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Hydrological Consequences of Timber Harvesting in Landscape Zones of Siberia

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Abstract: Despite a large number of publications covering various aspects of the influence of climatic factors on runoff, this direction in hydrological research acquires a new meaning in connection with global climate change and the increase in anthropogenic press on river systems. The authors of this work focused on the impact of anthropogenic factors on river runoff. Many rivers of Siberian taiga drain areas have experienced a dramatic land-cover change, with a decrease in overall forest area and a relative increase in deciduous trees. Land cover change in forest catchments impact water balance and accordingly, river flow. The study areas, the West Sayan and Northern Angara regions located in Central Siberia, are now a mosaic of forest regeneration sites including both post-human and post-fire regeneration patterns. Data of our own hydrological experiments conducted on clear cuts of different ages and reference materials for regular hydrological observations were analyzed. Dynamics of river flow under influence of timber harvesting were studied for 11 river basins in different landscape zones of Siberia. The studies showed that, in Siberia, forest cover changes lead to either reduction of, or increase in water yield depending on forest structure and climate. Dynamics of river flow after forest logging differ for continental and humid climates. Where precipitation is excessive, water yield increases twice that of control plots during the first several post-cutting years, due to reduction of transpiring phytomass. It takes 30–40 years and sometimes even over 50 years, depending on forest succession trajectories, for water yield to recover to the pre-cutting level. In an extremely continental climate, extensive forest cutting results in decreasing water yield during the first post-clearcutting years, because wind activity increases and enhances snow evaporation on vast clear cuts. Water yield exhibited an average annual decrease of 0.5–1.0 mm during the first two decades after cutting, i.e., until when clear cuts began to regenerate. With further development of forest vegetation, water yield increased by 1.5–3 mm annually. Obtained results show that at the regional level in conditions of anthropogenic press on the forests at the catchments of medium and small rivers, the climatic trends are offset by the felling and subsequent reforestation dynamics at clear cuts.

Keywords: Siberia; West Sayan; Angara River; timber harvesting; clear-cut; runoff; water balance

1. Introduction

One of the urgent problems of regional nature management in Siberia is that intensive timber harvesting inevitably reduces the stabilizing influence of the forest on the biosphere and, hence, has a negative impact on the natural environment, mainly on hydrological regimes. Clear cuts result in a decrease of forest cover in virgin stands, and an increase of young conifers and secondary small leaf tree species. Due to intensive forest harvesting, the vegetation of central Siberia has experienced considerable transformations over the past several decades. Human-caused changes in the forest cover structure are reflected in the ratio between evapotranspiration and water yield, the two major water balance components.

We attempted to analyze influences of clearcutting on water yield dynamics in a number of landscape zones of central Siberia.

Forestry experts and hydrologists have not agreed as to what influence forests have on the water yield. Some foreign [1–4] and Russian scientists [5–7] state that, as forests lose more water through evaporation and transpiration compared to other cover types, river flow is reduced. According to the opposite viewpoint adhered to among other researchers, such as Rakhmanov [8–10], Lebedev [11], Voronkov [12], and Hamilton [13], water yield increases with increasing forest area. Moreover, the ratio of evaporation-caused water loss between forested and open sites varies considerably from year to year in the same area depending on season-specific precipitation patterns and heat balance [1,14–16].

These disagreements regarding the influence of forest on river flow are rooted in methodological differences, and in large geographic differences in study areas (amount and distribution of seasonal precipitation, soil texture and genetic structure, features of flow formation and in forest composition and structure).

Of all economical activities practiced in river basins, forest clearcutting and post-cutting regeneration have the greatest influence on water balance and runoff [17–22]. Hydrological regime studies that covered 100 paired river basins [19] showed that clearcutting increased water yield considerably. Maximum water yield increase, from 110 to 825 mm, resulted from clear cuts of tropical rainforests [23].

The point of the highest controversy when discussing the hydrological role of forests is the influence of clearcutting on flooding. The 1988 catastrophic floods in Thailand and Bangladesh were attributed to clearcutting on slopes of the Himalayas [23]. Hewlett [24], Hofer, and Messerli [25] found no relationship between forest clearcutting and flood scale. Other authors [26–28] believe that clear cuttings or wild fires are a factor accounting for the occurrence of local flood peaks, but they do not contribute considerably to high-water situations on a large scale. The Center for International Forestry Research [29] analyzed multiyear study data and concluded that forests cannot prevent catastrophic floods that occur due to meteorological events.

2. Materials and Methods

We studied forest ecosystems and river catchments found in the West Sayan and Northern Angara landscape areas (Figure 1), located in Central Siberia. These two regions differ in orography, in climate, soil, and vegetation.

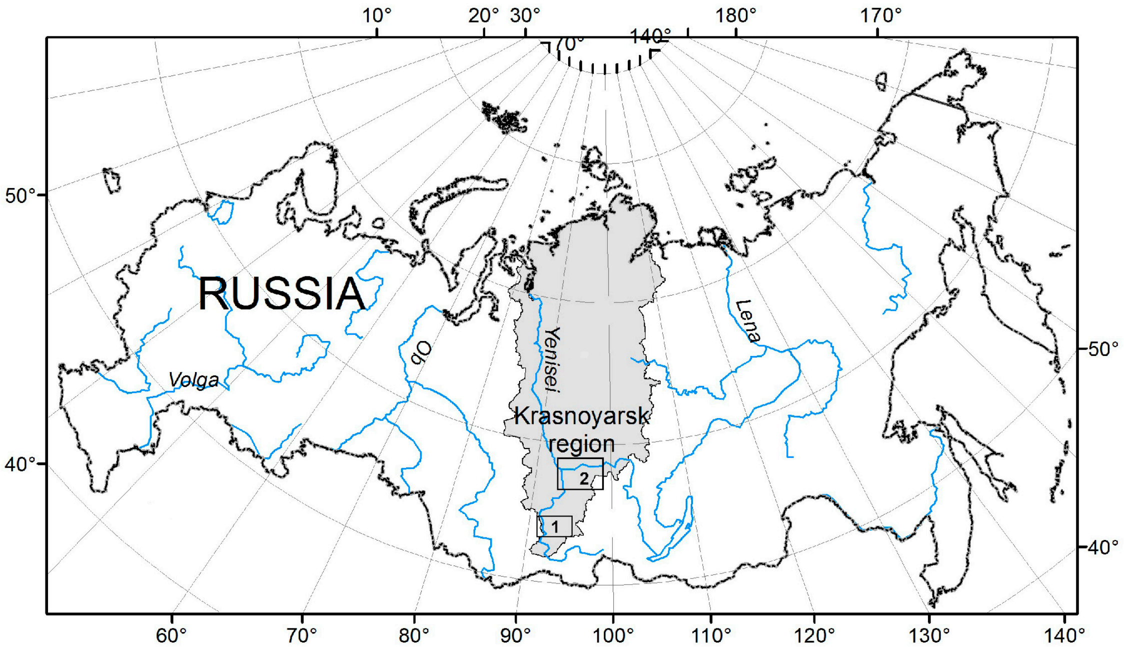

Figure 1. Study areas. 1—West Sayan area; 2—Northern Angara region.

West Sayan **A** mountain ridge [up to 2500 m above sea level (a.s.l.)] stretches like a wide strip from the Abakan River head eastward to the headwaters of the Kazyr, Uda, and Kizhi-Khem Rivers where it meets the East Sayan Ridge. In the north, West Sayan borders on the vast and hilly Minusinsk Hollow forest-steppe, and in the south, on Central Tuvan Hollow, consisting of dry steppe. This highland is in an area of continental climate that is characterized by long winters, cool summers, the predominance of summer precipitation, and high daily and annual amplitudes of climatic components. Near the Olenya Rechka Weather Station, the annual amplitude of air temperatures is over 30 °C (July air temperature +12.3 °C, January −18.4 °C).

The slopes of Western Sayan receive different amounts of precipitation and, hence, fall into different geographical zones and provinces. The landscape differentiation is caused by a variety of combinations of latitudinal vegetation zones, altitudinal vegetation belts (AVB), exposure of slopes regarding the prevailing air masses, and orographically isolated areas. The northern macro slope of West Sayan has all the altitudinal vegetation belts of the mountains of southern Siberia, from forest-steppe to highland tundra.

Right above the chern taiga AVB found between 300 and 700 m a.s.l. there begins mountain taiga forest AVB that is gradually replaced by mixed Siberian pine/fir open stands and alpine meadows at 1200–1300 m a.s.l. At elevations higher than 1400–1500 m a.s.l., open woodlands are replaced by tundra. AVBs of the dry south-facing slopes are covered by Central Asian rather than Siberian vegetation. Dry steppe AVB is replaced by larch AVB that dominates from 700–1000 m a.s.l. to 1400–2000 m a.s.l. Light coniferous forests are frequently replaced by tundra-meadow-steppe landscapes. Vegetation conversions are induced by both elevation and slope exposure. Above the tree line, low-grass alpine meadows occur, which are replaced by small-shrub-mass-lichen tundra at even higher elevations [30].

Northern Angara region, a part of the Angara River catchment, is located on Central Siberian Plateau. This is a heavily dissected area (310 m a.s.l. on average) without pronounced dividing elevations. Based on Boguchany Weather Station data, the mean annual air temperature is −4.0 °C and the mean annual precipitation is about 350 mm. Snow cover usually forms in late October. The earliest initial snow cover forms in early October and the latest is around 10 November. In the southeastern part of this area, the left bank of the Angara River, snow cover depth is 45–46 cm, whereas snow is as deep as 75–76 cm on the right bank of the river. Winters are long and soils become deeply frozen due to low air temperatures. This area falls within the Angara southern taiga region of mixed larch-Scots pine forests. Dark-needled conifers (spruce and fir) are limited to river valleys and bottoms of ravines. Deciduous stands are mostly found in old burns. Northern Angara region is, in general, an area of Scots pine with larch as a minor component. On some burned or logged sites having peat-bogged soil, birch stands occur [31].

We analyzed forest cover effects on water yield based on the results of our studies, other authors' data, and reference books. We divided the study results into two blocks. The first block included the results of our observations conducted on experimental plots. The results of analysis of our long-term data obtained for river catchments characterized by well-developed stream network and complex topography are represented in the second block.

In first block, we used the results from water balance calculations based on the data of our hydrological experiments conducted on clear cuts of different ages and of our multiyear observation of young stands, developed following clearcutting in various types of Siberian pine stands of West Sayan chern taiga AVB. These plots are permanent study sites of the V.N. Sukachev Institute of Forest established more than 50 years ago. Vegetation transpiration was determined by Equation (1) [32]:

$$T = N \times \left(\sum Ik\ Pk + \sum ik\ mk\right)/F \times 10^6 \tag{1}$$

where N is number of transpiration hours during the calculated period; Ik and ik are the transpiration intensity of the stand, shrub and grass vegetation [mg/(g ha)]; P is the phytomass of needles and leaves of trees (t/ha), m is the phytomass of the grass and shrub layer (t/ha), and F is the area of plot (km^2).

We used our own experimental [33,34] and literature data [35,36] on the transpiration intensity of woody, grass and shrub vegetation obtained for the virgin, secondary stands, and logged sites in the forests of Western Sayan. The number of transpiration hours was determined by the dependence of the frequency of precipitation on its total amount given in the work of Lebedev [32]. The phytomass of leaves and needles was calculated using the taxonomic characteristics of stands and conversion coefficients, which were determined by Equation (2):

$$Kf = aDbHc \tag{2}$$

where D and H are the average diameter and height of the stand or element of the forest, and a, b, and c are parameters for the main forest forming species [37]. Data of the phytomass of the grass-shrub layers and undergrowth were based on field observations. In assessing the interception of precipitation by the forest canopy, we used computational methods based on the dependences of precipitation retention on the taxonomic and biometric characteristics of forest stands [38,39]. To determine the amount of evaporation from the soil and snow we used the results of experimental studies on the natural evaporation on forest and treeless watersheds [32–34]. It was assumed that, for many years, there was no change in moisture in the soils and ground (underground) waters [17,18,32], so the total runoff is calculated as the difference between total moisture and total evaporation of the watershed area.

To identify regional hydrological regime characteristics, we analyzed spatial and temporal dynamics of water yield for 11 river basins found in northern Angara region and in western Sayan Mountains (Figure 2, Table 1). To perform this analysis, we used runoff data available for rivers of West Sayan and Northern Angara region, as well as precipitation and air temperature measurements from the weather stations within the areas of interest [40–45]. The duration of water yield observation was based upon when selecting rivers. For the rivers chosen, the observation period ranged twenty to sixty years and covered a wide variety of hydro-climatic situations.

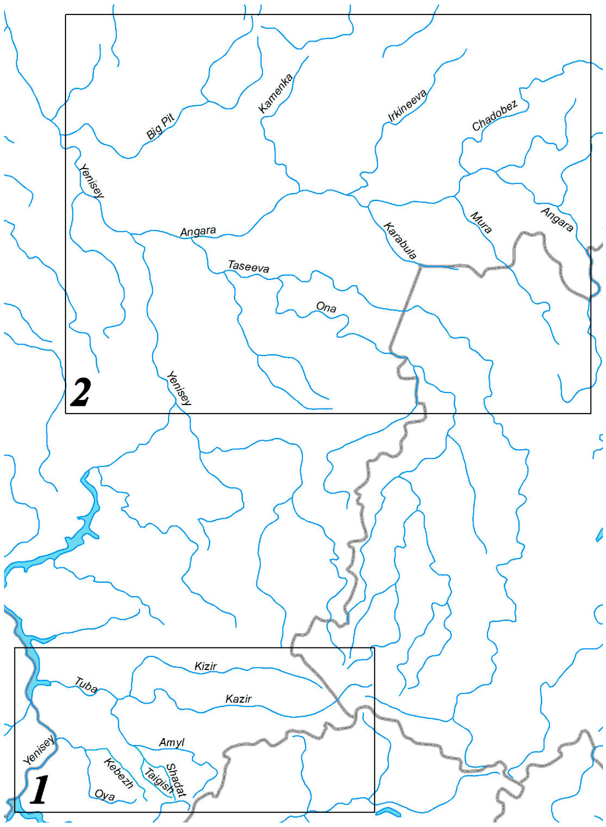

Figure 2. Study river basins: 1—Western Sayan; 2—Northern Angara region.

Numerical methods were used for hydrological calculations [46–48]. The statistical parameters necessary for the analysis were obtained after smoothing the time series by the method of the moving average. To build linear trends and to analyze the intensity of hydro-climatic parameters, we used the methodology by Shelutko [49]. The least-squares method was used to identify and analyze trends. We analyzed the changes of the forest area in the river basins with the help of forest inventory data [50]. For each five-year period, we summed the area of river catchment subject to clearcutting. To correct the data for separate years, we used Landsat images [51,52].

Table 1. Characteristics of the studied rivers.

River	Flows into River	Length (m)	Area of River Basin (km^2)	Average Height of River Basin (m)	Average Long-Term Runoff (mm)	Landscape Zone
West Sayan						
Migna	Oya	58	490	360	708	Forest-steppe
Kebezh	Oya	131	2110	742	2616	mountain taiga-forest steppe
Shadat	Amyl	99	1680	885	7018	Mountain taiga
Oya	Yenisei	254	5300	669	3596	Mountain taiga-forest steppe
Amyl	Tuba	257	9500	959	6623	Mountain taiga
Kazyr	Tuba	388	20,900	965	4783	Mountain taiga
Northern Angara Region						
Karabula	Angara	212	5060	300	686	South taiga
Mura	Angara	330	10,800	320	963	South taiga
Irkineyeva	Angara	563	13,600	369	1089	Meddle taiga
Chadobets	Angara	647	19,700	390	889	Meddle taiga
Taseyeva	Angara	1240	128,000	315	1875	South taiga

3. Results

3.1. Hydrological Effects of Clearcutting Dark-Needled Forests of West Sayan

In mountain taiga forests of the north-facing macroslope of West Sayan, forest harvesting was practiced from 1950s to mid 1970s. The largest-scale cutting was done in fir and Siberian pine stands with feather moss or grass as the ground vegetation in site classes III and IV. As much as over 40% of the total area of the catchments found on the north-facing macroslope is in post-cutting forests [51]. The forests of Chern AVB are the most disturbed among the forest ecosystems at West Sayan (over 65% of all forest is post-cutting stands). In the mountain taiga, the belt of secondary forests occupies 15–17% of the total area.

Multi-year field hydrological observations conducted in mountain forests in West Sayan were based upon assessment of the influence of post-logging forest recovery processes on the dynamics of water balance components. The evapotranspiration results based on field research are presented in the Table 2.

Investigations conducted on a sample logging site [33,34] showed that total moisture evaporation on this site in the first post-logging year did not exceed half of that found in undisturbed forest. In years to follow, the amounts of moisture lost through transpiration and evaporation of intercepted precipitation on the sample site changed depending on the rate of recovery of the vegetation. The difference in total moisture evaporation between sample logging site and undisturbed (control) forest site was insignificant in the eight years following logging. This characteristic tended to decrease in sample sites compared to undisturbed forest in the 12th post-logging year (Table 2).

In post-logging stands, total moisture evaporation amount and structure are determined by forest succession trajectories. While post-logging birch and aspen stands exhibited a clear trend for total moisture evaporation to increase between 25 and 50 years of age, fir stands showed maximum total moisture evaporation 35 years after logging, when the characteristic tended to decrease.

Total moisture evaporation experienced structural changes during post-logging vegetation succession. The ratio of transpiration to intercepted precipitation evaporation differed considerably between post-logging conifers and deciduous young stands. Fifty years following logging, the young birch and aspen stands were found to lose twice the amount of moisture in transpiration compared to the young fir stand. Thus, the evapotranspiration in post-logging stands was controlled by stand species composition, age structure, and transpiring biomass amount.

We analyzed the ratio of runoff to the annual amount of precipitation (Kr) in post-cutting plant communities and discovered that in the first three years after cutting, up to 60% of the amount of precipitation passes into runoff. The percentage decreases to 30% for 8–12 year-old clear cuts, with the remaining 70% being lost through evapotranspiration. Our studies of post-cutting vegetation successions in dark-needled forests of West Sayan revealed three trajectories: 25 years after clearcutting, fir, birch, and aspen stands are formed. Using water balance calculations, we obtained the water yield for different succession trajectories (Table 3).

Table 2. Dynamics evapotranspiration during succession after felling.

Successional Stage after Felling	Years after Felling	Phytomass (t/ha) abs. Dry Matter		Evapotranspiration, mm						% of Total Evaporation in the Forest
		Leaves or Needles	Grass and Shrub	Transpiration		Intercepted Precipitation	Soil Evaporation	Snow Cover	Total	
				Stand, Undergrowth	Grass and Shrub					
Grass and shrub plant community	1	0	3.1	0	206	52	70	40	368	47
	3	0	3.7	0	325	76	50	40	491	71
	8	0	6.0	0	386	90	30	30	536	102
	12	1.1	4.7	50	352	90	20	30	542	94
Fir stand	25	8.4	0.9	172	42	261	15	20	510	82
	30	9.5	0.8	207	36	288	15	20	566	86
	35	10.6	0.8	240	78	270	15	20	623	98
	40	11.3	1.1	269	81	221	15	20	606	100
	50	10.6	1.1	248	79	156	15	20	518	118
Birch stand	25	3.2	0.5	177	56	115	19	30	397	65
	30	3.8	0.6	237	75	164	19	30	525	80
	35	4.2	0.6	295	102	201	19	30	647	94
	40	4.5	1.0	357	122	242	19	30	770	98
	50	4.8	1.2	369	136	256	19	30	810	118
Aspen stand	25	7.5	0.5	212	40	121	19	30	422	72
	30	8.3	0.5	278	55	165	19	30	547	85
	35	7.4	0.6	312	71	198	19	30	630	96
	40	7.5	0.6	412	106	238	19	30	805	103
	50	7.0	0.8	401	104	258	19	30	812	121

Table 3. Water yield for the experimental plots after cutting in mountain taiga of the West Sayan.

Successional Stage after Felling	Years after Logging	Precipitation (mm)	Runoff (mm)	Runoff at Control Plot (mm)	Kr	K_{tr}
Grass and shrub plant community	1	731	458	224	0.62	2.04
	3	965	439	290	0.45	1.51
	8	859	280	239	0.32	1.17
	12	702	236	205	0.33	1.15
Fir stand	25	670	202	150	0.30	1.35
	30	910	287	250	0.32	1.15
	35	845	190	175	0.22	1.09
	40	689	155	159	0.22	0.97
	50	940	236	258	0.25	0.91
Birch stand	25	670	199	150	0.30	1.33
	30	910	302	250	0.33	1.21
	35	845	201	175	0.24	1.15
	40	689	169	159	0.25	1.06
	50	940	266	258	0.28	1.03
Aspen stand	25	670	185	150	0.28	1.23
	30	910	262	250	0.29	1.05
	35	845	203	175	0.24	1.16
	40	689	169	159	0.25	1.06
	50	940	234	258	0.25	0.91

Kr—Runoff coefficient (runoff/precipitation ratio); Ktr—Runoff transformation coefficient (ratio of runoff at experimental plot succession stage to runoff at control plots); The control was the uncut part of the experimental watershed (a mixed forest: Siberian pine (60%, 220 years old)—fir (40%, 110 years old) stand with a minor component of birch and the ground vegetation layer of large grasses and ferns; site class II; standing crop 300 m^3/ha).

To estimate the role of post-cutting forest cover on water yield, we compared experimental clear cuts, post-cutting stands, and untouched dark-needled (control) stands for water yield. The water yield trends obtained for different forest recovery stages are shown in Figure 3.

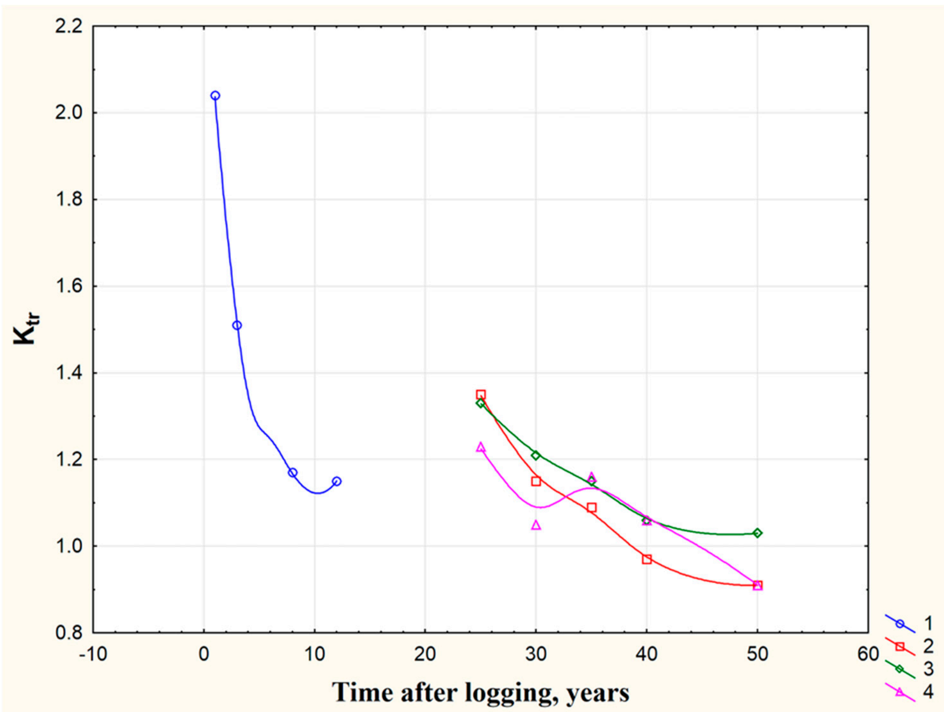

Figure 3. Runoff dynamics for experimental clear cuts and post-cutting stands vs. runoff for untouched dark-needled forest of mountain taiga AVB, West Sayan. (1) a clear cut (grass-small shrub community); (2) fir stand; (3) birch stand; and (4) aspen stand. K_{tr} is runoff transformation coefficient (see Table 3).

Intensive forest recovery and hence increasing evapotranspiration resulted in water yield decreasing gradually, and 12 years after clearcutting, its value was only 15% higher compared to the control. Runoff appeared to be somewhat higher for 25 year-old post-cutting stands compared to 12 year-old clear cuts. This seemed to be due to decreasing snow evaporation in winter, and small water losses through transpiration in the warm period. By the age of 40, water losses through evaporation increased in these stands because of increases in both transpiration and evaporation of snow intercepted by closed stand canopy.

The results of the multiyear hydrological experiment that we conducted in dark-needled forests of West Sayan showed that hydrological regime in general and runoff in particular change on once clear-cut sites depending on post-cutting forest succession trajectory and the current regeneration stage.

For large watersheds, where clear cuts are regular, forest regeneration is represented by a number of post-cutting succession stages, and it is more difficult to identify forest cover effects on water yield than for experimental sites (sample plots) or for elementary catchments. Moreover, the major factor controlling water yield is climate. In an attempt to avoid climatic influences, we chose six rivers, the catchments of which were in relatively similar geographic conditions on the north-facing slope of West Sayan. The characteristics of these catchments are summarized in Table 1. The results of calculating the coefficients of linear trends in precipitation and river flow are shown in Table 4.

Table 4. River flow and precipitation trends.

River Flow Trends				Precipitation Trends		
River—Hydrological Station	Basin Area (km^2)	Mean Runoff (mm)	Coefficient of Linear Trend	Weather Station	Mean Precipitation (mm)	Coefficient of Linear Trend
Amyl—Kachulka	9850	6623	−1.31	Verkhny Amyl	933	−0.522
Kazir—Tajaty	11,900	794.0	−1.91	Verkhny Amyl	933	−0.522
Kebezh—Grigorjevka	10000	554.7	+1.23	Grigorjevka	624	−1.728
Shadat—Ust-Shadat	1680	856.7	+1.65	Olenya Rechka	1235	−3.644
Oya—Ermakovskoe	2540	414.4	−0.67	Ermakovskoe	502	−0.760
Migna—Migna	190	177.5	−1.35	Grigorjevka	624	−1.728

Although climatically similar, the catchments of interest differed in water yield trend (Table 4). Most trends were negative and agreed well with precipitation tending to decrease in the study area (Figure 4). However, two catchments, those of the Kebezh and Shadat Rivers, showed positive water yield trends. We believe that this was due to intensive forest felling, since these two catchments are much easier to access for vehicles and forest harvesting machinery compared to other four catchments.

An analysis of the trends in the change in the runoff on the catchment areas that are subject to the most intensive logging (the Shadat and Kebezh rivers) indicates an increase in the runoff from the beginning of logging, despite a general decrease in precipitation in the study area. Low correlation coefficients between runoff and time from the beginning of cuttings (0.16–0.32) are explained by the high inter-annual variability of atmospheric precipitation and unevenness of logging. At the same time, the coefficient of the regression equation reflecting the relationship of the runoff with years of forest harvesting for River Shadat is significant by 95%, and for the river Kebezh at 74% confidence level.

Analyses of forest inventory records and remote sensing data [51,52] revealed that until the mid-1970s, clearcutting in the catchments of the Taigish River, Shadat River tributary, and Kebezh River was limited to chern taiga (lower) AVB. All large accessible forest stands were subject to clearcutting here before 1975. We analyzed the 1989–1999 space images and found that the total area of clear cuts this period was increased due to extending clearcutting into mountain taiga (higher) AVB. This visual conclusion was confirmed by our analysis of post-cutting forest stand structure. The youngest stands were found within mountain taiga AVB, whereas 40–50-year-old stands dominated in chern taiga AVB.

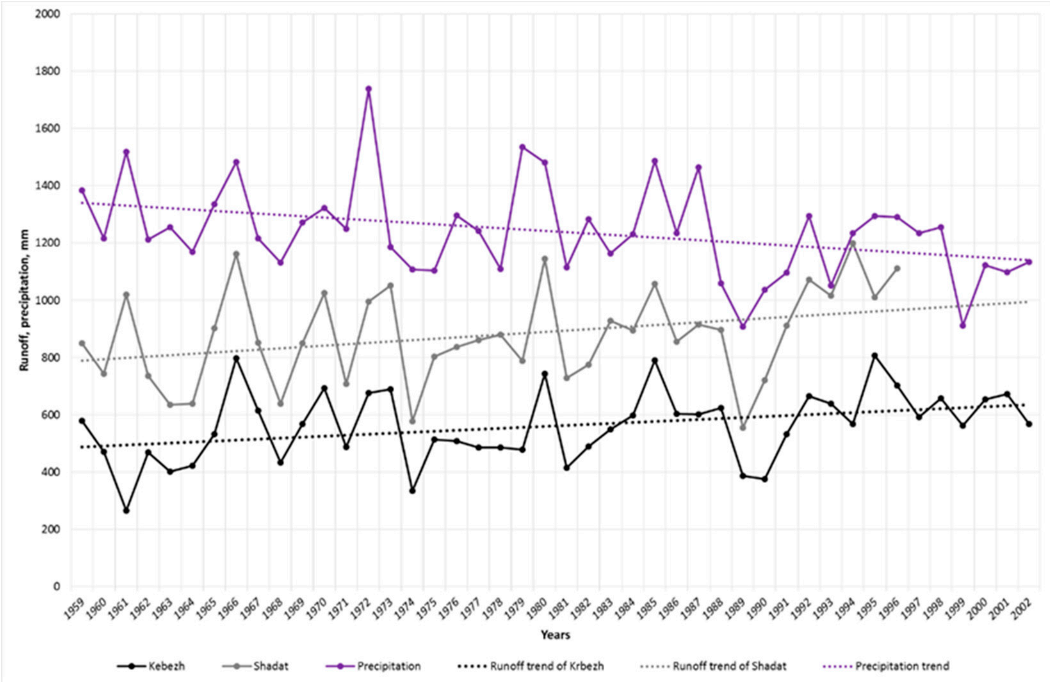

Figure 4. Kebezh and Shadat runoff trends vs. mean annual precipitation trend.

To study the effects of fresh clear cuts on water yield and to eliminate precipitation effects, we compared the dynamics of the runoff coefficient (runoff/precipitation ratio) with that of recently clear-cut areas on a five-year basis (we summed up the areas of one to five year-old clear cuts). As is clear from the graph in Figure 5, the maximum runoff coefficients that occurred for the Kebezh River during 1954–1958 and 1969–1973 coincided with increases in clear-cut areas. The period from 1984 to 1993 was a similar case. The runoff coefficient exhibited less pronounced variability compared to clear-cut areas. This may be due to changes of the water balance of this catchment as a whole, since in rapidly growing young stands evapotranspiration sometimes exceeds that in undisturbed conifer stands. It is noteworthy that the effect of felling was to some extent offset by the general trend of decreasing precipitation on the north-facing slope of West Sayan.

The most dramatic period occurred in the years 1954–1958, when about 30% of the catchment area was cut over five years, especially since the felling areas were concentrated in the lower mountain belt (the chern taiga). This effect was intensified by forest harvesting during the preceding years (1949–1953).

The studies we conducted in the mountain forests of West Sayan allowed us to conclude that the hydrological regime of a given area changes depending both on climate and forest succession. The effect of post-cutting (secondary) stands on water yield depends on their age structure, species composition, and the amounts of transpiring overstory and understory phytomass. The positive trends obtained for the Kebezh and Shadat catchments showed that clearcutting can result in temporally increasing water yield, even though the regional precipitation tends to decrease.

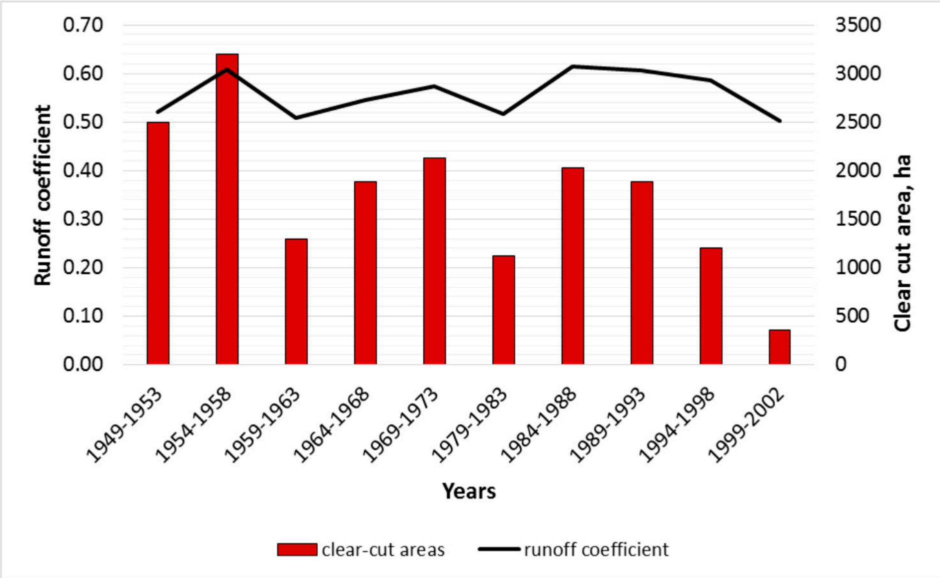

Figure 5. Dynamics of the runoff coefficient (runoff/precipitation ratio) and 1–5-year-old clear-cut areas in the Kebezh River catchment.

3.2. Hydrological Effects of Clearcutting in Northern Angara Region

In Northern Angara region, extensive forest harvesting began later than in West Sayan. Clearcutting became a widespread forest use in the catchment of the Angara River, Krasnoyarsk Region, in the early 1960s, and extracted wood amounted to over 10 million m^3 by 1990. In 1988, the total felling area was 2.4-fold the area in 1966 [53]. During this period, about 500 thousand hectares were clearcut, of which 350 thousand hectares were Scots pine forests. Our estimates [54] showed that, between 1966 and 1988, the average annual clearcutting was 1–3% of the areas of large and medium-sized catchments and as much as 45% for relatively small catchments. Since the largest Scots pine massifs were clear cut as long ago as the 1960s, the forests of Angara region are nowadays a patchwork of succession stages including post-fire young stands. Sites of undisturbed forests are found only along rivers and 100 km or farther from the Angara River.

Changes of water yield resulting from clearcutting are discussed for small catchments of Northern Angara Region in a number of publications [54–57]. According to these authors, clearcutting has the greatest effect on seasonal water yield structure. Our analysis of annual water yield distribution for the catchments of North Angara region showed that clear cutting large areas resulted in water yield redistribution, as the surface runoff component and, hence, spring-time water yield proportion, increased. This was especially evident where clearcutting covered large areas. For rivers with catchments of 4–5 thousand square kilometers, of which 1% is under fresh clear cuts, springtime runoff increased by 5–7%, with the increase being 10–20% where clear cuts total 40–45% of a catchment area. For small catchments subjected to clearcutting, springtime runoff appeared to account for as much as 70–90% of annual river flow.

We analyzed a large amount of water regime data collected for the rivers of the Angara catchment and developed an equation describing the dependence of water yield on hydro-climatic factors and time since clearcutting for each catchment [58].

A comparison of water yield changes with the dynamics of human-caused disturbance with regard for climatic and weather conditions for some catchments of the Northern Angara region enabled the identification of temporal water yield fluctuations unrelated to precipitation changes [16,57]. For the Karabula, Irkineyeva, and Mura Rivers of Northern Angara regions, we identified an approximate 20-year period, beginning from the early 1960s, when water yield was decreasing at a rate of 0.5–1.3 mm/year.

In a number of regions, the evaporation of snow moisture was of great importance in the structure of the water balance. In this regard, it should be noted that the intensity of evaporation of snow increased with increasing wind speed, especially at low air temperatures, when dry and small snow rises into the air and the area of the evaporating surface increases by a factor of 10–100-fold.

Many researchers [59–63] pay attention to effect of the specific climatic conditions on the evaporation of snow moisture, especially during blizzards. It is known that in open areas, with increasing size, the wind speed increases and, accordingly, the intensity of evaporation of snow increases [64]. This, in our opinion, is the main reason for the decrease of river runoff with the increase in the area of fresh cuttings, which activated the wind activity, and winter evaporation increased.

Over the first two decades following the start of clearcutting the forests of Angara region, river flow decreased by about 10–20 mm due to human-caused vegetation disturbances. For all the rivers studied, except the Karabula River, whose catchment was 45% fresh-cut in the second half of the 20th century, we identified the time point when water yield started to increase. These were 1975, for Taseyeva, 1984 for Irkineyeva and Mura, and 1986 for Chadobets. These time points agreed fairly well with when young stands began to extend in the 1950–1960s clear cuts. Post-clearcutting young deciduous and mixed conifer/deciduous stands accumulated much snow and no snowstorms, which are frequent on large open sites and enhance snow evaporation. This was confirmed by the increasing contribution of solid precipitation to water yield (the Taseyeva, Chadobets, and Irkineyeva Rivers). An estimated increase in water yield with increasing snow accumulation in post-clearcutting young stands occurred at 1.5–3.0 mm/year. During the past 20 years since deciduous young stands began to occur on clear cuts, mean annual water yield increased by 20–40 mm as compared to before clearcutting.

4. Discussions

The differences found between West Sayan and Northern Angara regions in water yield response to forest cover reduction by clearcutting were due to different climatic conditions. In the Northern Angara region, hydrological regime changes were controlled by extremely continental climates characterized by relatively low winter precipitation and harsh vegetation growth conditions hampering forest regeneration. In the first several years after clearcutting, wind increases on large clear cuts resulted in increasing snow evaporation due to frequent snowstorms and in decreasing snow storage. Therefore, background climatic conditions being equal, annual water yield decreased for clear-cut catchments. As woody vegetation recovered, especially where recovery occurred through species conversion, snow accumulation increased to, and even exceeded, pre-cutting levels, and water yields therefore increased.

On the north-facing West Sayan macro slope that was situated in a less continental climate, and had less wind and higher winter air temperatures than the Northern Angara region, more snow accumulated on clear cuts. This snow contributed to increasing water yield. We found that the changes of the water balance components had different trends over the first 2–3 decades after the regions of interest had been clear-cut. In West Sayan, water yield increased in the first several post-cutting years, and then it decreased gradually to pre-cutting levels over 40–50 years. In the northern Angara region, water yield showed a decrease in the first 20 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. Based on the current stand growth rate, it will probably take 20–30 years for water yield to recover to pre-cutting levels.

5. Conclusions

Clearcutting practiced in the mountains of southern Siberia and in Northern Angara region over the past several decades has changed the vegetation of these regions, and these changes have affected the structure of the water yield of areas with disturbed forest cover. The results of our multiyear studies allowed us to conclude that clearcutting in river catchments is a major anthropogenic effect on water yield.

The studies also showed that, in Siberia, forest cover changes lead to either the reduction of, or an increase in water yield depending on forest structure and climate. River flow dynamics, as forest cover recovers, depends on regional climatic conditions. Clearcutting in dark-needled forests of western Sayan, a humid area, results in a drastic increase in water yield. On the experimental clear cuts, water yield was twice that of the control. Where native forest regenerated without tree species conversion (e.g., through fir), water yield recovered back to pre-cutting values over 30–40 years following clearcutting, and over 50 years after cutting where native forest regeneration occurred through the conversion (through birch or aspen). Estimating clearcutting effects on water yield for large watersheds was a more complicated procedure compared to small experimental plots. The studies we conducted in the river basins under intensive forest cutting showed positive water yield trends, although the regional total precipitation tended to decrease.

In the northern Angara region characterized by an extremely continental climate, wind activity increased in vast clear cuts during the first several post-cutting years to result in increasing snow moisture evaporation and thus in decreasing water yield. Unproductive water losses caused by snow evaporation accounted for a 10–20 mm decrease in water yield between the mid-1960s, when intensive forest cutting in the river basins of the northern Angara region began, and during the early 1990s. As clear cuts gradually regenerated, particularly where regeneration occurred through tree species conversion, the capability of the forest to accumulate snow recovered, and even improved, compared to pre-cutting. As a result, the annual water yield increase was 1.5–3 mm during the two decades following the early 1990s. It was clear that the difference found between the western Sayan and northern Angara regions in the water yield response to forest cover reduction was due to climatic differences. This dependence agreed with the concept of geographic determinacy of the hydrological role of the forest [63].

A systems view and through studies of the mechanisms of forest hydrological influences enable the argument concerning the hydrological role of forests to be settled, and enabled the development of models predicting water yield changes with changing forest formation processes, in both natural and human-disturbed areas, allowing the improvement of the water-forest system management under different geographic conditions.

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