Influence of post-pyrogenic successions of the forests of the Urals on the formation of maximum rainfall flood discharges

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Abstract. The issues of losses on the crowns of forest stands in the conditions of forest successions after fires and associated changes in the maximum discharge of rainfall floods are considered. The results of complex field, experimental work, deterministic modelling are presented. It has been established that with the complete burnout of forests in the catchment, the maximum flow rates can increase by 40% compared to the initial state of the forests, and with the restoration of forests, the maximum flow rates of floods again decrease by 15-20% over a 20-year period.

1. Introduction
The full recovery period of coniferous forests after fires in the conditions of the Northern Urals is 200-250 years. During pyrogenic successions of phytocenoses, factors of rainfall flood formation are changing. For example, after fires the canopy surface area decreases, which reduces precipitation losses on wetting canopies. Moreover, precipitation loss on the leaf surface from evaporation and the values of infiltration in conditions of degradation of the root system of trees also decrease.

After fires, the volume of flood runoff and the maximum discharge of small rivers (with a catchment area of up to 200 km²) is expected to increase. The study is devoted to quantitative estimates of precipitation losses on wetting canopy during succession as well as estimates of rainfall floods and is based on the results of field, experimental works, and deterministic modeling of flood hydrographs.

2. Coverage of studies
The first studies of precipitation losses of individual rainfalls on tree canopies were carried out in the late 19th and early 20th centuries [1; 5]. Currently, there are several well-known models of rainfall retention by tree canopies during rainfall such as models of Horton, Merrian, Jackson, Gash, and Fan [3; 4]. The specific feature of each is that they are based on the materials of empirical observations of precipitation under canopies rather than on the results of physical modeling of moisture retention on leaf plates. The authors have developed a methodology for estimating the interception of precipitation of individual rainfall by tree canopies and a methodology for spatial mapping of the values of maximum rainfall retention by canopies over the catchment area [6]. Under conditions of different species state of forests during succession, modeling of hydrographs of individual rainfall floods and their comparison with hydrographs in an initial state before a fire were performed.
3. Materials and methods

Experimental work was carried out on the following species of grasses distributed in forest catchments. The catchment of the Pynovka River located within the North-Sosva upland, in the Lozva River basin was chosen as an experimental site. The area is swampy and covered with a mixed forest. In 2010-2013, the catchment was covered by fires, due to which the area of coniferous forests was halved. They were subsequently replaced by deciduous forests (undergrowth). The catchment area is 28.4 km², 79% of which is covered by forests, 64% by undergrowth of small-leaved species. On the burnt plots, contemporary vegetation is represented by birch and willow undergrowth of 5-7 years old, its canopy density is 100%, and stand height is 3-10 m. In the areas partly affected by fire, there is a premature and mature birch forest mixed with pine. It is 18-20 m high, canopy density is 90%, trunk diameter is 0.25 m, and stand age is 30-40 years old. The undergrowth of birch trees has a height of 10 m, canopy density is 30%, trunk diameter is 0.10 m, and age is 10 years old. The undergrowth is represented by young birch, mountain ash and aspen of 1-2 m high. In areas not affected by fire, there is a premature and mature pine-birch forest of 20-22 m high, its canopy density is 70%, trunk diameter is 0.35 m, age is 50-60 years old. The undergrowth is represented by birch and pine and grass cover - by sedge and gramineous plants.

The Pynovka River catchment is characterized by a decrease in forest cover in the period from 2010-2013 as a result of burnout of a part of the catchment with the subsequent growth of deciduous species. The proportion of deciduous forests increased from 43% to 64% over the period from 1987 to 2019, while the proportion of coniferous forests decreased from 42% to 19%. The share of meadows also decreased from 10 to 4%, which is associated with the colonization by vegetation of meadows and swamps after fires. Under such conditions, a decrease in the proportion of intercepted precipitation in the catchment with a simultaneous increase in the maximum flood discharge is expected. The numerical characteristics of the successional process based on the analysis of multi-temporal satellite images and the results of the field survey in 2020 are presented in the table 1.

| Characteristics of phytocenoses          | Areas by years, ha | Relative areas by years,% |
|------------------------------------------|--------------------|---------------------------|
|                                          | 1987   | 2013   | 2019   | 1987 | 2013 | 2019 |
| Coniferous forests                        | 3468   | 2826   | 1424   | 12.2 | 9.9  | 5.0  |
| Deciduous forests                         | 1476   | 2998   | 3062   | 5.2  | 10.5 | 10.8 |
| Mixed with a predominance of conifers     | 8356   | 3505   | 3843   | 29.4 | 12.3 | 13.5 |
| Mixed with a predominance of deciduous    | 10755  | 13326  | 14219  | 37.8 | 46.9 | 50.0 |
| Herbs - meadows, swamps                   | 3082   | 1177   | 869    | 10.8 | 4.1  | 3.1  |
| Anthropogenic territories and open ground | 1073   | 4376   | 4048   | 3.8  | 15.4 | 14.2 |
| Water surfaces                            | 215    | 215    | 215    | 0.8  | 0.8  | 0.8  |
| Young growth                              | 0      | 0      | 744    | 0.0  | 0.0  | 2.6  |

Maps of forest species composition, height, and tree canopies were created for the experimental catchment for selected years. Based on these maps and the results of the field survey, the age of the forests and the leaf surface area of the stands within a regular grid of 100×100 m were determined. According to the author's empirical dependence of the maximum rainfall retention on the leaf surface area [6], the limiting value of rainfall losses on wetting canopies was determined. The method of experimental works and the method of spatial mapping are described in detail in [6] and in [7] respectively.

The spatial pattern of values of rainfall interception by canopies in selected years in the Pynovka River catchment is shown in Fig. 1. As can be seen, after the fire in 2013 the catchment area with zero losses of precipitation significantly increased. By 2019, the area of zero losses had gradually decreased, which is associated with colonization by vegetation of burnt areas with undergrowth. At the same time, precipitation losses in the catchment area as a whole are increasing, which is due to forest maturing,
increase in canopy area, and gradual replacement of small-leaved species by conifers. In this regard, the result of mapping for 1987 is illustrative when the catchment was covered with small-leaved forest and pine undergrowth and had, in general, less precipitation loss than the forested part of the catchment in the year of the fire (2013).

4. Results and discussion

Modeling of flood hydrographs for August 1-19, 2020 was based on the assessment of the spatial distribution of precipitation losses on canopy wetting at different stages of forest succession as well as on the data on actual precipitation amounts and values of evaporation from the leaf surface.

The modeling was performed using the Rainfall-Runoff Library program developed by eWater Toolkit. This program is designed to simulate catchment runoff by using data on daily precipitation, discharge, and evapotranspiration. It can be used for catchments having an area of 10 - 10,000 km². The software of this program (RRL) allows calibrating models of runoff hydrographs.

The design hydrograph for the flood period (from June to September inclusively) was scaled as close to the discharges measured during the fieldwork as possible by calibration. Further modeling was performed with the same parameters, both with and without taking into account the precipitation interception at the level of 1987 (before the fire). The AWBM model described in detail in [2] was used for modeling. The modeling results are shown in figure 2.

![Figure 1](image-url)

**Figure 1.** Results of mapping the limiting values of the interception of rainfall by the leaf surface of forest plantations on the catchment area of the Pynovka River for various years of development of the succession process.
Figure 2. Modeled rain flood hydrographs for the catchment area of the Pynovka River for 1987 (before the fire), 2020 (after the fire) and for the case of the complete absence of forests.

5. Conclusion
The results of calculations show that changes in forest conditions in the catchment area during succession lead to significant changes in maximum flood discharges. For example, in the experimental catchment, maximum flood discharges increased by 18% over a 20-year period following a fire. In case a forest in the catchment area is completely burnt out, the maximum discharges will increase by 35-40%. This should be taken into account when carrying out hydrological calculations and planning forest management works.

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References
[1] Buhler Dr A 1891 Swiss Central Bureau for Forest Research Investigation. Proceedings 1(1) Contains detailed results of Adiisbeig and other Swiss stations
[2] eWater Toolkit [Available online // URL: https://toolkit.ewater.org.au/]
[3] Gash J, Lloyd C and Lachaud G 1995 Estimating sparse forest rainfall interception with an analytical model *J. Hydrol* 170 pp 79–86 doi:10.1016/0022-1694(95)02697-n
[4] Herbst M, Rosier P T, McNeil D D, Harding R J and Gowing D J 2008 Seasonal variability of interception evaporation from the canopy of a mixed deciduous forest *Agric. For. Meteorol.* 148 pp 1655–1667 doi:10.1016/j.agrformet.2008.05.011
[5] Horton R E 1919 Rainfall interception. *Mon. Weather. Rev.* 47 pp 603–623 doi:10.1175/1520-0493(1919)472.0.co;2
[6] Klimenko D Ye, Ostakhova A L, Tuneva A 2019 Experimental Data on Maximum Rainfall Retention on Crowns of Deciduous Tree Species of the Middle Ural *Russia. Forests* 10 (2):183, doi: 10.3390/f100201832019
[7] Klimenko Dmitry E, Cherepanova Ekaterina S and Khomyleva Alena A 2020 Spatial Modeling of Maximum Capacity Values of Irrecoverable Rainfall Retention by Forests in a Small Watershed *Forests* 11(6) P 641 [Available online https://doi.org/10.3390/f11060641]