ПРОСТРАНСТВЕННО-ВРЕМЕННЫЕ АСПЕКТЫ ГИДРОЛОГИЧЕСКОГО РЕЖИМА НА ВОДОСБОРАХ ПОСЛЕ СПЛОШНЫХ РУБОК

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SPATIAL-TEMPORAL ASPECTS OF THE HYDROLOGICAL REGIME IN CATCHMENTS AFTER CLEARCUTTING

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Аннотация. В статье рассматриваются пространственно-временные аспекты гидрологических процессов на водосборах после рубок для различных ландшафтных условий Средней Сибири. Для обсуждения были привлечены результаты собственных исследований в Саянах, Енисейском кряже, бассейне реки Ангара, хребте Хамар-Дaban и литературные данные. Было проанализировано влияние вырубок на изменение речного стока и развитие эрозии на водосборе. Годовой сток, его сезонная структура и сток наносов существенно меняются в зависимости от площади сплошных рубок и площади речного бассейна. Авторами проанализированы результаты наблюдений за восстановлением водного баланса на опытных лесосеках малых водосборов и за динамикой стока крупных рек. Исследования показали, что структура растительного покрова на вырубленных участках постоянно изменяется во время восстановления леса после вырубки, и будущие сценарии гидрологического режима после вырубки определяются как дальнейшими климатическими изменениями, так и траекториями сукцессии растительности. Роль времени как фактора в уменьшении эрозии на водосборе после вырубки леса зависит от многих региональных и местных особенностей ландшафта и исходной минерализации почвы в результате рубок. Для лесов горного хребта Хамар-Дaban в бассейне Байкала разработана модель эрозии почв на водоразделах после рубок.

Abstract. This article discusses the spatial and temporal aspects of hydrological processes in catchments after logging for different landscape conditions of Central Siberia. For this discussion, the results of our own research in the Sayan Mountains, the Yenisei Ridge, the Angara River basin, the Khamar-Daban ridge and literature data were involved. It analyzed the impact of felling area to change the river flow and development of the erosion at the catchment area. The annual runoff, its seasonal structure and sediment discharge change significantly in dependence on as area of clearcutting so area of river basin. The authors analyzed the results of observations of the restoration of the water balance in the experimental logging sites of small catchments and the dynamics of runoff in large rivers. Research has shown the vegetation cover structure changes continuously on logged sites during post-logging forest regeneration and future post-cutting hydrologic regime scenarios are determined both by further climatic changes and by vegetation succession trajectories. The role of the time as a factor to decrease erosion at watershed after logging depends of many regional and local features of landscapes and of initial soil mineralization by logging. For the forests of Khamar-Daban mountainous in Baikal basin the model of soil erosion at watersheds after logging was developed.

Ключевые слова: гидрологический режим; сток; вырубка; эрозия почвы; лесовосстановление; после рубочных сукцессии
Keywords: hydrological regime; runoff; felling area; soil erosion; reforestation; post-felling successions
**Introduction**

Space and time are the fundamental categories of modern natural sciences. In hydrology, spatial and temporal regularities of water regime are the most important subjects of study. The water balance changes and erosion in watersheds are often a result of large-scale soil and forest disturbances in river catchment areas. Of all human activities, forest logging and post-logging regeneration have the greatest influence on water budget and total runoff from watersheds [1-4].

Reported first-year increases in water yield following forest clearance in the humid tropics, for instance, range from 110 to 825 mm, depending on local rainfall [5]. A review of almost 100 paired catchment experiments throughout the world [6] indicated that all of those involving removal of forest cover resulted in higher stream flow totals. Many scientists consider that spatial factors such as area of cuttings or ratio of forested area and area of a watershed (%) are the most important for hydrological consequences of forest logging on river basin [7-12]. The extent of erosion in the catchment and the loss of the fertile soil layer depends on the mineralized surface area or ratio of mineralized surface area and area of a watershed (%) [13-15].

Time factor is connected with restoration of primary conditions at the watershed. First, this is recovery of runoff-forming role of the forests after forest felling [1-2, 16-18] and second, it is a stabilization of erosion processes at watersheds [19-21]. The periods of forest restoration and, accordingly, recovery of their hydrological functions are very different.

In the exploited forests of Siberian taiga, clearcutting is, other conditions being equal, the major human disturbance, far exceeding, as to hydrologic consequences, fire. The authors tried to analyze the spatial and temporal aspects of changes in the hydrological regime after felling at the river catchments for different landscape conditions of Central Siberia.

**Study areas**

This study covered forest ecosystems and watersheds in different parts of Central Siberia to include West Sayan Mountains, Ridge Khamar-Daban (South-Eastern Baikal region), Angara Area, and Yenisei Mountain Ridge (fig. 1).

**Sayan Mountains**, a wide strip of mountains with elevations above sea level (a.s.l.) of up to 2500 m, stretches from west to east about 600 km. In the north, Sayan Mountains borders on the territory covered by forest-steppe vegetation, and central Tuvian Hollow occupied by dry steppe is adjacent to this mountain ridge in the south. The regional commercial woody species, of which the most valuable are Siberian pine (Pinus sibirica) and Siberian fir (Abies sibirica) constitute a wide altitudinal belt of dark-needled conifers. All the altitudinal vegetation belts, from forest-steppe to mountain tundra, common in the mountains of southern Siberia can be found on the slopes of Sayan Mountains.
Yenisei Mountain Ridge stretches for over 400 km, from Angara River to Podkamennaya Tunguska River. The elevation is mostly 800-900 m a.s.l. and the lowest point (30 m a.s.l.) at the northern end of Yenisei Ridge, near Yenisei River. The west-facing slopes of the ridge go steeply down to Yenisei River valley, whereas its east-facing slopes descend softly down to the adjacent plains and plateaus. Yenisei Ridge topography varies considerably. The interfluves are mostly flat or dome-like, river valleys, deep and surrounded by steep slopes, divide the ridge into several massifs. The territory is occupied by dark-needled taiga forest growing on permafrost mountain-podzolic soils. The highest sites (over 500-700 m a.s.l.), found on the western macro slope, are under dense dark-needled taiga forests dominated by Siberian fir (Abies sibirica), with a considerable Siberian pine (Pinus sibirica) contribution. Lower elevations and river valleys provide good habitats for mixed spruce-fir taiga forest containing a large proportion of Siberian spruce (Picea obovata), with feather moss as the major ground vegetation component. On the eastern macro slope, at elevations lower than 500 m, increasing climate continentality results in the occurrence of mixed Scots pine-larch stands with small shrubs as the ground vegetation layer and large sites of tall-grass taiga meadows and dwarf birch thickets. The highest mountains are bald, the tops are covered by dwarf birch and subalpine meadows broken by taluses and rock outcrops.

Angara Area is a part of Angara Basin River located in central Siberian Plateau. This is a rough terrain (av. 310 m a.s.l) having no pronounced upland sites and characterized by extremely continental climate. The study area contains various types of soil, which are seasonally deep-frozen due to long, cold
winter. The area falls within the vegetation zone of southern taiga mixed larch/Scots pine forests, with dark conifers, such as spruce and fir, limited to river valleys and small flat-bottom ravines. Deciduous forest stands are common on old burns and logging sites. Pine forests prevalence in the region, these forest stands cover 40.2% of the area; larch forests are occupied 25.5%, spruce and fir forests -12.5%, birch forests - 16.7% and aspen forests - 4.7%.

Khamar-Daban is the one of the highest mountain chains of southeastern Baikal region. Contrasting geographical conditions of Khamar-Daban are reflected in distribution of meteorological elements across this area. Khamar-Daban elevation above sea level averages 1200-1300 m, with some mountain tops as high as 1500 m; talus is abundant on hill crests, slopes are dissected by deep and narrow valleys. Climate of the area of interest is controlled by Baikal Lake and considerably elevated topography. Distribution of meteorological elements largely controls soil and vegetation patterns. While the moister Khamar-Daban macro slope supports mixed fir/Siberian pine communities, south-facing (shaded) slopes are covered by light-needled Scots pine/larch stands.

Materials and Methods

The discussion presented used numerous literature sources, results of the authors’ studies, and archived results of hydrology and forestry studies carried out at the research stations of Sukachev Institute of Forest. To estimate the effects of post-clearcutting forest communities of different age on water yield the authors employed results of water balance calculations based on the data of own hydrological experiments conducted on clear cuts of different ages in study areas [22-26]. Snow measurements and other hydrological studies were carried out according to standard methods [27]. To analyze snow cover distribution and snow water balance, we measured snow depths and weighed of snow in situ during the highest-snow cover water equivalent.

Soil erosion was studied in Khamar-Daban mountain range in elementary catchments (from 0.4 to 2.0 ha) and drainage sample plots. A detailed description of the objects and research methods is given in the publications [17, 28]. Surface runoff and sediment load at the sites located in the forest, in clearings and burned-out areas was studied by the volumetric method. This method involved measuring the amount of water runoff at sample plot and then converting it to the one ha and sampling for the determination of water turbidity. Authors also employed published results of studies of erosion in the basin of Lake Baikal obtained by the method of artificial sprinkling of small plots [29]. To analyze changes of water balance structure for catchments in Angara basin, we used reference materials for regular hydrological observations, as well as precipitation measurements from the weather stations within the areas of interest [30-32]. The dynamics of the areas of forest cover in the river basins was obtained from forest inventory data [33] and we used a number of Landsat images from 1974 through 2014. All the initial data were subject to multiple regression analysis [34]. The model of soil erosion and restoration of protective functions of the forest in the basin of Baikal was developed. The model is based on GIS-technologies and includes digital relief, hydro-meteorological, geomorphologic, soil-vegetative and erosive blocks [35].

Results

Space and water yield

We studied the influence of the felling area on the hydrological regime both in small catchments and in large river basins. Our catchment experiments conducted in dark-needled forests of Sayan Mountains showed that the catchment water balance changed after 50% of its forest had been cut. Moisture consumption for transpiration decreased twice and evaporation of precipitation intersected by vegetation became 5 times less as compared to before clearcutting. Evaporation from the soil surface and snow evaporation, on the contrary, increased five times and twice, respectively, and water yield of the catchment totaled over twice that of pre-cutting in the first year following the treatment.

Our approach to estimating clearcutting hydrological effects at large river basins considered both the total and most recent cutover areas of a catchment. We analyzed the temporal trend of the correlations of the total area under clearcutting with water yield for the Mana, Shadat and Kebezh Rivers found in Sayan Mountains at south of Krasnoyarsk Region.

For the Mana River, a positive trend of runoff was recorded for the entire observation period, beginning in the mid-thirties of the 20th century, but it was most pronounced from the mid-sixties to the early nineties. The average decade runoff for 1986-1995 increased by 40 mm compared with the average runoff in 1967-1976 [36]. Based on the analysis of forest inventory data and space images [37] it was determined that in the central part of basin of Mana at the territory of the Maganskiy lesghoz (forest enterprise) by 1950 up to 30 thousand hectares of forests were cut down. By 1977, the area of felling was 25 thousand hectares and the secondary forests occupied 15 thousand ha. In 1989, the area of felling was markedly reduced (up to 10 thousand hectares), but in total with the secondary forests this area reached 40 thousand hectares. This indicates that for almost 40 years the formation of runoff in this part of the basin of Mana was associated with logging.

Similar trends in runoff dynamics appear on Shadat River, but a more significant increase in the coefficients of linear trends occurs from the 60s of the last century to the mid-1990s. For thirty years, the runoff on the Shadat River has increased by almost 100 mm. The analysis of the forest inventory data at the river basins of Western Sayan show that in this region the forests were cut down at great areas since the mid-1950s until the end of the 60s of the 20th century [26].

We studied runoff differences due to changes in FCP from clearcutting at the catchments of the Angara River tributaries and found that runoff responded not only to the total area subjected to clearcutting over certain periods of time, but also to the area of the most recent cuts. Especially fresh felling affects seasonal
redistribution of river flow. It is noteworthy that catchment size matters greatly. For catchments of 4000-5000 km², with fresh cuts accounting for about 1% of the total catchment area, springtime runoff increased by 5-7% after cutting, while post-clearcutting spring runoff from catchments less than 300 km² contributed more than 90% to annual water yield, which contributes to decreasing summer runoff lows. Such a situation occur in small river basins; small rivers - tributaries of the Irkineyeva, Karabula, Mura and Chadobets grew shallow because of the 1960s forest harvesting.

As snow water is an important source of runoff formation of most Siberian rivers, the spring flood behavior alters with changing snow amount at a catchment after clearcutting. Numerous studies conducted in different climatic conditions revealed a significant impact of forest ecosystems on snow moisture balance and influence of logging on its transformation [38-42]. Our studies of snow cover formation on open sites and in adjacent forest stands were carried out at the basin of Lake Baikal [43].

\[ K = 1.01 - 0.04lnV \times lnT - 0.02lnV \times lnS \] (1)

\[ R^2 = 0.81 \sigma = 13.4 \]

where \( K \) is coefficient of water equivalent (%), \( V \) is wind velocity (m/s), and \( S \) is cutover area (ha).

Equation shows the correlation of snow accumulation index with size of open sites, wind speed and winter air temperature, \( R^2 \) is multiple determination coefficient; \( \sigma \) is standard error, (%).

It was found that influence of the size of cutover area on snow amount (water equivalent) varies both among geographic conditions types and among territory ranks. For elementary catchments of 1-5 km² found in mountain taiga forest and receiving 300—500 mm of solid precipitation annually, water equivalent may additionally increase, because of forest cover structural specificity, by 80-100 mm, while in the forest-steppe zone with lower winter precipitation, the increase is only 20-30 mm. Moreover, the size of cutover area may have the opposite effect on water equivalent due to climatic conditions. On large open sites found in an extreme continental climate, winds are stronger and induce low-level snow drifting, increase snow evaporation, and reduce water equivalent [49].

One of the most pressing problems occurring due to clearcutting is soil erosion and, hence, channel water deterioration. We analyzed the sediment load for a number of catchments in Angara Area and identified a close connection between sediment discharge and intensive clearcutting. The 1997 clearcutting in the Chadobets River basin that covered as little as 1% of the catchment area increased sediment discharge twice to triple in the first two post-cutting years. The relatively high water yield in 1982-1983 combined with even very little (0.4% of the total catchment area) clearcutting lead to a 2-fold increase in sediment discharge. The unit sediment discharge (tons per square km per year) from the Karabula River catchment increased 5-6 times following clearcutting that was only 2-3% of the total catchment area.

Our analysis of sediment load dynamics in catchments of northern Angara region revealed its strong correlation with river flow, area of burned and logging sites. Our regressions derived for Irkineyeva (2) and Chadobets (3) catchments describe sediment load dependence on the latter factors [28].

\[ LnM = -2.87 + 0.41ln(YSw) + 0.21ln(YSg) \] (2)

\[ R^2 = 0.47 \sigma = 1.2 F = 18.4 \]

where \( M \) is sediment load, t/sq.km; \( Y \) is runoff, mm; \( Sw \) is total area of logging sites up to 15 years old; \( Sg \) is total area of < 5 year-old burned sites, \( R^2 \) is multiple determination coefficient; \( \sigma \) is standard error, t/sq.km; and \( F \) is Fisher criterion.

\[ LnM = -0.937 + 3.188lnSw + 0.098lnSg + 0.008Y \] (3)

\[ R^2 = 0.43 \sigma = 2.1 F = 16.2 \]

where \( Sw \) is previous year logging area, %; \( Sg \) is previous year area burned, %, the remaining symbols are the same as in (2).

Two forest logging options were analyzed: (1) a clear cut, when 20% of forest was left on a watershed and (2) two-stage gradual felling on another watershed. In the latter case, the felling was conducted twice during 40 years, with wood extraction being 40% of the watershed forest area at each felling stage, totaling, as a result, the same forest harvesting percentage (80%) as in the clear cut. Snow accumulation analysis indicated forest logging to be generally favorable for snow accumulation on leeward slopes. However, an average snow pack increment was calculated to be 60-70 mm in the case of gradual felling vs. 30 mm for the clear cut at watershed. The results of study of snow cover formation on open sites conducted in different landscapes found in Khamar-Daban mountain range were used to develop regional patterns describing open-site snow pack dependence on site size and the snow amount precipitated at control site [41, 43].

Using our own results and published data [44-48] authors identified general snow accumulation trends for open sites and developed Equation (1).
being more pronounced than that of area burned. Fresh logging sites were found to have the major impact on sediment discharge. Calculation shows fresh logging sites, accounting for up to 5% of the total catchment area, increase sediment load 9-fold (from 2 to 18-20 t/sq.km/yr.). However, no drastic soil erosion increase was observed where logging was timed properly. About 20% of a catchment forest area removal during 20 year lead to a sediment load increase twice to 2.5 times (i.e., sediment load module has increased from 2 to 4.5 t/sq.km/yr.) as compared to its multiyear average.

\[
\ln M = -9.3 + 0.95\ln X - 0.064\ln L + \frac{0.069\ln X \ln m}{\ln L} + 5.03K + 1.49ln I + 0.0162\ln \left(\frac{X-W}{in}\right) * i - 0.00026\ln \left(\frac{X-W}{in}\right) * i^2
\]

\[R^2 = 0.86 \sigma = 1.04 F = 221\]

where \(M\) is sediment load, t/sq.km; \(N\) is time since human disturbance (logging or fire), years; \(X\) is precipitation, mm; \(I\) is precipitation intensity, mm/min; \(m\) is soil mineralization rate, %; \(L\) is slope length, m; \(W\) is forest litter moisture capacity, mm; \(In\) is soil water permeability, mm/min; \(i\) is slope, degrees; \(K\) is indicator reflecting study methodology characteristics (it was assumed to equal 1 when using sprinkling small plots with water and 2 for soil erosion at catchment observations); \(R^2\) is multiple determination coefficient; \(\sigma\) is standard error, t/sq.km; and \(F\) is Fisher criterion.

All these coefficients appeared to be significant at a confidence probability level of 95%.

**Time and water yield**

The question of how the time factor affects the restoration of the hydrological regime in clear-cut areas is very difficult. First, the reconstruction of the moisture circulation in the catchment where the forest was cut down is associated with the restoration of the forest ecosystem itself. As we know, restoration of the primary forest after felling can take a very long period.

Based on our multiyear observations carried out in different parts of Siberia, authors developed a generalized mathematical model [28]. Our study used a methodology that allowed us to use a single model to describe soil erosion rate, which was estimated using different methods for the watersheds ranging in size from a micro slope to an elementary watershed. The model includes combinations of the factors control soil erosion, while the size of mineralized area accounts for the total sediment discharge.

In some regions of Siberia, felling areas are not overgrown with forests at all.

The data we collected in multiyear hydrology studies conducted in the dark-conifer (dark-needled) forests of Sayan Mountains enabled analysis of water balance structure both for elementary and for large catchments. As is clear from Table 1, evapotranspiration decreases drastically due to decreasing transpiration and evaporation of precipitation intersected by vegetation in the first year following cutting. With gradually increasing vegetation biomass, evapotranspiration in a cutover site grows and by 6 years after cutting equal to 80% of evaporation in surrounding forest.

Transpiration is the prevailing evapotranspiration component (50-70%) at fresh clearcuttings, and after the closure of the crowns of the tree layer, the proportion of transpiration decreases, whereas evaporation of intercepted precipitation increases.

**Table 1.**

<table>
<thead>
<tr>
<th>Objects</th>
<th>Annual precipitation, mm</th>
<th>Evapotranspiration structure on an experimental felled area in the monitoring catchment and control site *</th>
<th>Physical Evaporatio from the Snow</th>
<th>1st year after felling</th>
<th>2nd year after felling</th>
<th>3rd year after felling</th>
<th>4th year after felling</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Evaporation, mm</td>
<td>Total Evaporation</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Transpiration</td>
<td>Precipitation Intercepted by Tree Crowns</td>
<td>Physical Evaporation</td>
<td>Physical Evaporation</td>
<td></td>
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<tr>
<td></td>
<td></td>
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<td>from the Soil</td>
<td>from the Snow</td>
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<tr>
<td>Experimenta 1 cutting site</td>
<td>731</td>
<td>187</td>
<td>60</td>
<td>77</td>
<td>46</td>
<td>370</td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td></td>
<td>303</td>
<td>280</td>
<td>15</td>
<td>18</td>
<td>616</td>
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<tr>
<td></td>
<td>951</td>
<td>229</td>
<td>91</td>
<td>70</td>
<td>42</td>
<td>432</td>
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<tr>
<td>Forest</td>
<td></td>
<td>379</td>
<td>323</td>
<td>16</td>
<td>19</td>
<td>737</td>
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<td></td>
<td>965</td>
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</tr>
<tr>
<td>Forest</td>
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<td>380</td>
<td>305</td>
<td>15</td>
<td>20</td>
<td>720</td>
<td></td>
</tr>
</tbody>
</table>
Apart from the above experimental site, we looked at study sites established by other scientists where R. Babintseva [50], P. Ermolenko [51] and V. Kuzmichev with coauthors [52] conducted forest inventory and geobotanical studies. Using our data at experimental cutting site [22-23], data on vegetation biomass in post-cutting vegetation communities [50-51, 53], and correlations between intercepted precipitation and vegetation biomass [35], we calculated evapotranspiration components and, hence, water yield obtained for secondary stands].

When analyzing the water yield dynamics with respect to the vegetation succession, we found that the water yield decreased remarkably by the cut age of eight and then a certain increase occurred, because of the transition of the grass stage to young deciduous stand stage. The diagram in Fig. 2 shows water yield from cuts occupied by secondary deciduous stands tends to decrease with stand aging, obviously due increasing transpiration. As for fir stands, water yield is much controlled by evaporation of crown-intercepted precipitation, which interception depends, in turn, on differences of fir stands in age. Therefore, dynamics of runoff at the logging sites is connected with transformation of grass community to young growth. For secondary forests, it is related with change of tree age and transformation of the forest structure.

**Figure 2. Changes runoff coefficient (runoff/annual precipitation ratio) at different forest formation stages.**

Time is a necessary factor for post-cutting recovery of catchment water balance and, hence, hydrological regime. Large-scale clearcutting in Angara Area in the last century resulted in forest hydrological functions not yet recovering to pre-cutting. We studied hydrologic regime changes for five tributaries of the Angara River, the basins of which were under extensive clearcutting in the 20th century. Table 2 summarizes the 1966-1988 changes in the forest cover spatial structure for the catchments of interest. Most of the catchment exhibited increases in forestland percentage ranging 4% to 8%. However, fresh cutover sites dropped in area and young stand proportions increased correspondingly.
Analysis of the hydrological regime in the catchments in the Angara basin, eliminating the dynamics of climatic indicators, made it possible to identify temporal fluctuations in runoff irrespective changes in precipitation [37]. For three rivers of interest (Karabula, Irkineyeva and Mura), we determined a period of about twenty years, starting in early 1960s, during which water yield decreased, because of, we presume, increasing freshly cutover sites, where wind grew more active and snow evaporation was increased. Water yield dropped by about 0.5-1.0 mm/year to give the total decrease over the first two decades from the beginning of large-scale forest cutting in Angara Area of ~10-20 mm.

For all the rivers studied, except the Karabula River, we specified points in time, when water yields from their catchments started to increase. The points were 1975 for the Taseyeva River, 1984 for the Irkineyeva and Mura Rivers, and 1986 for the Chadobets River. These points in time appeared to coincide rather closely with when secondary young stands began to increase in area on sites cut over in 1950s-1960s. This coincidence was most probably related with decreasing snow interception by tree crowns and increasing young stand snow accumulating capability. This assumption was confirmed by a syneffect that indicated increasing contribution of solid precipitation to water yield in the course of time. We estimated the increase in water yield with increasing snow accumulating capability of young secondary stands to range 1.5 mm/yr. to 3.0 mm/yr. Mean annual water yield of the catchments studied thus increased by 20-40 mm over the first 20 years after young deciduous stands started on cutover sites, as compared to pre-cutting.

To dispose of hydrological consequences of disturbed forest cover at watersheds, the time factor is very important in restoring the erosion stability of the ecosystem. The recovery duration of erosion-preventive functions of forest ecosystems depends both on geographical and climate conditions and on level of human disturbances, such as forest floor disturbance and soil mineralization scale. For Lake Baikal and in Sayan Mountains, it was established that, where clearcutting did not disturb soil heavily so grasses and trees spread successfully, eight to ten years post-treatment is enough for soil infiltration capacity to recover and for erosion decrease remarkably, while recovery of soil water-cleaning capacity takes 15-20 years after forest canopy had closed. According to our data collected in catchments found on 5° slopes in Yenisei Mountain Ridge, five years following clearcutting is sufficient for sediment (hard substances) washout to cease, where initial cut-caused soil mineralization was up to 2%, and as long as 17-20 years with 60% post-cutting mineralization. On slopes of 10°, the process lasts 15-25 years depending on the initial mineralization level.

As mentioned above, the period of restoration of the soil-protective functions of forest vegetation in catchments after felling depends on a large number of factors. Based on equation 4, the authors obtained the dependence of erosion on time since last human disturbance and immediate post-disturbance soil mineralization rate (fig. 3). It allows calculating the duration of restoration a stability of forest ecosystems capable of performing water protection functions.

The results of our study of erosion process at logging sites and generalized mathematical model (equation 4) were used to develop a GIS-based soil erosion model for Khamar-Daban mountain forests. We combined our precipitation distribution and erosion data collected in catchments found on 5° slopes in Yenisei Mountain Ridge, five years following clearcutting did not disturb soil heavily so grasses and trees spread successfully, eight to ten years post-treatment is enough for soil infiltration capacity to recover and for erosion decrease remarkably, while recovery of soil water-cleaning capacity takes 15-20 years after forest canopy had closed. According to our data collected in catchments found on 5° slopes in Yenisei Mountain Ridge, five years following clearcutting is sufficient for sediment (hard substances) washout to cease, where initial cut-caused soil mineralization was up to 2%, and as long as 17-20 years with 60% post-cutting mineralization. On slopes of 10°, the process lasts 15-25 years depending on the initial mineralization level.

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<table>
<thead>
<tr>
<th>River</th>
<th>Catchment Area (CA), km²</th>
<th>Clearcutting, % of CA</th>
<th>Young Stands, % of CA</th>
<th>Catchment Forestland, %</th>
<th>Clearcutting, % of CA</th>
<th>Young Stands, % of CA</th>
<th>Catchment Forestland, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taseyeva</td>
<td>127000</td>
<td>8.7</td>
<td>14.8</td>
<td>72</td>
<td>3.4</td>
<td>10.3</td>
<td>76</td>
</tr>
<tr>
<td>Chadobets</td>
<td>13300</td>
<td>21.3</td>
<td>8.9</td>
<td>76</td>
<td>4.7</td>
<td>22.1</td>
<td>84</td>
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<tr>
<td>Irkineeva</td>
<td>8950</td>
<td>18.6</td>
<td>8.5</td>
<td>80</td>
<td>8.3</td>
<td>19.4</td>
<td>80</td>
</tr>
<tr>
<td>Mura</td>
<td>9320</td>
<td>15.1</td>
<td>9.2</td>
<td>83</td>
<td>8.4</td>
<td>12.6</td>
<td>89</td>
</tr>
<tr>
<td>Karabula</td>
<td>4190</td>
<td>15.7</td>
<td>7.9</td>
<td>79</td>
<td>7.9</td>
<td>16.3</td>
<td>85</td>
</tr>
</tbody>
</table>

Table 2.

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Discussion

When estimating forest, contribution to water behavior in a catchment, forest hydrologists consider the role of space in river flow formation by using forest cover percentage (FCP) [9, 54-55]. Extensive clearcutting changes FCP considerably, therefore, it would be logical to express the spatial aspect of clearcutting influence on water yield as a clear-cut area/total catchment area ratio.

Our studies have shown how clear-cutting affects the hydrological regime of the territory, depending on the area of felling and the area of the catchments itself. In small catchments, we observe a remarkable influence on annual runoff, especially on spring flood and high water after heavy rainfall. This is confirmed by the literature data.

O. Krestovsky [2] concluded that clear cutting effect on minimum runoff at small and middle rivers of Russian plain more contrast because the most volume of water consumption by forest occurs during warm period. In the clear cuttings having regeneration minimum runoff totals 0.35 of mean value. M. Muratov [56] analyzed runoff of South Ural rivers (Big and Small Inzer) and concluded that logging of 40% of watershed area causes significant decrease of summer minimum discharge (June-August) ranging from 21-22% to 13-14%. A. Pobedinsky [57] emphasizes that clear cutting of entire area of small river catchment causes the drying up of streams, it is observed in the Middle and South Ural. Clear cuttings of mountain spruce forests [58] affect significantly on stream-flow regime particularly during spring-summer period. Breach of stream-flow regime is expressed as discharge irregularity during year. In spring, it occurs as short, but strong flood. However, a number of studies [59-61] showed that logging-caused conversion of forest areas to grasslands only leads to local flood increases and is not among the key controls of large-scale high water.

We believe that this statement is justified for large watersheds. Large catchments are complex ecosystems, for which clearcutting effects on water is not an arithmetic mean of areas cut in their elementary catchments. The larger the catchment, the more even the water yield distribution through the year; both spring flood and high water grow more persistent, but relatively less intensive [16, 62]. According to statements by N. Voronkov [63] and V. Vodogretsky [64] catchment disturbances of different types are more manifested for small rivers.

It is noteworthy that recovery of water balance, i.e. of quantitative indicators, including water yield, does not always coincide with that of channel water quality. Water quality recovers with decreasing soil erosion on cutover sites. Post-cutting vegetation recovery and slowdown of soil washout take time, and the time varies widely [13, 65].

Soil erosion and water deterioration was determined to be controlled more by the size of cutting-caused mineralized area, than cut size alone. Literature data on sediment discharge and water turbidity, at soil surface mineralization scale being equal [13-14, 19-20, and 29] vary by orders of magnitude due to region-specific climate and to the characteristics of the site under the treatment.

Numerous experiments on large-scale clearcutting effects on hydrology conducted in forest regions all over the planet have developed very much information on connection of forest cover with runoff and enabled determination of the percentage of forest cover needed to maintain natural hydrologic regimes. In the central taiga forest zone of north European Russia, forestland area should not be less than 45% for catchments of <100 ha [66]. As for Ural Mountains, reducing catchment forest area from 100% to 60% has, in fact, very little effect on annual water yield redistribution, provided that cut-over sites are evenly distributed over the catchment under treatment, with the lowest acceptable (FCP) being 50-60% [15].

Studies done by A. Lebedev and L. Uskova [13] showed that for Baikal water to be permanently clear, fresh (unrecovered) cuts in mountain forests should not exceed 0.1-0.03% of the total forest cover area. Moreover, since cutover sites take long to recover (5-8 years), annual felling should range 0.02% to 0.04% of the total catchment area. The upper forestland (FCP) threshold was estimated to be 40-50% for Sakhalin Island [67], 75-90% for the Caucasus [21], and 60-70% for the middle mountains of Sikhote-Alin Highland.
According to A. Pobedinsky [57], forest should be cut on not more than half of the area of highly forested small watersheds and, on catchments with FCP less than 40-50%, only selective and sanitary wood felling is acceptable.

Using literature [8, 18, 69-70] and our data [28, 71], we calculated FCP lower limits for catchments found in mountain taiga and in the southern taiga zone (Table 3). In mountain taiga, annual clearcutting should not exceed 2% of the total catchment area on small (up to 5 km²) catchments, with forestland being maintained at 70%. For catchments from 6 km² to 100 km² and over 100 km², the values are 2% and 1% for annual felling and FCP - 80% and 85% for river basins, respectively. In the southern taiga zone, FCP should be maintained at 70-75%, with annual allowable cut being 6-9% of the total catchment area.

<table>
<thead>
<tr>
<th>Forest Zone</th>
<th>Cutting Type</th>
<th>Catchment size, km²</th>
</tr>
</thead>
</table>
|               |                                                  | up to 5 6-100 100+
| Mountain taiga| Large-scale (up to 50 ha) clearcutting            | 70/3 80/2 85/1      |
|               | Cutover sites (up to 10 ha each) scattered over a | 60/7 70/5 75/2      |
|               | catchment                                       |                     |
| Southern taiga| Large-scale (up to 50 ha) clearcutting            | - 70/9 75/6         |
|               | Cutover sites (up to 10 ha each) distributed over | 60/12 65/9          |
|               | a catchment                                     |                     |

The influence of the spatial characteristics of clearcuttings on runoff is directly related to another spatial characteristic - the forest cover of catchments. The question of the relationship between the forest cover of the basin and the river runoff is one of the most complex and heatedly discussed issues of forest hydrology [49]. The problem is rooted in the necessity to consider many characteristics, such as catchment location, the size of a study area, the methodology used, and the size of the catchment of interest. A perfectly consistent assessment of FCP effect on water yield could only be possible if the number of catchments under study were statistically significant and they were perfectly compatible as to size and landscape features, which would, in fact, be an unfeasible task due to the complexity of flow formation.

The time factor in hydrology is manifested through climatic indicators: precipitation, air temperature and other characteristics. In forest hydrology, they are supplemented by successive changes in the vegetation cover, which are most pronounced in the catchments after clearcutting. Vegetation structure changes permanently as catchment cutover sites recover, and post-clearcutting hydrological condition depends, apart from climatic factors, on vegetation succession trajectories. High successional variability induces a wide variety of probable redistributions of evapotranspiration and river flow in response to clearcutting, even under rather homogeneous geographic conditions.

As our studies have shown on the experimental sites in the Sayan Mountains, reforestation can follow different trajectories. Secondary forests begin to perform their runoff-forming functions, reaching the age of 50 years. In northern Angara region, water yield showed a decrease in first twenty years following clearcutting and increased to exceed the water yield for undisturbed (control) conifer plots over the next two decades, when deciduous and mixed conifer/deciduous stands began to extend in clear cuts. Our field observations and modeling results showed that the cessation of erosion and restoration of soil protective functions of forest ecosystems is delayed for a longer period.

Forest hydrologists are of different opinions regarding the time needed for rivers with clearcutting-disturbed catchments to recover their hydrologic regimes. Some authors [18, 69] believe that the period needed for complete recovery of river hydrologic regime, water yield and water quality to pre-disturbance ranges from 10 years to 50 years. Based on the data obtained by Krestovsky [1-2] for taiga forests of European Russia, the recovery of the water balance characteristic of old forests may take up to 100 years. This wide time variability obviously is due to regeneration of vegetation and other natural components varying in succession trajectory among landscapes and climates.

Our recent studies [26, 72] show that clearcutting-caused forestland percentage changes may lead, depending on climatic conditions, to either increasing, or decreasing water yield. A comparative analysis of water yields and forestland percentage changes of catchment found in three landscape zones (forest-tundra, northern taiga, and central taiga) of northcentral Siberia allowed us to reveal the connection of water yield with FCP according geographical zonality. At higher latitudes, water yield increases with increasing FCP and, down south, decreases. Changes in forest cover percentage influence water yield more substantially in forest-tundra as compared to northern and central taiga. It is logical to assume that the effect of changing forestland percentage on water yield varies among landscape zones.

Conclusions

Our study has shown the spatial factor, i.e. large-scale clearcutting, has a negative influence on hydrologic regimes of small and middle-length rivers. As for elementary catchments, it is critical to estimate surface runoff from and soil erosion in them, because these are the major factors accounting for worsening of water quality of small water bodies. In relatively big
river basins, clearcutting results in water deterioration and distortion of hydrologic regimes and water balance structure. As influences on hydrologic regime increase in number with increasing catchment rank, the effects of forest uses of the same scale (e.g., the same percentage of wood extraction) vary qualitatively and quantitatively among catchments. For an elementary catchment, it is not very problematic to predict post-cutting vegetation succession and, hence, hydrologic regime behavior, whereas diverse topography and vegetation of a considerably large catchment require to carefully analyze both of the parameters.

Our research has shown the vegetation cover structure changes continuously on logged sites during post-logging forest regeneration and future post-cutting hydrologic regime scenarios are determined both by further climatic changes and by vegetation succession trajectories. Therefore, water redistribution between evapotranspiration and water yield in response to forest cover disturbance is and will be highly variable, even under homogeneous geographic conditions. Post-cutting forest rate of regeneration controls water losses through transpiration and evaporation of precipitation intercepted by tree crowns, as well as water yield and soil erosion rate. Our study allow to estimate periods of time needed by forest to restore its erosion prevention function taking into account the influence of orography, precipitation and the initial area of mineralization after logging.

In other words, the time for the restoration of water balance and other water protection functions will differ at both the zonal, regional and local levels under a range of forest growing conditions.

The above discussion of the effects of time and space on water circulation as manifested in a range of catchments subject to clearcutting allowed us to conclude that, under homogeneous landscape and climatic conditions, hydrologic regime recovery is a function of a combined influence these two factors. Factor of space in situation “consequences of forest harvesting” influence on quality and quantity of water in rivers, but factor of time in this situation “works” to stabilization hydrological regime owing to regeneration of vegetation.

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Conflicts of Interest: The authors declare no conflict of interest

References

Oleinyk V.S. Water protection and water regulation role of mountain forests of the Carpathians.
In: The hydrological role of forest ecosystems. Snytko V.A (Ed); Novosibirsk; Publishing House Nauka, Siberian Branch; 1989. (In Russ).
Gorbatenko V.M., Koziiova L.N., Onuchin A.A. Transformation of water balance elements by dark- and light coniferous forest plant formations at the Khamar-Daban ridge under different afforestation degree of catchment basins. In Ecological forest impact on...


Forest inventory data. http://lesproektgrup.ru


Bochkov A.P. The influence of forests and agroforestry measures on the water yield of rivers in the forest-steppe zone of the European part of the USSR. Leningrad: Gidrometeoizdat; 1954. (In Russ).


