Hydrological characteristics of snow melt erosion areas in the Krasnoyarsk forest-steppe

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Abstract. Hydrological factors determine the features of relief formation in all territories where surface runoff is formed. They determine the degree of ruggedness and the nature of the relief. Changing from year to year, they interact with the underlying surface, activating the processes of erosion and planar flush of the fertile topsoil on it. The need to model and determine their intensity in different periods is due to the annual use of these territories for agricultural needs, during their plowing and sowing. The article analyses the main characteristics of surface runoff on the territory of the Krasnoyarsk forest-steppe. The result of hydrological and geomorphological analysis of the catchment area in the key study area is presented. The main indicators of autumn soil moisture are characterized and their effect on the washout of the solid fraction within the key site Dolgiy Log is estimated.

1. Introduction
The territory of the Krasnoyarsk forest-steppe is located on the Ket'-Yenissey high, inclined, hilly, alluvial plain, dissected by the erosion activity of rivers - tributaries of the rivers Yenissey and Ket'. On the plan, it looks like a semi-closed depression with an open north-western edge. It is represented by two types of lowland landscapes - accumulative and denudation. Height fluctuations - from 200 m in the north to 400 m in the south, the length of the territory from south to north - 110 km, from west to east - about 80 km.

In the period 2009 - 2019, field studies of soil washout from melt water were carried out in the middle part of the forest-steppe zone of Central Siberia (Krasnoyarsk forest-steppe). Detailed results are published in [1,2]. The analysis of observations showed that the highest values of washout for the period from 2009 to 2019. were on arable land in the northern zone of the Krasnoyarsk forest-steppe, on the experimental site Dolgiy Log (the average washout value is 6.1 mm).

To assess the general moisture content of the study area, the impact of surface runoff and moisture indicators on washout, the corresponding hydrological indicators were calculated and updated for 2019.

2. General characteristic of analogue rivers
The intensity of erosion processes in the study area is largely determined by its hydrological indicators, such as module, surface runoff layer, etc. located closest to the study area. The Buzim River is located 20 km southeast of the Dolgiy Log site, river Nizhnyaya Pod’yomnaya - 20 km to the north.
• Nizhnyaya Pod’yomnaya River (Bolshaya Murta hydrological station) is located in the northern part of the Krasnoyarsk forest-steppe. Its length is about 98 km, the catchment area is 788 km². The river is fed by snow, rain and mixed. The average catchment height is 258 m.

• The Buzim River (hydrological station Malinovka) is located in the central part of the Krasnoyarsk forest-steppe. It originates in the Kemchug taiga. The river is about 124 km long, the catchment area is 2230 km². The average catchment height is 259 m.

Let us consider such parameters of river surface runoff as the surface runoff modulus (M, l / s × km²), surface runoff layer (y, mm), water level (H, cm) and the amplitude of its fluctuations (A, cm) over the period of stationary observations carried out at posts Malinovka and Bolshaya Murta in 1964 - 1968 (table 1) [3]. The flow module and layer, the amplitude of water level fluctuations in the northern zone (Nizhnyaya Pod’yomnaya river) is significantly higher than in the rest of the territory.

Here is a general description of the values of the surface surface runoff of the Buzim and Nizhnyaya Pod’yomnaya rivers. Due to the fact that water-erosion processes occur mainly at increased surface runoff rates, let us consider the maximum values of the surface surface runoff of the above rivers over a long-term period.

The surface surface runoff reaches the highest values during the flood period. Due to the noticeable variability of meteorological conditions over the years, in snowy and rainy years, the value of the annual surface runoff can exceed the average long-term values by 1.5 - 2 times (table 2).

**Table 1.** Water regime parameters [3].

| Observation point (river) | Average over the observation period (1964 - 1968) |
|---------------------------|--------------------------------------------------|
|                           | M, l / s × km² | y, mm | Hmax | Hmin | A |
| Bolshaya Murta (Nizhnyaya Pod’yomnaya) | 4.38 | 138 | 245.5 | 61.75 | 183.75 |
| Malinovka (Buzim) | 1.9 | 60 | 527.5 | 156.5 | 371 |

Note: notation in the text.

**Table 2.** Characteristics of the maximum values of the layer of surface water surface runoff (y) during the flood (long-term period) [3].

| River                          | During the observation period | Over a longstanding period |
|--------------------------------|-------------------------------|---------------------------|
|                                | The greatest y, mm | year | Average y, mm | y, mm |
| Buzim                          | 97 | 1966 | 50 | 35 |
| Nizhnyaya Pod’yomnaya          | 161 | 1966 | 106 | 91 |

Thus, at river Nizhnyaya Pod’yomnaya, located north of the river Buzim, the module and the surface runoff layer are generally higher due to the higher general moisture content of the territory. On the flat territory, starting from the spurs of the Eastern Sayan Mountains (region of Krasnoyarsk), the surface runoff increases in a northern direction. In the Krasnoyarsk forest-steppe region, the average annual river flow is approximately 1.2 l/sec. km², the river flow coefficient is 0.1 [3].

**3. Characteristics of the spring and annual surface runoff at the experimental site**

For the hydrological characteristics of the main experimental site, Dolgiy Log, let us consider the surface runoff of the Log Dolgiy stream, which flows at the base of the southern massive of the site (figure 1). Its catchment area significantly exceeds the area of the Dolgiy Log site proper and amounts to 28.8 km²;
The length of the stream is 9.5 km, the width is 2.0 m and more, the depth is 0.4–0.7 m, the flow velocity of the stream during the flood is on average 0.1–0.2 m/s.

To calculate the hydrological parameters of the Log Dolgiy stream, we used the method of calculating surface runoff for small rivers of A. V. Petenkov (Siberian Scientific Research Institute Of Hydraulic Engineering And Melioration), based on long-term field observations in the basins of the Upper Yenisei, Upper Chulym and Lower Angara [4]. The initial data for the calculations are presented in table 3.

![Map symbols:](image)

**Figure1.** Diagram of the catchment area of the Log Dolgiy stream.

Table 3. Initial data for calculating hydrological parameters, stream Log Dolgiy.

| P / p No. | Index                                      | The quantity |
|----------|--------------------------------------------|--------------|
| 1        | Annual precipitation rate, mm              | 361.1        |
| 2        | Station height, m                          | 164          |
| 3        | Coefficient of annual precipitation variation | 0.18         |
| 4        | Catchment height (slope), m                | 236          |
| 5        | $F$, $\text{km}^2$                        | 28.8         |
| 6        | The largest daily water formation layer (mm) from snow melting and rain 1% - prov. (according to A.V. Petenkov, [4]) | 20           |
| 7        | The largest daily precipitation (mm) 1% -prov. in summer | 70           |
| 8        | forest cover, %                            | 32.2         |
| 9        | waterloggedness, %                         | 0            |
| 10       | amplitude of heights                       | 92           |

The rate of annual precipitation and the height of the station were determined from the data [4, 3]. The coefficient of variation of annual precipitation, the largest daily water formation layer (mm) from
snow melting and rain, and others were determined using isoline maps compiled by A.V. Petenkov [4]. The calculation method determined the annual, maximum spring and rainfall surface runoff.

The results of calculating the maximum spring and rainfall surface runoff for the Log Dolgiy stream (Krasnoyarsk forest-steppe) were obtained using the software developed by D.A. Burakov at the Krasnoyarsk Hydrometeorological Center, are presented in table 4.

**Table 4. Maximum spring and rainfall surface runoff, Dolgiy Log stream, Krasnoyarsk forest-steppe.**

| Provision, % | 1   | 5   | 10  | 20  |
|--------------|-----|-----|-----|-----|
| numerator – Qmax, m³/s | 8.08 | 5.63 | 4.61 | 3.80 |
| denominator – Mmax*, l/s*km² | 280.55 | 195.49 | 160.07 | 131.94 |

**Table 5. Annual surface runoff parameters for the catchment area of the Log Dolgiy stream, Krasnoyarsk forest-steppe.**

| P / p No. | Index                                      | Value   |
|-----------|--------------------------------------------|---------|
| 1         | Basin flow rate, l / s × km²               | 0.30    |
| 2         | Basin surface runoff at P = 50%, l / s × km²| 0.29    |
| 3         | Theoretical flow rate of complete drainage, l / s × km² | 0.83    |
| 4         | Full drainage flow rate at P = 50%, l / s × km² | 0.80    |

The data in the table show that the values of the maximum spring and rainfall surface runoff are generally comparable to each other. In this case, the ratio of the values of the maximum surface runoff changes depending on their availability. So, if the rainfall surface runoff of the 1% probability of exceeding is slightly higher than the spring surface runoff of a similar supply (11.04 and 8.08 m³ / sec, respectively), then at a 20% probability, the spring surface runoff exceeds the rainfall (3.80 and 3.29 m³ / sec).

The value of the annual surface runoff was determined with a probability of exceeding 50%. The results of calculating the annual surface runoff for the catchment area of the Log Dolgiy stream are presented in table 5.

It is clearly seen that for the territory of the Log Dolgiy stream basin, the flow rate is lower than the total drainage flow. From this, we can conclude that the Log Dolgiy stream belongs to the drying up watercourses, operating only during the period of high water and rain floods.

Comparison of the results of calculating the annual surface runoff in the Log Dolgiy stream basin with the data of the map of the average annual surface runoff of rivers presented in [3] shows that the calculated value of this quantity (0.3 l / s × km²) is significantly lower than the values determined from the map of the annual surface runoff (1.2 l / sec × km²). This is due to the fact that the method of A.V. Petenkov is designed specifically for calculating the surface runoff parameters of small rivers, while the map was compiled mainly for medium and large streams.
forestedness and swampiness of the catchment area of the Dolgiy Log stream is lower than that of the Nizhnyaya Pod’yomnaya and according to these indicators corresponds to the river Buzim. Thus, the values of losses of melt surface runoff for absorption and evaporation in the catchments of the Log Dolgiy stream and the Buzim can be comparable with each other.

Table 6. Comparison of the characteristics of the catchments of the Log Dolgiy stream and analogous rivers.

| Name                      | Catchment height (slope), m | F, km² | Watercourse length, km | Lake percentage, % | Woodiness, % | Marshiness, % |
|---------------------------|-----------------------------|--------|------------------------|--------------------|--------------|--------------|
| r. Nizhnyaya Pod’yomnaya  | 258                         | 788    | 66                     | 0                  | 61           | 2            |
| st. Log Dolgiy           | 236                         | 28.8   | 9.5                    | 0                  | 32.2         | 0            |
| r. Buzim                 | 259                         | 2230   | 101                    | 0                  | 36           | < 1          |

The supply curves of analogous rivers were used to determine the flow supply on the territory of the Krasnoyarsk forest-steppe during the years of detailed studies of soil washout and accumulation. Assuming approximately that the provision of water discharge over the years of observations of the river Nizhnyaya Pod’yomnaya - settlement Bolshaya Murta and the stream Log Dolgiy are the same, we obtain the values of the maximum spring surface runoff over the years of observations for the Log Dolgiy with the help of the transition coefficients proposed by A.V. Petenkov [4]. Table 7 presents data for three years (2009-2011), representative for the entire period of author’s observations (2009-2019).

As can be seen from the table, in 2010, the magnitude of the modulus of the maximum spring surface runoff in the study area was the highest over the years of research, the availability was 4%. Calculations showed that the values of this value in the catchment area of the Log Dolgiy stream, with the same abundance, exceed similar data for the river Nizhnyaya Pod’yomnaya by more than 40%, along the river Buzim - more than 2 times. The reason for this is the reduction of the surface runoff module over the catchment area [5]. Due to the significant difference in catchment areas, the value of the travel time in the basins of the stream Log Dolgiy and its analogues are very different. In a small area of the catchment of the stream Log Dolgiy surface runoff occurs faster, as a result of which the calculated value of the maximum spring surface runoff is higher than that of analogous rivers.

Table 7. Module of maximum spring surface runoff of analogous rivers.

| Year | r. Nizhnyaya Pod’yomnaya | r. Buzim | str. Log Dolgiy |
|------|--------------------------|----------|-----------------|
|      | M max average day, 1/s × km² (availability,%) | M max urgent, 1/s × km² (availability,%) | M max average day, 1/s×km² | M max urgent, l/s×km² (according to A.V. Petenkov's method) |
| 2009 | 82.7(27)*                | 89.5 (22) | 51.6            | 51.6                | 110.82 |
| 2010 | 148.5 (4)               | 152.3 (4) | 71.3            | 71.3                | 208.73 |
| 2011 | 55.2 (55)               | 59.6 (50) | 30.8            | 32.5                | 77.71  |

Note: *) the value of security is indicated in brackets.
***) the calculated values for the rest of the observation years (2009-2019) are in the range of values of the indicated representative sample.

In addition, in 2010, the melt surface runoff was significantly influenced by the late onset of floods (2.5 weeks later than in 2009 and 2011). This was expressed in the fact that for a significant period of time from the beginning of snow melting to the onset of floods, the snow melt was very slow and intermittent due to low values of the average daily air temperatures. During this time, a significant amount of precipitation fell. The water reserve in the snow (measured before the beginning of melting)
in 2010 was the highest in the years of research (110 mm). These factors together increased the water inflow and, accordingly, the flood surface runoff.

4. Autumn soil moisture

Meteorological conditions in October-November have an indirect effect on the spring flood surface runoff and soil washout. This influence consists in the formation of soil moisture and, accordingly, the degree of soil water resistance [6, 7, 8]. The amount of water absorbed by the soil surface is determined by the degree of freezing and moisture before the beginning of snow melting.

The influence of autumn moisture, which is associated with the amount of ice in the soil, in areas of insufficient or unstable moisture, clearly affects the amount of melt water losses: the greater the autumn moisture and, consequently, the ice content of the soil, the less the loss of melt surface runoff. The severity of Siberian winters almost every year provides deep (more than 60 cm) soil freezing. Under these conditions, the depth of freezing is a kind of “constant background”. Consequently, the variability of surface runoff losses in Siberia is mainly determined by the variation of the autumn moisture content of the basins [8, 9].

For the territory of the Krasnoyarsk forest-steppe, the indicator of autumn soil moisture for the studied period was calculated. The method for calculating the indicator used for the purposes of hydrological forecasts is considered in [9,10,11]. It consists in the following: an indirect characteristic of autumn moisture is determined by the sum of daily precipitation values at the nearest meteorological station Sukhobuzimo in October - November (before the date of the final transition of the air temperature through zero degrees). In November, part of the precipitation falls in the form of snow, which melts on days with a positive air temperature. The layer of melted snow was determined by the value of the average daily positive air temperature and the melting coefficient (taken 5 mm / deg. per day). When determining the characteristics of autumn moisture, the layer of melted snow is summed up with the amount of liquid precipitation.

The results showed that the value of indirect autumn moisture in the above representative years of field studies of washout varies from 28.9 mm to 57.6 mm. This indicator correlates with the module of the autumn surface runoff of analogous rivers and the average measured values of soil washout (table 8). At the same time, the experimental values of washout correlate less strongly with quantitative data on spring surface runoff. This may be due to the fact that low autumn moisture, especially with increased snow accumulation, can increase the infiltration capacity of the soil cover and reduce erosion. Thus, 2010 was marked by high values of melt surface runoff (208.73 l / s × km²) and good snowmelt, but low autumn soil moisture. High snow accumulation and low autumn moisture (28.9 mm) reduced cold reserves in the soil, the average washout in this year was the minimum over the period of field observations (4 mm).

Table 8. Hydrological indicators and soil washout in the Dolgiy Log area (representative sample 2009-2011).

| Year | M max, l / s × km² (according to the method of A.V. Petenkov, Dolgy Log stream) | Snow reserve and precipitation during the period of snow melting (S + X), mm | Calculated indicator, mm | Prior autumn moisture | Drain module M, r. Buzim, vil. Malinovka (October + November, for the previous year), l / s × km² | Drain module M, r. Nizhnyaya Pod’yomnaya - vil. Bolshaya Murta (October + November, for the previous year), l / s × km² | Average flush, mm (section Dolgiy Log) |
|------|----------------------------------------|--------------------------|-------------------------|-------------------|-----------------------------|---------------------------------------------|-----------------------------------|
| 2009* | 110.82 | 242.9 | 123.4 | 57.6 | 1.9 | 7.2 | 15.5 |
| 2010 | 208.73 | 30.0 | 154.9 | 28.9 | 1.2 | 3.7 | 4 |


Note: *) the calculated values for the rest of the observation years (2009-2019) are in the range of values of the indicated representative sample.

5. Conclusion
Based on the results of observations and calculations, the following conclusions can be drawn.

- The values of the maximum spring and rainfall surface runoff in the study area are generally comparable to each other. The ratio of their values varies depending on the water availability.
- Log Dolgiy stream belongs to the drying up watercourses, its flow rate is less than the full drainage flow.
- In 2010, the value of the modulus of the maximum spring surface runoff in the study area was the highest in the years of research.
- The value of the maximum spring surface runoff in the catchment area of the Log Dolgiy stream with the same flow rate is significantly higher than that of analogous rivers. The reason for this is the reduction of the surface runoff module over the catchment area.
- Amount of soil washout correlate well with the previous autumn moisture and weakly with the value of spring surface runoff. Low autumn moisture, especially with increased snow accumulation, can increase the infiltration capacity of the soil cover and reduce erosion.

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