 1988; Hamilton, 2008; Ellison et al., 2012; Sun, Liu, 2013; Onuchin, 2015; Onuchin et al., 2016).

N. A. Voronkov (1988) formulated three major concepts of the hydrological role of forests. One of them states that forests have a drying effect, and this is the concept most forest hydrologists adhere to. This concept is based on the idea that the evapotranspiration in high-productivity forests with closed canopies is always higher and runoff is always lower than those for open (treeless) sites including agricultural land. This effect can be accounted for by the action of the root systems of large trees working as powerful pumps to transport water from the root zone to the surface where evapotranspiration takes place (Kleidon, Heimann, 2000; Hamilton, 2008). The followers of this concept refer to the data obtained for some regions of North Eurasia and North America, which indicate that the cumulative runoff increases after logging and decreases after the forest has recovered (Hewlett, Hibbert, 1961; Hibbert, 1967; Lall, 1970; Fedorov et al., 1986 and others). Post-logging increases in runoff are observed mainly for tropical and deciduous temperate forests and, according to these observations, the greater the area of forests in the catchment area and the greater the intensity of logging, the more pronounced the effect of increasing the annual runoff (Bosch, Hewlett, 1982).

The second concept of N. A. Voronkov (1988) is that forests contribute to an increase of moisture entering the ecosystem. Its followers refer to the observations of paired basins, which confirm a positive correlation of the amount of forest cover and precipitation, to state that forests ‘attract’ clouds and thereby promote precipitation (Protopopov, 1975; Rakhmanov, 1984). This phenomenon, they believe, occurs due to forest canopy roughness, which enhances ascending airflows transporting water vapor to the cold upper atmospheric layers, where moisture condensation takes place. This results in increasing precipitation in forested areas. However, the critics of this concept, based on pointing out the weaknesses on the analyses of the cause-effect relation, believe that the positive correlation occurs because forests grow in higher-precipitation areas, rather than because forests ‘attract’ clouds (Lall, 1970; Leyton, Rodda, 1970). To disprove these objections, much more convincing evidence, based on experimental field data analysis is required. The existing evidence is not sufficient yet.

The third concept by N. A. Voronkov (1988) of an ambiguous hydrological role of forests has many followers amongst forest hydrologists. The uncertainty of the hydrological role of forest is caused by the variability of meteorological and climatic factors. Specific conditions of the hydrothermal regime in particular years and seasons can cause significant differences in the redistribution of precipitation between evaporation and runoff in certain years even for the same landscape type. The major weakness of this concept is that it does not reveal the water cycle mechanisms, which induce different hydrological effects.

L. S. Hamilton (2008) reviewed many publications concerned with the hydrological role of forests. According to these studies, the water cycle is different not only for forests of tropical and temperate biomes, but also for boreal forests.

SEASONAL PECULARITIES OF WATER CYCLE

Local and regional contrasts of the hydrological functions of boreal forests caused by ecosystem and climatic characteristics are determined to a large extent by the differences of water cycle characteristics in warm and cold periods. In the warm period, all the components of terrestrial ecosystems, including the soil, are involved in contributing to active water cycling. Precipitation becomes immediately involved in active moisture cycling (physical evaporation, transpiration and runoff), with the intensity and direction of moisture flows being determined by soil and vegetation conditions and plant phytomass, including transpiring foliage amount. The ratio between evapotranspiration and runoff is determined by vegetation productivity, rather than by site type (forested or open) (L′vovich, 1974). Studies conducted in tropical forests also show that evapotranspiration increases with increasing vegetation productivity. Interestingly, the evapotranspiration in closed-canopied evergreen forests is always higher and river runoff is always lower than on open sites, including croplands, because the roots of large trees work as powerful subsurface pumps and spend moisture on transpiration from both upper and deep soil horizons (Hamilton, 2008).

In the cold period, when precipitation becomes solid and is stored for long periods as snow cover without any transpiration, active moisture cycling occurs mainly above-ground. The most important components of moisture flows, and thus of the water balance during winter season, are evaporation of snow intercepted by tree crowns, snow evaporation from the ground, and snow redistribution and evaporation during snowstorms. In winter, vegetation productivity does not influence the intensity and directions of moisture flows and they are mostly controlled by whether the site is forested or open and by environmental conditions.

MECHANISM OF SNOW WATER CYCLE

The mechanism of the hydrologic cycle during the cold period of the year is more complicated than in the warm period, since a whole complex of factors, the significance of which can vary in time and space, determines the total evaporation of moisture in this period. In the warm period of the year, the evapotranspiration depends mainly on the productivity of forests. In winter the external conditions of environment and the type of the vegetation, the size of the open areas and the features of their spatial distribution will determine the specificity of snow moisture flows and their directionality. All these factors act on the snow moisture cycle simultaneously and, depending on the combination, cause a different effect. Nevertheless, in many cases, the forest vegetation is a most important factor among others in transformation of solid precipitation and it determines the water content in snow.

To date, a large number of studies have been conducted comparing the accumulation and evaporation of snow in the forest and in open areas. Summarizing the results of many researchers, A. Varhola et al. (2010) concluded that the snow storage decrease with increasing forest cover at the watersheds and the canopy closure. At the same time, the authors of this work remark that to make a more accurate analysis of the joint influence of all factors on snow accumulation, in the publications presented, more data are needed on the characteristics of the terrain (steepness and exposure of slopes) and the weather conditions under which the experiments were conducted. Therefore, further research should be based on on the data for all the factors affecting snow accumulation processes, including inter annual variation of meteorological data during the monitoring period (Varhola et al., 2010). Though a large number of works is published on the study of the specificity of snow accumulation in forests, the situations when snow accumulates in the forests in higher quantity than in the open sites are not considered in literature and this phenomenon has not been discussed.

Moisture flow intensity and direction depend on a combined influence of many factors, of which forest vegetation type and pattern, open site parameters, topography and background climatic conditions are the major controls of the winter water balance structure. Recent studies (Onuchin, 2015; Onuchin et al., 2016, 2017) demonstrated that the water cycle of a forest ecosystem is dependent on the background climatic conditions and that the differences of analysis of the hydrological role of forest are the result of insufficient consideration of the snow water balance specifically for forest and open sites. The hydrological role of forests and non-forest lands is manifested in their ability to redistribute precipitation between the total evapotranspiration and river runoff. To estimate the hydrological role of the forest from this viewpoint, the mechanisms of water cycling in the forest plots and woodless sites (regardless of the type of vegetation) are compared. In the boreal zone, where snow cover is an important component of the hydrological cycle, the estimates of the hydrological role of forests should be thoroughly analyzed taking into account the specific character of snow accumulation in the forest compared to open sites. Forest hydrologists realize that to do this, the terms ‘forest’ and ‘open site’ should reflect landscape characteristics (Kolomyts, 1976; Schleppi, 2011) and should be interpreted with regard for forest and open site vegetation parameters.

Forest sites. Hydrological cycles in the boreal forest are determined to a large extent by interception of snow by tree crowns, how long it remains in the tree crowns (residence time), and how much of it drops down to the ground or is evaporated from crowns. The contributions of the above factors to snow cover formation depend on the regional climate, weather and biometric parameters of forest stands (Rutkovskiy, 1956; Protopopov, 1975; Harestad, Bunnel, 1981; Hedstrom, Pomeroy, 1998; Snow ecology…, 2001; Onuchin, 2001). The importance of canopy-intercepted snow for the structure of the water is still being debated. Several studies (Lundberg, Halldin, 1994; Schmidt et al., 1988 and others) reported that the interception and the following evaporation of snow are critically important controls of the amount of snow accumulated under forest canopy. However, A. Lundberg and S. Halldin (1994) doubt that sublimation of tree crown-intercepted snow is that critical and emphasize, instead, the importance of wind-caused redistribution of the snow that has dropped from the forest canopy down to the ground.

Therefore, interception by the canopy of boreal forests in a climate with severe winters (extreme continental climate) differs from that in the southern part of the temperate climate zone. In an extreme continental climate, snow may remain in tree crowns from several days to several months (Pomeroy, Schmidt, 1993), whereas in a climate with mild winters the canopy-intercepted snow usually disappears completely by the next snowfall. Environmental conditions (air temperature, relative humidity, and wind speed) have a marked influence on the snow water budget. According to some authors, this is where a contradiction occurs. For example, interception of snow by tree crowns increases with increasing air temperature because the warm and moist snow becomes adhesive and, hence, more adherent to the crowns (Miller, 1964; Onuchin, 2001). Some researchers (Wheeler, 1987; Schmidt, Gluns, 1991) note that low air temperature-induced wind speed and low snow density contribute to snow interception by forest canopy, and a warm spell following a snowfall enhances amount of the intercepted snow falling to the ground.

The relationship between air temperature and snowfall from crowns may vary because of the effect of branch counteraction and because of snow adhesion, and hence, solidity (Pomeroy et al., 1996). At air temperatures close to melting point, tree branches become elastic and unable to hold the snow accumulated on them in a cold period and as a result, the snow falls from tree crowns to the ground (Schmidt, Pomeroy, 1990). The intercepted snow evaporates and, as a result, snow storage decreases. However, snow cover under the forest canopy is less subjected to blowout and sublimation during snowstorms than on open sites. Although there are different and often conflicting views of how the forest influences snow cover, many scientists (Rutkovskiy, 1956; Protopopov, 1975; Harestad, Bunnel, 1981; Onuchin, 2001) agree that general trends of under-canopy snow storage changes take place with changing forest stand age, density, species composition and aboveground biomass.

Tree species composition is a major factor controlling snow interception by the canopy of a forest stand. The canopy made up by deciduous species intercepts less snow than a conifer canopy, with the most extreme example being birch stands, whose snow storage coefficients are close to 1.0 (Rakhmanov, 1984). In these stands, snow interception by the canopy is virtually non-existent. In larch stands, the snow storage coefficient is 0.8, so up to 20 % of the total winter precipitation evaporates from the tree crowns (Tupikin, 1993). The reported information on snow interception by different conifer species is inconsistent. Multiannual observations made in European Russia (Rutkovskiy, Kuznetsova, 1940; Sabo, 1962) have shown that spruce canopies on average intercept more snow than Scots pine canopies, whereas in Siberia the highest-to-lowest snow intercepting capability sequence for conifer canopies is Scots pine, Siberian pine, spruce, followed by fir, all other conditions being equal (Grudinin, 1979). Our studies conducted near Lake Baikal (Onuchin, 1984, 1987) confirmed the conclusion of Grudinin (1979, 1981). Snow interception by forest canopies is highly dependent on foliage biomass, leaf area index and other easily measurable biometric characteristics of forest stands (Onuchin, 2001).

To estimate snow accumulation in the forest and, accordingly, the amount of solid snow precipitation intercepted by tree crowns, we used relative values, the so-called snow storage coefficient or snow accumulation coefficient. It is the ratio of snow storage in the forest to that on relatively small open sites in the forest or in deciduous forest (Rutkovskiy, 1956; Protopopov, 1975; Kolomyts, 1976; Golding, Swanson, 1978). This coefficient can be expressed in units from zero to one or in percent.

Fig. 1 shows snow interception by tree crowns for different conifers to be dependent on stand age and canopy closure. It has been observed that canopies of mature and old stands intercept more snow than young stands, with canopy closure being equal. This occurs because regardless of geographic conditions branches of old trees are stronger, have higher bending resistance, and are thus capable to hold more moist snow than young branches.

Using the results of our studies and data from numerous literature sources for the boreal forests of Russia, Belarus and Kyrgyzstan, we built a model (Eq. 1) showing snow storage changes under the forest canopy to depend on stand characteristics and climatic conditions (Onuchin, 2001). This model is based on the data of 460 snow surveys during the period of maximum snow reserves in 212 forest stands under various climatic conditions, which differed in age, stocking, with species composition ranging. These were 10–270-yr.-old stands with standing stem wood volume of 16–680 m^3, 0.2–1.7 stocking, and canopy closure of 0.2–1.0 that occurred on sites of Va to Ia productivity classes (bonitet). Annual precipitation varied from 250 to 1600 mm, background snow pack from 30 to 600 mm, and mean January temperature from –6 to –40 °C. We also used the results of several studies carried out in the USA in order to predict snow pack for conifers (Harestad, Bunnel, 1981).

This highly generalized model applies across the boreal forest zone, if no long thaws take place.

$$K = 118.1 + 0.016S_0 - \frac{15.8 \ln A}{\ln T} - \\ -1.3LC - 2.4NC, \qquad (1)$$

$$R^2 = 0.71, \quad G = 9.6, \quad F = 209.7,$$

where K is the snow storage coefficient, %; S_0 is background snow storage, mm; T is absolute mean January air temperature, °C; A is average stand age, years; L is proportion of larch in a stand; N is number of conifer species; C is canopy closure; R^2 is coefficient of determination; G is standard error of snow storage coefficient, %; and F is the Fisher criterion.

The model shows that below-canopy snow storage decreases with increasing stand age, canopy

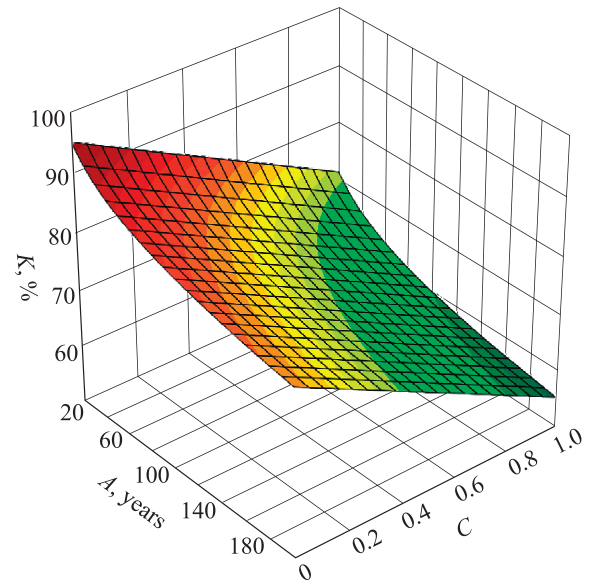

Fig. 1. Dependence of snow storage coefficient (*K*) on conifer stand age (*A*) and canopy closure (*C*).

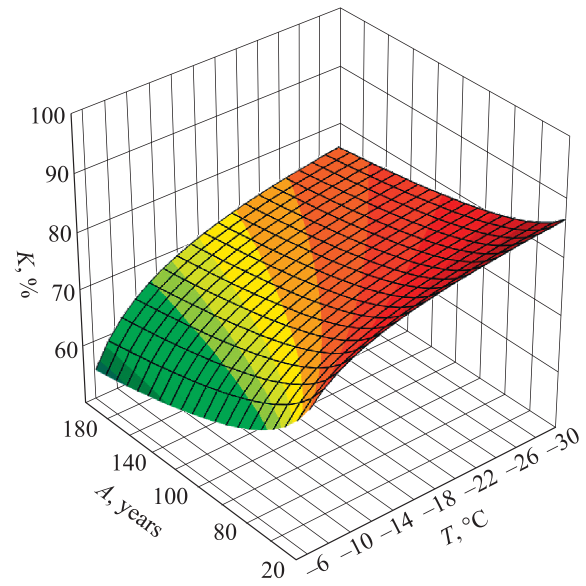

Fig. 2. Dependence of snow storage coefficient (*K*), on stand age (*A*) and January air temperature (*T*) for closed conifer stands.

closure and proportion of conifers. An effect of joint influence of stand species composition and canopy closure is also observed. Increasing canopy closure results in decreasing snow storage only when the canopy is made up of tree species capable to intercept large amounts of snow. Otherwise, no such effect occurs and increasing canopy closure does not increase the amount of intercepted snow. Decreasing snow storage with increasing stocking density and canopy closure of the stands close in age and productivity was observed in all forests, except deciduous stands, regardless of climatic differences (Rutkovskiy, 1956; Harestad, Bunnel, 1981). Deviations from the general trend of snow storage to decrease with increasing stocking density and canopy closure found for some years are attributed to wintertime thaws during which, due to more intensive snowmelt in low-density stands compared to high-density stands, the difference in snow interception by the forest canopy is obscure (Rutkovskiy, Kuznetsova, 1940).

The amount of solid precipitation also affects their interception by forest canopy. In equation (1), this is reflected through the variable S_0. Since the branches cannot hold an unlimited amount of snow, the relative interception of precipitation decreases as the snowfall increases (McNay et al., 1988; Varhola et al., 2010). This trend obviously has a general character, as the results obtained in North America are in good agreement with observations in northern Eurasia (Onuchin, 2001).

According to equation (1) absolute average January air temperature is a very important parameter of the storage changes under the forest canopy. However, the formation of snow cover in the forest depends on many factors, different combinations of which yield different effects. Dry snow and freezing weather and rare but heavy snowfalls enhance solid precipitation penetration through the forest canopy. A combination of light but frequent snowfalls with increased air temperatures are conducive to snow sticking to crowns, and results in increased snow interception by the forest canopy. At air temperatures above freezing point, snow may, however, slide off from tree crowns and add to below-canopy snow storage (Fig. 2).

Open sites. The area of open sites is a very important factor for snow accumulation. Small forest glades contribute to the accumulation of snow, while in large open areas snow storage is reduced. This is due to snow transport during snowstorm or the so called wind erosion (Pomeroy et al., 2002; Golding, Swanson, 1978, 1986) and enhanced evaporation of snow during snowstorms (Berkin, Filippov, 1972; Onuchin et al., 2016).

The experimental data collected near the southeastern shore of Lake Baikal, in central areas of Krasnoyarsk Krai, and on Taimyr Peninsula were analyzed to reveal the important role of snowstorms in snow cover formation on open sites. Apart from making snow more compact, snowstorms lead to redistribution and increasing sublimation of snow.

However, snow sublimation during snowstorms is understudied. There is indirect evidence obtained by the balance method that snow evaporates intensively during snowstorms (Dyunin, 1961; Berkin, Filippov, 1972). In the mountains near Lake Baikal, snow sublimation in winter amounts to 140–200 mm (Berkin, Filippov, 1972).

This was confirmed by our experiments conducted in a specially designed wind tunnel. The experiments showed that, under otherwise equal conditions, dry, fine snow is sublimated 1.5–3 times more intensively than a compacted snow monolith. Increasing airflow velocity from 2 to 12 m per sec resulted in increasing evaporation from 0.3 to 2 mm/day for dry snow and from 0.20 to 0.65 mm/day for the snow monolith. Snowstorms occur at different wind speeds depending on air temperature and humidity. In the Siberian continental climate with low temperatures and low air humidity in winter, snowstorms can occur when wind speed exceeds 3 m per sec.

Estimating open sites capability of accumulating snow traditionally is usually made using a precipitation preservation coefficient (Sosedov, 1967; Onuchin, 1984). This coefficient is the ratio between snowpack and precipitated snow amount: $K = Sn/X$, where K is precipitation preservation coefficient; Sn is water amount in open site snow cover, mm; and X is the total amount of solid precipitation at the time of measuring snowpack, mm. This coefficient is, in essence, analogous to the snow accumulation coefficient used in estimating the snow accumulation functions of the forest.

We generalized the information on snow accumulation developed for a range of sizes of open sites located in different parts of Siberia to obtain the following equation that reflects snow evaporation dependence on open site size and wind speed.

$$K_r = 1.01 - 0.04\ln V \times \ln T - 0.02\ln V \times \ln B, \quad (2)$$

$$R^2 = 0.81,\ G = 13.4,$$

where K_r is precipitation preservation coefficient, %; V is wind speed, m/s; T is absolute January air temperature °C, and B is open site size, ha.

The equation (2) shows that open site snow storage decreases with increasing site size and wind speed. This dependence is very pronounced for climate with severe winters. For climate with mild winter, sizes of open sites have little influence on snow accumulation. However, the greatest amount of snow is accumulated on relatively small open sites regardless of climatic conditions. The dependence of snow accumulation on site size also grows weaker where a persistent high-pressure region is observed, provided there is no wind (Onuchin et al., 2016).

COMPLEX INFLUENCE OF FACTORS ON SNOW ACCUMULATION

Weather conditions, including wind speed, have a significant impact on the processes of snow accumulation and snow cover ablation (Woods et al., 2006). Indirectly, this impact is effected through exposure, steepness of slopes and size of the open sites (Golding, Swanson, 1978, 1986; Veatch et al., 2009; Varhola et al., 2010).

Despite the general patterns of snow accumulation in the forests and open sites have been described in a number of publications, the processes of snow cover formation in terms of understanding the mechanisms are better presented in literature. There are few models that allow obtaining quantitative estimates of the combined influence of climatic, landscape and phytocenotic factors. H. W. Anderson (1967, p. 23) wrote in the last century: «The forest processes acting during snow accumulation have always been better described than evaluated». Apparently, the situation with quantitative assessments is still problematic.

Attempts to identify specific correlations between water content in the snow cover and such factors as exposure, steepness of slopes, heterogeneity of forest cover, weather conditions did not give positive results (Woods et al., 2006; Veatch et al., 2009). The reason for such failures was that most of the factors affecting the snow accumulation processes act together. The effect of one of the factors can be changed to the opposite depending on the availability and kind of influence of other factors. Therefore, there are conflicting assessments of the role of the forest in the snow accumulation in literature.

The uniform thinning of the lodgepole pine stands in Montana resulted in a decrease in interception of solid precipitation and an increase in snow storage compared to the control, and group thinning had no effect, as the decrease in interception was compensated, according to the authors, by the increasing sublimation due to rising of wind speed. Woods with co-authors (Woods et al., 2006) conclude that exposure and steepness of slopes, the size of the open sites affect the wind speed and interdependently affect snow accumulation. In the Central Sierra Nevada, in California, the group thinning of the forest canopy increased the snow accumulation compared to the control by 40 %, while the uniform thinning of the same intensity – only by 10 % (Anderson, 1967).

According to C. A. Troendle et al. (1980) in Colorado, maximum snow accumulation observed in forest glades having a diameter of not less than five heights of a tree, while in Saskatchewan J. W. Pomeroy with co-authors (1997, 1999) found that there were no differences in snow accumulation on the vast open areas and small forest glades. The authors attribute this to the weak wind activity in this region compared to adjacent areas. In our opinion, obtaining a quantitative assessment of the influence of various factors on the snow moisture balance can be successful if the modelling of the processes is confined within certain limits of topography, climatic and phytocenotic conditions. By following these rules, it is possible to make a more objective assessment of the hydrological role of forests in general and to organize a system of sustainable forest management, taking into consideration the interests of joint rational use of forest and water resources in different geographical conditions.

The hydrological cycle in boreal forest is largely determined by regional and location-specific snow processes, which manifest themselves for snow intercepted by the forest canopy, residence time of intercepted snow in tree crowns, and its subsequent falling to the ground or evaporation from tree crowns. The trends discussed above show that snow interception by forest canopies increases with increasing stand density, age and proportion of conifers. Long-lasting snow retention in tree crowns and increasing air temperature result in increasing snow evaporation from crowns, whereas the proportion of canopy-intercepted snow decreases with the increasing of the amount of precipitated snow. The effect of wind varies. In freezing weather, wind easily blows dry snow off tree crowns, which leads to increasing snow cover under the forest canopy and to decreasing evaporation of canopy-intercepted snow. In mild winters, moist snow remains in the tree crowns longer and moderate wind enhances its evaporation.

We suggest that the role of boreal forest in snow accumulation changes with changing climatic conditions. This assumption is in full agreement with N. R. Hedstrom and J. W. Pomeroy's (1998) statement that the contributions of the factors that determine snow cover formation depend on regional climate, local weather, and on whether the site is forested or open.

In winter in the forest, snow moisture is lost through snow cover evaporation and tree crown-intercepted snow evaporation. As a rule, these two moisture fluxes are unequal. Snowstorm-induced moisture evaporation is a very rare situation in the forest and occurs only on windward mountain slopes. Snow intercepted by forest canopies has a large surface area, is screened neither from solar radiation, nor from wind, and, therefore, is evaporated more intensively in the absence of snowstorms than from under the forest canopy or from open sites. However, during snowstorms, the vaporizing area of elevated snow increases tens and even hundreds of times to result in increasing snow water evaporation (Dyunin, 1961; Berkin, Filippov, 1972), which is usually the case in vast open areas.

In regions with mild and snowy winters, snow water evaporation is higher in the forest than on open sites (Hubbart et al., 2015), and vice versa in countries with harsh winters and strong winds. This largely explains the differences in the quantification of the hydrological role of the boreal forest. In freezing weather, wind easily blows dry snow off tree crowns, which leads to increasing snow cover under the forest canopy and to decreasing evaporation of canopy-intercepted snow. In mild winters, moist snow stays long in tree crowns and moderate wind enhances its evaporation.

In order to better understand the role of boreal forests and hydrological processes in the forest ecosystems, it is necessary to provide a comparative analysis of the water budget changes resulting from changing forest cover. Hydrological estimation of the forest of a particular catchment area is a harder task than a comparison of the water cycle of forested vs. open sites, because catchments, except for elementary catchments, have complex landscape structure. Even within the same forest vegetation zone a river catchment area may be a mosaic of forested and open sites. Moreover, open sites may be of native (rocks, bogs, rock outcrops, meadows, and river floodplains) and secondary character (burns, wind-fallen sites, insect-disturbed sites). Forest disturbances may also be human-caused (forest harvesting, mining, road building and pipelining).

It has been reported in many papers that the parameters of the cumulative runoff from a particular drainage basin is determined by the amount of the forested area of the basin. According to V. V. Protopopov (1975), the hydrological role of forests in any river basin depends on the forest/non-forest area ratio, relief, soil conditions, biomass amount and distribution; a complex analysis of all these factors enables to calculate an optimal percent of forested area. We analyzed available publications and the results of our studies related with this issue (Onuchin, 2001) and concluded that river runoff is determined by distribution of forested sites across a drainage basin, rather than by the forest/non-forest ratio.

Studies conducted on the northern windward macroslope of Khamar-Daban Range (Onuchin, 1987) and computational modeling carried out to identify the influence of relative forest cover and the distribution pattern of the forest (size and mosaic of the distribution of forest areas at the catchment) on snow accumulation allowed to obtain the following results:

1) when clearing was carried out on windward mesoslopes, where wind activity is the greatest, with a decrease in the forest cover of the catchments snow storage dropped from 250 mm at 100 % forest cover vs. 205 mm in a treeless basin) (Fig. 3, *b*1);

2) on otherwise exposed mesoslopes, a reduction of forest cover from 100 to 60 % resulted in an increase of about 20–25 mm in snow storage. Further reduction of forest area lead to decreasing snow storage (Fig. 3, *a*1). During group selection and mosaic clear cutting the forest cover decreased to 30 and 20 % on windward and lee mesoslopes, respectively, enhancing snow accumulation. Further forest cover reduction increased snow water losses by evaporation and, as a result, snow storage decreased drastically (Fig. 3).

With initially similar relative forest cover, snow storage was higher for basins subject to group selection cutting compared to clear-cut basins. The felling methodology caused differences in snow accumulation in drainage basins, which appeared to be especially pronounced at forest cover from 20 to 70 % for leeward slopes and from 30 to 80 % for windward slopes. In the former case, applying clearcutting instead of group selection cutting resulted in increasing snow evaporation by 40–50 mm and, in the latter case, the increase was about 100 mm.

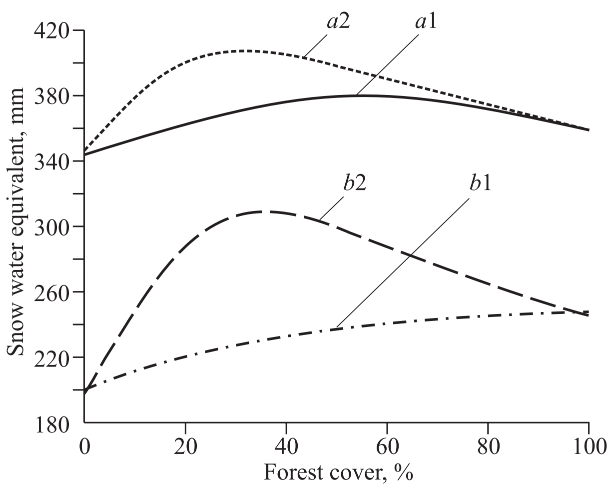

Fig. 3. Snow water equivalent dependent on forest cover in basin subject to forest cutting. *a*1 – clear cutting at lee slopes; *a*2 – group selection cutting at lee slopes; 1*b* – clear cutting at windward slopes; *b*2 – group selection cutting at windward slopes.

We conclude that snow accumulation in drainage basins depends on how the forest is distributed across a basin, along with its overall relative forest cover. The pattern of the forest vegetation mosaic is an important control of snow accumulation and its redistribution within basins. In the forest-steppe ecotone the forest regulates the water cycle through reducing water evaporation in winter and increasing soil water which is used for transpiration in the summer. In taiga forests, additional snow accumulated due to a near-optimal forest distribution may contribute to runoff and increase it by 40 mm. The increase can be as high as up to 60 mm in forest-tundra and mountain taiga.

Today, one of the issues critical for understanding hydrological processes in the boreal forest is to develop an approach adequate for the extrapolation of the results (Cohen, Bredemeier, 2011). Using data collected for relatively small sites to obtain estimates of hydrological cycles of large areas may present a number of problems (Hewlett, 1970; Ellison et al., 2012; Sun, Liu, 2013). When transferring data on a large scale with the involvement of additional factors the accuracy of the experiment may be lost, since large-scale hydrological processes are subject to more influences than small-scale ones.

Of much interest in this regard is Green Great Wall (GGW) Project of afforestation of large areas in northern China. Although the project is underway, its high ecological impact is clear by now. The regional influence of GGW on climate and water were examined using a modeling approach (Liu et al., 2008). The simulation results show that afforestation leads to overall increases in precipitation, soil moisture and air relative humidity and decreases in wind speed and air temperature in the afforested areas. In addition, the results also show significant influences outside the afforested areas, suggesting a role of afforestation in changing the climate conditions in surrounding regions.

Interestingly, seasonal precipitation has changed in the afforested areas, with the changes being reflected in seasonal river runoff. The precipitation regimes of the afforested areas of northern China were compared with those of afforested areas of Korea and Mongolia and proved to be similar to those in Korea and different from those in Mongolia. Afforestation in Mongolia showed no sizeable precipitation changes compared to the pre-afforestation seasonal precipitation dynamics (Sun, Liu, 2013).

Today's studies of carbon cycling on a global scale confirm the great importance of forests for the regional and global water cycles. Recent papers (Ellison et al., 2012) discuss how forests influence flooding, droughts and other extreme events caused by natural and human factors. However, the level of the influence of forests on water resource formation is still understudied. As mentioned above, extrapolation of the results of the hydrological studies carried out in small drainage basins to hydrological cycles on a regional or global scale would be inaccurate. Therefore, the scales of the hydrological effects of the forest and underlying surface remain an open question.

Topography can considerably transform the influence of vegetation on the structure of the snow water balance. We analyzed snow accumulation under the forest canopy and on open sites found across the altitudinal vegetation zones (AVZ) of the mountains near the southeastern shore of Lake Baikal, and considered the terrain aspect. The analysis showed that in all AVZs and both in the forest and on open sites of windward slopes of the northern macro-slope of Khamar-Daban, the total snow water evaporation was 1.5 times to twice that on lee slopes. This increase in snow evaporation is due to strong winds that cause snowstorms during which snow evaporates intensively. It is noteworthy that on windward slopes snowstorms occur even under the forest canopy, especially in mature and dense stands, where the crown-to-ground distance may exceed five meters. Under the canopy of such forests growing in the upper parts of windward slopes, strong airflows occur during snowstorms causing snow redistribution and intensive evaporation.

On planes and on lee slopes, below-canopy snow storage depends on stand species composition and canopy closure, whereas on windward slopes snow storage is determined by the horizontal structure of the forest canopy and by crown-to-ground distance. An indirect indicator of a considerable influence of slope exposure on snow cover is the non-uniformity of snow cover distribution (Onuchin, 2001). In dense mature Siberian pine stands found on windward slopes and in valleys at the heads of the rivers flowing northwestward, snow distribution is mostly non-uniform, with the snow depth variation coefficient (SDVC) being 25–30 %. SDVC is 15–17 % for open subalpine fir stands of the south-facing macro-slope of Khamar-Daban and 8–12 % for dark-needled and small-leaved deciduous stands found in lee locations of the north-facing macro-slope of Khamar-Daban. Similar trends of snow cover distribution were observed for the forests of Yenisey Mountain Ridge (Burenina et al., 2013).

We conclude that relief indirectly influences the structure of the snow water balance by transforming micro-climatic factors, both under the forest canopy and on open sites. Relief determines the importance of some of the forest vegetation characteristics for snow accumulation on slopes with varying aspect.

The reasons, that some of the models of accumulation and ablation of snow cover in the forest prove invalid, are related not only to the lack of information concerning the description of the entire range of environmental conditions, but also to the fact that scientists try to describe processes, that are multidirectional in time and space, by universal models. In conditions when there are synergistic effects of the influence of variable factors on the result, and when the limited values of these variables influence the direction of the process, a complex of particular models should be used. Different combinations of air temperature and wind speed will differently affect the interception of snow and its evaporation. In the absence of winter thaws, an increase in air temperature will promote the interception of snow by forest canopy and evaporation. With frequent winter thaws, positive temperatures will contribute to slippage-thawed snow under the forest canopy, where it is protected from evaporation and melting.

Thus, the use of particular models, each of which is suitable for their specific conditions, can provide not only more accurate estimates of the amount of water in the snow cover, but also can help us to better understand the mechanism of the simulated processes. The authors obtained models for interception of solid precipitation with a relatively high level of generality for part of the boreal zone where long winter thaws are not characteristic (Onuchin, 2001). The results obtained in the northwest of the US state of Idaho (Dobre et al., 2011) are the confirmation that variables influencing snow moisture balance are detected more easily in harsh climatic conditions. According to our data, in the alpine zone and at high altitudes the variables affecting snow accumulation are revealed more easily than at low altitudes, where the process of snow accumulation is due to the entire complex of climatic parameters and topography.

THE CONCEPTUAL MODEL OF THE HYDROLOGICAL ROLE OF FORESTS

We conclude that the hydrological role of the boreal forest changes with climatic conditions and forest structure. In a climate with severe winters (extreme continental climate), a decrease in forest area results in increasing snowstorms, and correspondingly, higher snow evaporation and decreasing river runoff. In a warm and moist climate favoring forest productivity, the forest is a better evaporator than open sites due to increasing snow interception by the canopy of highly productive dense forest stands. In these conditions, the forest contributes to reducing river runoff.

These arguments are backed up by the dependences of the total river runoff on forested areas observed under a range of climatic conditions of Northern Eurasia, including forest-tundra transition zones of central Siberia (1) and spruce forests of the Lake Issyk-Kul basin (2) (Fig. 4).

It should be noted that the transformation of the water balance of the river basin depends on its size and geological structure and background climatic conditions. Synergies of climate and landscape interactions may also contribute to annual river runoff.

The divergent estimates of the hydrological role of the forest are largely caused by differences between the results of hydrological studies conducted in different geographic conditions.

There have been few attempts to develop a conceptual view of the hydrological role of boreal forests that would reveal the roots of the existing contradictions between estimates of the water balance.

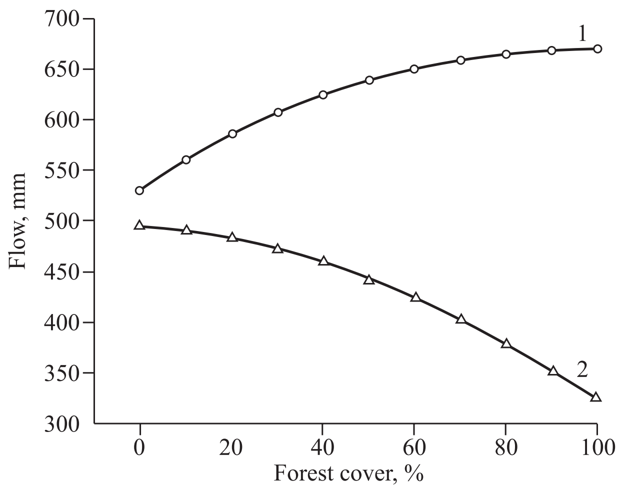

Fig. 4. Dependence of river flow on forest cover in extreme continental climate with severe winters (1) and in climate with mild winters (2).

American forest hydrologists (Sun et al., 2001) developed a conceptual model of the hydrological role of waterlogged forests growing in the south of the USA.

This model enables the estimation of the hydrological effects of forest management accounting for topography, climate and vegetation. However, it only works well for a certain region and is inapplicable to other regions, in particular, in the boreal biome.

Knowledge of the hydrological role of the boreal forest has progressed due to new information on the water cycle in forest ecosystems as a function of forest structure under different geographic conditions and due to the application of systems analysis to quantitative estimates and models (Liu et al., 2008; Onuchin, 2015; Onuchin et al., 2016, 2017). Using these new methods has improved the knowledge of hydrological functions of forests and allowed us to understand that studies of the hydrological functions of the forest must consider their direct relationships with geographic conditions, forest structure and vegetation parameters (i. e., in the simplest case whether a site is forested or open). The systems analysis enables us to investigate the causes of contradicting studies and to develop models that predict water balance changes based on trends of forest regeneration and disturbance in natural and managed conditions against the background of global climate change.

We developed a conceptual model of the hydrological role of boreal forests, which reflects hydrological effects of changes of forest cover and considers wind and wintertime air temperatures. This model is based on the results of our and other researchers' multiyear studies carried out in the interior regions of northern Eurasia. The way the model works is described above. According to this model, for harsh winters, increased forest cover has a positive hydrological effect in that it enhances river runoff. However, increasing wind reduces river runoff only for scarcely forested basins, whereas wind influence on runoff is obscured for basins with high forest cover (Fig. 5, *a*).

For mild winters, increasing forest cover results in decreasing river runoff. The contribution of wind to runoff reduction in treeless basins is less pronounced than for harsh winters and it remains the same for basins with either high or low forest cover (Fig. 5, *b*). It should be emphasized once again that this conceptual model holds for interior (continental) conditions. In a maritime climate characterized by high humidity, the role of the forest in water cycling may change drastically due to adhe-

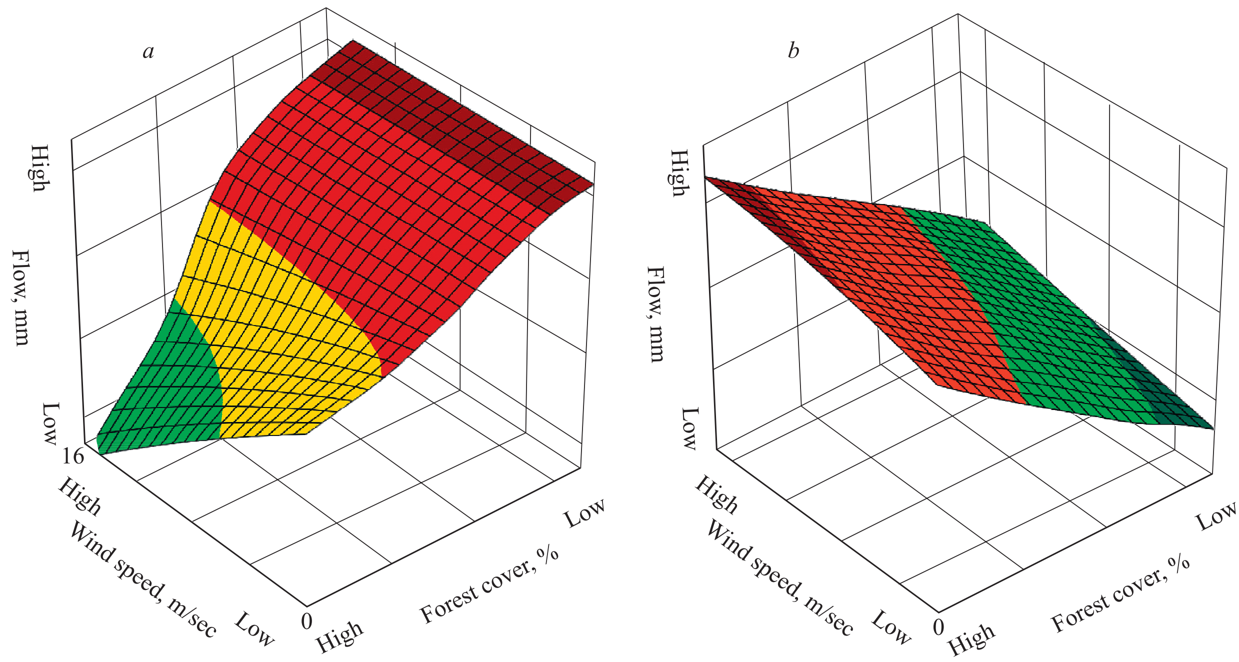

Fig. 5. Conceptual model of the hydrological role of boreal forests for harsh (*a*) and mild (*b*) winter.

sion and formation of condensation precipitation, regardless of winter air temperature (Miller, 1964; Rakhmanov, 1984).

In these conditions, wind enhances moist air penetration through the forest canopy to the ground and thereby increases runoff in forested basins (Miller, 1964).

This conceptual model thus can be called a geographically deterministic one, since it describes water cycle mechanisms which cause different hydrological effects of forest ecosystems depending on geophysical background. To realize this concept in practice, it is very important that the concepts of «forest» and «non-forest» should be viewed as related to landscape characteristics and be quantified. The boreal forest as a whole is hydrologically important. However, we would like to remark that the most clearly manifested forest hydrological effect of either increasing or reducing river runoff, depending on forest management practices, may be obtained for the zone of long-lasting snow cover.

CONCLUSIONS

In Siberia, the boreal forest influences water cycle functioning largely by changing the snow moisture balance. A significant increase in snow storage resulting from decreasing unproductive evaporation is achieved due to the forest structure produced by mosaic of vegetation cover (a combination of forested and open sites) and due to increasing proportion of deciduous tree species in stands.

The snow accumulation effect of the forest depends on the distribution of forests and is most pronounced at a forest cover of 20–40 %, while the differences in snow storage, which are controlled by the spatial structure of the forest cover, increase with increasing solid precipitation, intensification of wind activity and with decreasing air humidity.

At a local level, forests are most likely incapable of increasing precipitation, since it is determined by the global water cycle. Precipitation differentiation at local and regional levels is mainly controlled by orography. Forests have a considerable influence on water balance partitioning into evapotranspiration and runoff; they transform evapotranspiration processes by changing the ratio between unproductive evaporation and water used for transpiration.

There are several universal points in the framework of the landscape deterministic concept of the hydrological role of the boreal forest:

– deciduous stands found in the boreal forest biome contribute more to river runoff than conifer stands because they accumulate more snow, as deciduous tree crowns intercept less snow than conifers;

– runoff from forested drainage basins may be increased by appropriate forest management practices.

Studies have shown that the hydrological role of forests depends on their location in the system of climatic and phytocoenotic coordinates. In a climate with severe winters (extreme continental climate) under high precipitation forest ecosystems (open stands of low stocking density) work as a water accumulator and thereby contribute to river runoff. Compared to the forest areas, the open areas have amplified snowstorms and the unproductive evaporation of snow moisture exceeds evaporation in forest ecosystems.

In a climate with mild winters, when vegetation productivity is higher, forest works as a better evaporator than open sites. In mild winters, forests become a factor accounting for river runoff reduction. This explains the divergent estimates of the hydrological role of the boreal forest among geographic regions. With insufficient solid precipitation, the forest's influence on the water cycle drops to a minimum in both extreme continental climate and climate with mild winters.

Our study generalizes knowledge about the hydrological consequences of forest management in boreal forests. This can be used as part of a systematic approach to ensure integrated use of forest and water resources, and when considering the potential effects of climate change and the adaptation of our policies and practices to this change.

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НОВЫЙ ВЗГЛЯД НА ПОНИМАНИЕ ГИДРОЛОГИЧЕСКОЙ РОЛИ ЛЕСА

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Статья посвящена раскрытию причин противоречий, существующих в оценке гидрологической роли лесов. Авторы утверждают, что накопление новой информации в отношении, казалось бы, хорошо изученных процессов и явлений обусловливает необходимость пересмотра традиционных взглядов и приводит к получению новых знаний о гидрологической роли лесов. Рассмотрены разные концептуальные подходы к оценке гидрологической роли лесов в различных географических условиях. Системный анализ собственных материалов и литературных данных позволил выявить особенности гидрологического цикла в зависимости от структуры лесов и климатических условий. В работе использованы данные 460 снегосъемок в период максимальных снегозапасов в 212 насаждениях, произрастающих в неодинаковых климатических и лесорастительных условиях. Сопоставление особенностей баланса снеговой влаги лесных и безлесных экосистем в несхожих климатических условиях позволило понять причины противоречивых оценок гидрологической роли лесов. Авторы показали, что в условиях мягких и теплых зим леса по сравнению с безлесными пространствами являются более мощными испарителями снеговой влаги, а в условиях жестких зим с частыми метелями – накопителями снеговой влаги и источниками формирования стока рек. В работе представлена концептуальная модель, описывающая механизмы влагооборота в лесах бореальной зоны, которые определяют особенности влияния лесных экосистем на речной сток в зависимости от геофизического фона.

Ключевые слова: *бореальные леса, лесная гидрология, гидрологические циклы, баланс снеговой влаги, географический детерминизм.*