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Influence of Trees and Their Fallen Trunks on the Formation of Hydrobionts Habitat in the Mountain Rivers of Sikhote-Alin

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Abstract—The morphological diversity of the channel relief of small mountain rivers of Sikhote-Alin was established, caused by the specific impact of dense woody vegetation on the intensity of horizontal and vertical deformations of the channels. The role of large trees in the spatial stability of river beds, the structure of stretches and riffles, and the combination of areas with sediments of different granulometric compositions has been revealed. The causes and mechanism of furcation of the channels of mountain rivers in the region, caused by the formation of small blockages consisting of several large trees, are considered. Based on the analysis of the distribution of current velocities, depths, and composition of bottom sediments on the adjacent elements of the channel relief, the diversity of habitat conditions for river hydrobionts is shown. Small streams in mountain-taiga regions, when the channel flow interacts with trees growing and lying in the river, significantly increase the heterogeneity of the channel, contributing to a sharp differentiation of various ecological niches for aquatic organisms. Thus, trees in the beds of small rivers can be considered as ecosystem engineers that contribute to the formation and stabilization of aquatic habitats.

Keywords: small streams, woody vegetation, blockages, sediment runoff, aquatic organisms, habitats, ecosystem engineers

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INTRODUCTION

The terrestrial and aquatic ecosystems of the Sikhote-Alin mountainous country, located in the extreme southeast of the mainland Russian Federation in the Khabarovsk and Primorsky Krais, are characterized by one of the highest biological diversity of species and natural communities in Russia due to the pronounced diversity of climatic, altitude, and soil conditions [1]. Woody vegetation has a significant impact on the morphological, morphometric, and hydrobiological characteristics of the channels of small mountain and semi-mountain rivers in the region and their main elements – reaches and riffles [2–6]. In some watercourses, accumulations of wood reach significant sizes, forming wood dams (blockages) that are often the only stable habitat for aquatic organisms, a refuge for fish and other aquatic organisms during periods of low or extremely high water, influence the distribution of spawning grounds and young fish in various forms of river channels [7–12].

The hydrological and hydrobiological conditions of small river watercourses depend to a large extent on the condition of forest ecosystems, since the main formation of multi-species river phyto- and zoobenthic communities occurs in the catchments of small rivers [13, 14]. At the same time, for small mountain rivers of Sikhote-Alin, the role of woody vegetation in the dynamics of their channels has not been previously considered, including in a general work devoted to the channel regime of the rivers of Northern Eurasia [15]. Only in recent years have studies been conducted on the channel-forming role of tree clusters in the channels of mountain rivers in the Far Eastern region in connection with the assessment of spawning grounds and the development of measures to preserve the spawning stock of Pacific salmon [16–18], but these studies relate to fairly large rivers. The features of the structure of the main forms of the riverbed relief of Sikhote-Alin rivers presented in the article correspond to the existing classification of reaches and riffles of mountain rivers [19] and clarify it for small watercourses that experience the impact of woody vegetation on the development of their channels.

Objective—To identify the influence of trees and their fallen trunks on the structure and dynamics of channel landforms, i.e., on the formation of habitats for aquatic organisms in small mountain forest watercourses of Sikhote-Alin.

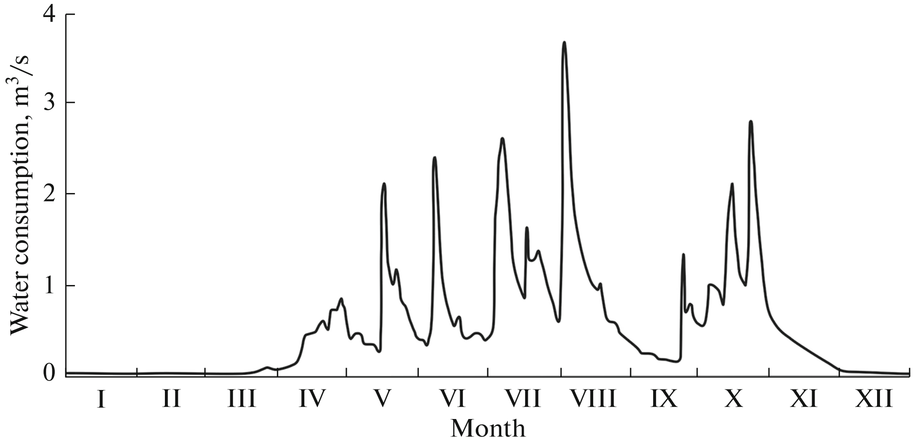

Fig. 1. Typical hydrograph of small river of Sikhote-Alin (Buya creek, Tumnin River basin).

MATERIALS AND METHODS

The largest area of Sikhote-Alin is occupied by forest vegetation. The main forest-forming trees are Korean cedar *Pinus koraiensis* Siebold & Zucc., Ayan spruce *Picea ajanensis* (Siebold & Zucc.) Carriere, whole-leaved fir *Abies holophylla* (Maxim.), valley elm *Ulmus propinqua* (Koidz.) and Mongolian oak *Quercus mongolica* Fisch. ex Ledeb. Of the associated species, the most common is the white fir *Abies nephrolepis* (Trautv. ex Maxim.) Maxim., Amur and Manchurian lindens—*Tilia amurensis* Rupr. and *T. mandshurica* Rupr. & Maxim., birch trees *Betula* spp., willows *Salix* spp. and others.

The density of the Sikhote-Alin river network is on average 1.2–1.4 km/km^2, and the largest total length (more than 95% of all rivers in the region) falls on small watercourses up to 20 km long, which approximately corresponds to 60–70 km^2 their catchment area. The study of the morphological characteristics of the riverbeds was carried out during expeditionary research on many small rivers on the western and eastern slopes of Sikhote-Alin, the width of which did not exceed the height of the trees. The main attention was paid to watercourses with a channel width of 3–6 m.

The structure of the channels of small watercourses in the basins of the Tumnin, Ussuri, Anyui, Khor, Gur, and other rivers has been studied in most detail. During the work, the morphological and morphometric characteristics of the main elements of their channels, stretches and riffles, as well as the composition of the channel alluvial deposits were determined.

For some small watercourses detailed surveys of riverbed sections were carried out at a scale of 1 : 200 using standard ground-based geodetic equipment. The density of woody vegetation with trunk diameters greater than 10 cm in the vicinity of the studied river sections was assessed. High-resolution satellite images were used to analyze the conditions for the formation of watercourses, as well as the locations of tree falls.

RESULTS

Channel relief forms of small mountain rivers. The small watercourses of Sikhote-Alin, in terms of their hydrological regime, belong to the Far Eastern type, widespread in the territory influenced by the northern variant of the East Asian monsoons [20]. They are characterized by low winter low water and several high summer floods with a sharp increase in water flow and high flow rates caused by heavy rainfall in their basins (Fig. 1). The duration of floods, which have mainly a local erosive impact on the banks and bottom of rivers, usually lasts several days. When flood waters pass, the maximum annual flow of traction and suspended terrigenous sediments, as well as organic material, occurs.

The morphological and morphometric characteristics of rivers are determined by the size of watercourses, the slopes of valley bottoms, water and channel regimes, the composition of sediments, and the nature of the interaction of river flow with floodplain banks. The special conditions for the formation of the channels of small rivers in the region are associated with the dense forestation of river valleys, which has a significant impact on the uniqueness of the morphological types of reaches and riffles.

The channels of small mountain streams are mostly single-branch and slightly meandering. Bends in the riverbed are formed in areas with local obstacles in the form of protrusions of bedrock, accumulations of large boulders, or large trunks of growing or fallen trees. Watercourses are characterized by a stable spatial position, since their lateral erosion in forested conditions is insignificant and occurs in local areas. Instrumental surveys of the upper reaches of the Shivka and Birushka rivers (Ussuri River basin), carried out at intervals of more than 30 years, did not reveal significant changes in the shapes of their channels and the spatial position of stretches and riffles [5].

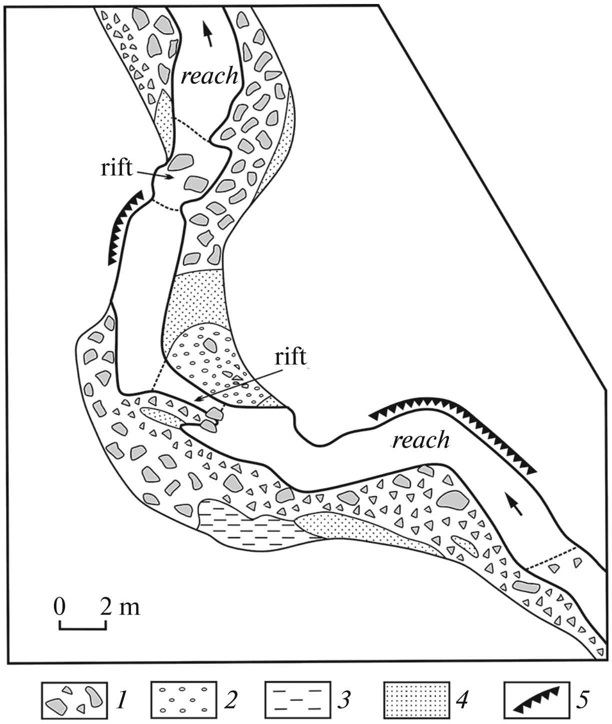

Fig. 2. Channel structure of the Birushka River (Ussuri River basin) in a section lacking forest vegetation: (*1*) boulder-pebble deposits; (*2*) gravel with small pebbles; (*3*) silt; (*4*) sand; (*5*) eroding river bank.

Particularly significant transformations of riverbeds occur during catastrophic rises in water levels in rivers, which occur once every 100–150 years [5, 21], and are expressed in the formation of long-term, stable, extended stretches, and short boulder-pebble riffles, which are transformed only during the next catastrophic flood. The riffles are composed mainly of small boulders brought by the stream from the nearby stretch. In treeless areas, the ratio of the length to the width of the stretches ranges from 3 : 1 to 6 : 1 (Fig. 2).

During floods of lesser intensity, large reaches of the riverbed are filled with sediment due to partial erosion of the riffle, forming secondary reaches of small sizes (Fig. 3). Their formation occurs as a result of the deposition of the finest pebble material in the form of an underwater ridge on the bottom of an existing stretch of water. According to observations in the riverbed. In the Birushka River, the secondary reaches are 3 × 5 m in size, with a depth of 0.5–1.0 m, while the primary reaches extend up to 15 m and are up to 2.0–2.5 m deep. During subsequent significant floods, the secondary reaches are destroyed, and their alluvial deposits are carried downstream, forming coastal spits in the hydrodynamic shadow of the water flow. Thus, they are ephemeral formations, characteristic of rivers with a multi-flood water regime. In this case, the structure of the riverbed usually does not change and only a redistribution of sediments of different granulometric composition occurs in it.

The influence of growing trees and their fallen trunks on riverbed processes. An analysis of the structure of the channels of small mountain streams in Sikhote-Alin in the thoroughly studied areas of the Birushka and Shivka river basins showed that the morphology of the channel forms and the composition of the bottom sediments depend on the conditions of interaction of the water flow with large trees growing on the banks or lying in the channel.

For small streams, the width of which does not exceed 3–4 m, large trees standing alone on the bank are a significant obstacle. In this case, deep erosions with sharply defined boundaries are formed in front of the tree (Fig. 4). They have an isometric shape and are fairly stable stretches of water no more than 3 × 3 m in size, which are characterized by the maximum depths for rivers. Below such reaches, short, shallow riffles are formed, composed of pebble and boulder deposits carried out from the reach. Individual boulders and even clusters of them protrude above the water surface, breaking the flow into a large number of separate, chaotically located streams.

The flow rates in such sections of rivers vary significantly depending on the shape of the riverbed and the water content of the flow. At low water levels in the reaches, the current speed does not exceed 0.1 m/s, while in the riffles it reaches 0.4–0.5 m/s. During floods, the flow speed in the rapids increases to 2–3 m/s, and in the upper part of the reaches it reaches 4–5 m/s. In this case, in front of an obstacle in the form of a tree, the flow acquires a vortex motion along

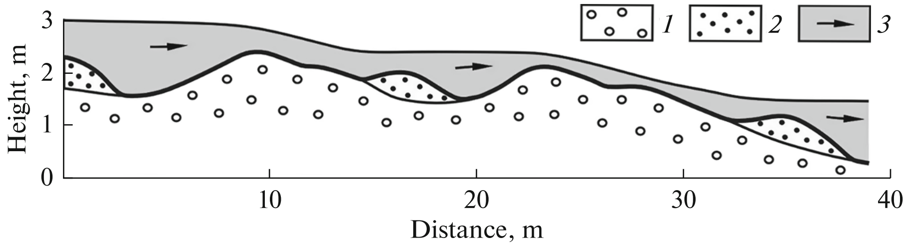

Fig. 3. Ridge formation in the upper parts of pools during low floods in mountain river channels of the western Sikhote-Alin (Birushka River): (*1*) large boulders; (*2*) pebble–gravel material; (*3*) flow direction.

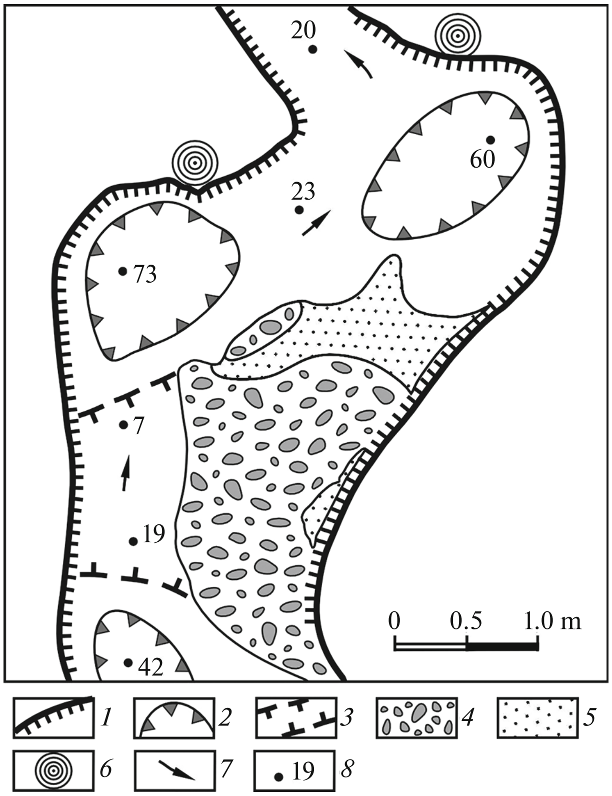

Fig. 4. Channel structure in a section with standing trees, upper Shivki River (Ussuri River basin): (*1*) channel boundary; (*2*) pool; (*3*) riffle; (*4*) pebbles and gravel; (*5*) sand; (*6*) standing tree; (*7*) flow direction; (*8*) depth marks, cm.

one of the banks, the erosion of which is prevented by the growing tree. The depth of the watercourse in such areas often reaches 1.5–2.0 m.

The sediments at the bottom of the reaches consist of tightly packed, weakly rounded boulders. In places where the current speed slows down in the upper parts of the pool depressions, there are accumulations of gravel-pebble deposits and small sand spits.

The formation of unusual channel morphology is also caused by single trees with trunk diameters over 20 cm falling into the watercourse (Fig. 5). When the width of the water flow is not capable of carrying individual trees or their large fragments, unique reaches and riffles are formed in the channel, the shape and size of which depend on the position of individual trees in the channel.

On densely forested banks, even on short sections of the river, there are various conditions for the placement of tree trunks relative to water levels. If a tree lies on the bottom of a watercourse, it forms a low threshold, below which a washout hole (reach) of insignificant length and depth is formed across the entire width of the channel. When the water level rises, trees act as dams and in front of them, pebble and boulder material accumulates, while below the tree, specific morphological reaches of up to 0.8–1.0 m in depth are formed (Fig. 6). Their distinctive feature is that their width significantly exceeds their length.

The deposits of riffles, part of which are trees lying in the riverbed, are the most diverse in composition. They are dominated by gravel and pebble material of varying sizes, including small boulders, with a smaller proportion of sand. The sediments located below the tree in the riverbed are characterized by less diversity in grain size distribution than the sediments accumulated upstream. However, they form various small accumulative formations, the increase in size of which causes the channel to divide into two branches.

In watercourses more than 5 m wide, in some areas, conditions are created for the formation of blockages consisting of clusters of 3–5 or even dozens of tree trunks and debris (Fig. 7). Their position in the riverbed is determined by its morphological features, and therefore the “cores” of one or several large trees, which became the basis for the formation of blockages, are confined to the upper reaches of channel islands, underwater accumulative formations, as well as to river bends and areas where the riverbed divides into branches [21]. Many of the blockages are of considerable size and are constantly growing in length due to the influx of trees floating down the river. The capacity of the water flow (the cross-sectional area of the flow) under them decreases, and the increase in the flow velocity as a result contributes to the formation of stretches of 2–3 m deep along the entire length of the blockage.

Large accumulations of tree trunks in the beds of small streams in areas with dense forest vegetation form dams of several dozen trees and numerous small wood debris 3–4 m high, blocking the channel from bank to bank. In some sections of small rivers, the length of the blockages reaches several tens of meters. Due to the reduction in the cross-sectional area of the channel and the increase in the flow velocity, extended stretches are formed under the blockages.

However, compact wooden dams with dense packing of tree trunks in watercourses up to 5 m wide, while passing water, retain pebble and boulder material, which quickly accumulates and completely blocks the flow. This process is one of the main reasons for the formation of a new channel and contributes to the beginning of the formation of multiple branches. Abandoned old branches form bays or oxbow lakes in which there is no current at low water levels.

The reaches of small mountain rivers in areas with dense woody vegetation in floodplains are 2–4 times shorter than similar forms in treeless areas (Table 1). They are also characterized by a shallower depth, since their small size and frequent alternation with short riffles cause a significant reduction in the river flow rate during floods, which is the main reason for the reduction in the erosive capacity of the watercourse even during high floods.

Fig. 5. An in-stream tree forming a rapid with high flow velocities.

Effects of alteration of riverbed processes by trees and fallen trunks on aquatic organisms. The presence of wood in streams and small rivers is associated with many ecological processes, such as the formation of habitats critical for fish and many other aquatic organisms. So, deep washouts in front of large trees standing alone on the bank during the dry season provide vital refuge for aquatic organisms when the continuous flow of water in the river is interrupted. In winter, such stretches of water become ice-free wintering pits. In small mountain rivers, the presence of tree clusters in the water stabilizes the channel relief forms, protects the banks from erosion during floods, ensuring the stability of vegetation in coastal zones and the preservation of floodplain biodiversity [22]. The alternation of stretches and riffles slows down the transfer of bottom sediments during floods and leads to the appearance of accumulative forms in the riverbeds, composed of sediments of varying granulometric composition.

Dense forest vegetation promotes the accumulation of organic matter in the alluvial deposits of the reaches, which is carried in suspended and tractional states. A similar phenomenon has also been noted in the channels of small rivers in the eastern spurs of the Appalachian Mountains in the United States [23] and in the lowland watercourses of Great Britain [24].

The nature of the distribution of reaches and riffles influences the productivity of aquatic organisms [12, 25, 26]. For example, research in the Bomnak River bed (Zeya river basin) showed that in summer the density of organisms on the riffles is lower, and the biomass is higher than on the pools. This difference in biomass is due to the development of large midge lar-

Table 1. Morphometric characteristics of channel forms in the middle reaches of the river Birushka

Watercourse location	Reach			Rapids		
	length, m	width, m	depth, m	length, m	width, m	depth, m
Treeless areas	11–15	3–4	1.5–2.5	2–4	3–5	0.2–0.5
Woody vegetation	4–5	2–4	1.5–2	3–4	2–5	0.1–0.3

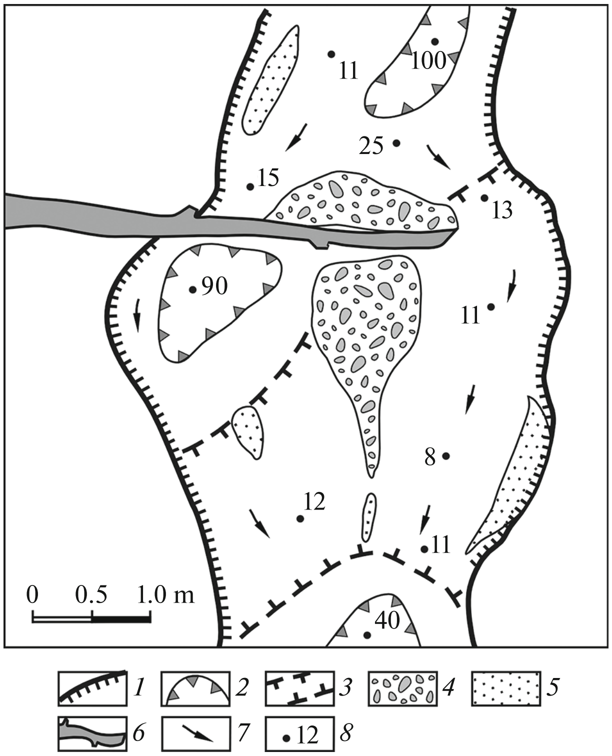

Fig. 6. Channel structure in a section with a fallen tree, middle Birushka River (Ussuri River basin): (*1*) channel boundary; (*2*) pool; (*3*) riffle; (*4*) pebbles and gravel; (*5*) sand; (*6*) large woody debris (fallen tree); (*7*) flow direction; (*8*) depth marks, cm..

vae on the riffles, *Gnus subvariegatum* (Rubz.), *Gn. Cholodkovskii* (Rubz.) and *Archesimulium vulgare* (Dorogost., Rubz. et Vlas.), as well as caddisfly larvae *Glossosoma altaicum* (March.) [12]. This relationship is disrupted immediately after floods, when the parameters of the density and biomass of zoobenthos of various forms of channel relief become close in their quantitative indicators.

It is well known that fallen trees in riverbeds provide habitats for microorganisms (biofilms on organic substrates), aquatic invertebrates, and fish, thereby influencing the increase in diversity and productivity of aquatic communities [7, 8, 27]. For some invertebrates, submerged wood serves as a food source. For example, the wood consumer caddis fly *Pycrocentria funerea* R. McLachlan can produce woody faeces in quantities ranging from 22 to 168% of its body weight per day in New Zealand streams [28]. The habitat and food sources created by submerged wood and its associated invertebrates in turn form the basis for higher trophic levels, including fish. In particular, it was established that in the Satilla River (southeast Georgia, United States) Invertebrates living on submerged wood are the main food source for insectivorous fish: At least four of the eight major fish species received at least 60% of their diet from wrecks [27]. Besides, many species of fish use large trees and breaks for spawning (attachment of eggs, nesting material, etc.) [8].

CONCLUSIONS

The channel relief forms of small mountain rivers of Sikhote-Alin in areas with dense woody vegetation are characterized by specific structural features caused by the water-regulating role of forests in combination with the hydrodynamic characteristics of the flow in areas in front of obstacles in the form of a free-standing tree or a tree lying in the riverbed, a small or large tree block. Trees growing in water or fallen into water in this case can be considered as ecosystem engineers, contributing to the formation of a modified habitat for aquatic organisms in accordance with the concept of "ecosystem engineering" proposed more than two decades ago [29]. Despite the fact that in the environmental literature of recent years a significant redundancy of views on "ecosystem engineers" has begun to be recorded, especially in terms of direct trophic impacts of key species on environment formation [30, 31, etc.], the identified role of trees fallen into the river in the creation of new aquatic biotopes basically corresponds to the original content of the concept. In particular, its authors noted that "ecosystem engineers" are organisms that are capable of modifying the environment and resources not because of their trophic effect, but because of their ability to significantly alter, maintain, and/or create habitats for other species in ways not directly related to one's own energy exchange.

The ecosystem role of trees growing on the shore and fallen into the water can be compared with the habitat-forming activity of river beavers, which initially serve as a classic example of "ecosystem engineers" [29, 30, 32, etc.]. Beaver dams, like natural dams, alter the morphology and hydrology of streams and small rivers, retain mineral and organic matter in the riverbed, influence the chemical composition of water and the nature of materials transported downstream, and ensure the diversity of aquatic communities. In addition, as a result of beaver activity, wetlands are created and maintained, and the structure and dynamics of the soil and vegetation cover of the coastal zone are changed.

With a significant density of woody vegetation and the entry of trees into rivers, only the aquatic environment is physically changed, when the total number of stretches in the watercourse increases by 2.0–2.5 times compared to areas with sparse forest vegetation or treeless, in particular meadow, areas. Clusters of trees in riverbeds, as in the case of beavers, are the cause of the formation of fairly long and deep stretches of river, a factor in increasing the heterogeneity of riverbeds, contributing to the pronounced differentiation of various ecological niches for aquatic organisms, and the stabilization of their habitats. In some cases, a certain "competition" in the accumulation of wood in small

Fig. 7. Debris dams in a river channel forming upstream of a submerged bar.

streams and rivers is observed between wood and beaver dams [7].

At the same time, between the activities of beavers, purposefully felling trees for the construction of dams, there is a significant difference between the natural formation of river dams and the beavers' environment, which primarily serves to support their own livelihoods, while river dams create a new habitat for aquatic organisms. In the latter situation, trees entering a watercourse should be considered "ecosystem engineers" that do not participate in the formation of their own habitat, since fallen trees, unless they are dead wood, eventually die, but nevertheless have a significant impact on the riverbed topography and the species diversity of aquatic communities.

In conclusion, it should be noted that, in the context of the ongoing loss of forest vegetation caused by clear-cutting and fires, the water-regulating role of forests in deforested areas is also lost, resulting in increased unevenness of water flow, especially in the summer seasons, and soil degradation. During the low-water period, the rivers' water levels noticeably decrease, and during the rainy season, catastrophic floods form, eroding the banks and destroying previously formed dams. At the same time, salmon spawning grounds are disappearing in Far Eastern rivers due to their drying up during the dry season and freezing in the winter, and the overall diversity of rheophilic communities is decreasing.

AUTHOR CONTRIBUTION

A.N. Makhinov contributed to the hydrological component of the article, and V.V. Bogatov contributed to the ecological component. Both authors contributed equally to the writing and editing of the text.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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