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PHYSICAL-STATISTICAL MODEL FOR FORECASTING MAXIMUM SNOWMELT-INDUCED STAGES (THE OB RIVER NEAR THE CITY OF BARNAUL AS A CASE STUDY)

Samoilova S. Yu., Mardasova E. V., Kolomeytsev A. A.

Abstract For the regions with a long-term snow cover, the amount of solid precipitation is one of the driving factors in the formation of floods. The article considers the possibility of using the orographic correction to the velocity of vertical movements of air masses due to the relief in estimating winter precipitation and forecasting maximum snowmelt-induced stages. The significant influence of autumn freezing on the floodplain inundation and, accordingly, maximum water levels of the Ob River near the city of Barnaul is shown.

Key words: Upper Ob basin, medium-term forecast, maximum water levels, Barnaul, winter precipitation, snow reserves, orographic correction to the velocity of vertical movements

AMS Mathematics Subject Classification: 86A05, 62H20.

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1 Introduction

Occurrence of maximum floods on Siberian Rivers with long cold periods depend primarily on the amount of accumulated solid precipitation (snow reserves). For the Upper Ob basin, mostly located in the Altai Mountain Region, it is hard to estimate atmospheric precipitation because of highly heterogeneous landscapes and climatic conditions, as well as a rare network of weather stations not covering the slopes and peaks of the mountain ranges where maximum snow reserves are formed. To estimate snow reserves in the mountain watersheds, it is reasonable to use the regional models of precipitation distribution with due regard for the relief features (elevation, slope exposure, slopes, proximity to the orographic barrier, etc.) and landscapes. Among the promising methods for assessing atmospheric moisture for a complex relief are the models of the orographic precipitation component based on changes in the orographic correction to the velocity of vertical movements of air masses due to a relief [1–4]. Such a model was developed by V.P. Galakhov to evaluate snow reserves in the mountainous regions of Western Siberia [5, 6].

Owing to this model, the calculated solid precipitation amounts were successfully used as the main predictor in forecasting volumes and maximum flood levels on the tributaries of the rivers Ob [7–9] and Yenisei [10]. It is worth noting that the model demonstrates better results than the absolute elevation dependence of precipitation traditionally applied in hydrological forecasts [10]. The article presents a physical-statistical model built on the relationships between winter precipitation amounts and maximum snowmelt-induced stages of the Ob River. This model is applicable to forecasting dangerous hydrological phenomena at the city of Barnaul.

2 Object of study

During our investigation, the section from the Upper Ob up to Barnaul city was studied. The Ob River is predominantly characterized by snow alimentation. In terms of hydrologic regime, the Ob is a river with spring-summer floods providing on average 65% of annual runoff. Floods begin early April and late July. Usually two flood waves occur on the Ob: the first is formed due to snowmelt on flat, foothill and low-mountain parts of the basin, whereas the second – on mid- and highlands.

The main volume of the Ob River near Barnaul (about 75%) is provided by the rivers Biya and Katun (Table 1). During the flood period, the volume share of these rivers may exceed 80%. Runoff from foothills and low-mountain watersheds is discharged into the Ob River floodplain. The Biya River is regulated by Lake Teletskoye and, hence, does not play a decisive role in the formation of maximum levels near the city of Barnaul.

Table 1: Main hydrological characteristics of the Ob River and its tributaries

River–gauge	Year of establishment	Watershed area, km^2	Average annual discharge, m^3/s	Annual runoff, km^3/year
Biya–Biysk	1894	36900	471	14.9
Katun–Srostki settlement	1919	58400	616	19.4
Peschanaya–Tochilnoye village	1931	4720	34	1.1
Anui–Anuisky farm	1961	4870	31	1.0
Charysh–Charyshsky farm	1933	20700	192	5.9
Alei–Aleisk	1953	18700	34.8	0.95
Ob–Barnaul	1893	169000	1470	46.4

From the data analysis of flow hydrographs of the Ob River it follows that the surface runoff of the Katun River is responsible for maximum stages formation near Barnaul. As a rule, maximum water levels of the Ob are noted during the second flood wave, i.e. at the end of May – beginning of June. In some years, a short-term rise in water level may be caused by heavy rainfalls.

Height of a water rise depended on a water content of the year and varied within 4.5 m. At the Barnaul gauging station, a water level was maximum (737 cm) in 1969 and minimum (285 cm above gauge zero) in 2012. Water discharge into the floodplain was recorded at levels above 500 cm, and economic facilities inundation – above 560 cm.

3 Calculation of precipitation amounts for the cold period

In this study, a distributed model that takes into account the orographic correction to the velocity of vertical movements is used to construct the maps of annual winter precipitation and to calculate their averages for the basin. It depends on surface slopes, absolute elevation of the terrain, velocity and direction of prevailing air masses. A detailed algorithm for calculating the orographic correction is given in the monograph [6]. The matrix of the orographic correction has been built for the territory of the Upper Ob basin with a grid spacing of 25x25 km (Figure 1).

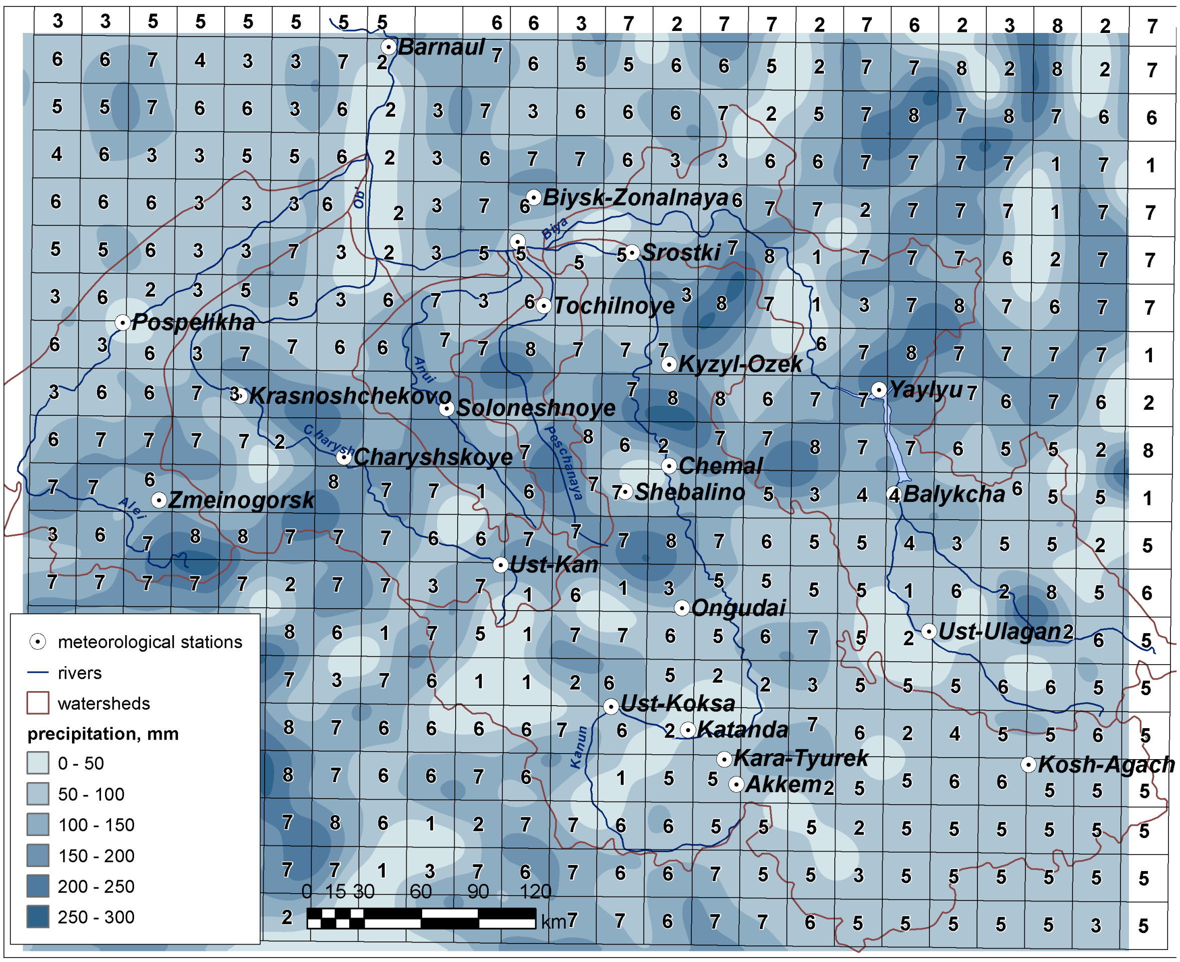

Figure 1: Matrix of the orographic correction to the velocity of vertical movements in the Ob basin up to the Barnaul section and long-term precipitation for the cold period (November-March). *The grid spacing is 25 km. 1 from -1 to -0.5; 2 from -0.5 to -0.1; 3 from -0.1 to -0.01; 4 from-0.01 to0; 5 from 0 to 0.01; 6 from 0.01 to 0.1; 7 from 0.1 to 0.5; 8 from 0.5 to 1 m/s. The value of the orographic correction (Vz) refers to the lower left corner of the square.*

The observational data on atmospheric precipitation at meteorological and gauging stations are used as input information of the model. For each year, precipitation X for the cold period (from November 1 to March 31) is determined. Then, a dependence

$X = f(Vz)$ is derived based on the obtained values of X and the orographic correction to the velocity of vertical movements Vz for each weather station.

Figure 2 shows the dependence of the average long-term precipitation for the cold period (November–March) and the orographic correction to the velocity of vertical movements. The dependence demonstrates a close ($R^2 = 0.81$) relation between the precipitation amount in the mountain basin and the orographic correction. Consequently, similar relationships can be used to estimate annual precipitation. The data on the flat weather stations, including Kosh-Agach w.s. located at the bottom of a large intermountain basin, deviate from the dependence. Apparently, it is associated with the redistribution of snow caused by blizzard events.

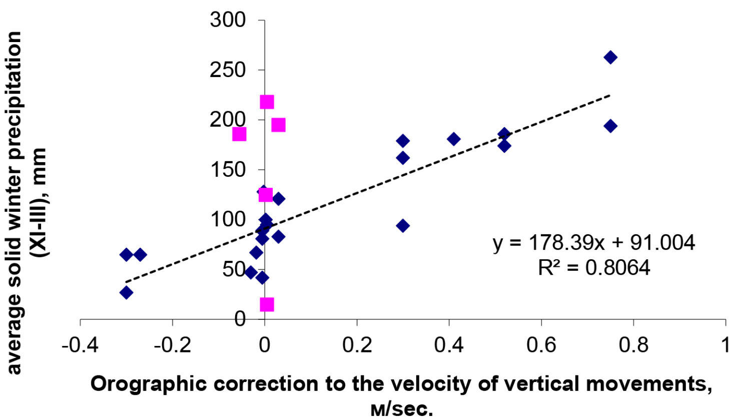

Figure 2: Relationship between the orographic correction and the average long-term precipitation for the cold period (XI-III). "Squares" show flat weather stations: Barnaul, Biysk, Srostki, Tochilnoye (above) and Kosh-Agach (below). The graph was built based on the data from [5].

Using the obtained regression equations $X = f(Vz)$ and matrices of the orographic correction, a series of winter precipitation maps for the Upper Ob basin were constructed in the ArcGis environment. Examples of maps are given in Figure 3. The winter of 1968–1969 was snowy, and the year was one of the wettest in the history of observations. In the year (2012) with an extremely low water content, the amount of winter precipitation was close to minimum.

4 Relationship between precipitation amounts for the cold period and maximum levels of the Ob River near Barnaul

To estimate maximum snowmelt-induced stages, the complex graphs, containing the data on water levels at the Ob–Barnaul g.s., i.e. daily precipitation and air temperature at the representative Ongudai and Kyzyl-Ozek w.s. were analyzed (Figure 4). We excluded maximum levels formed by rainfalls from the analysis at this stage. The research period lasted from 1967 to 1987 (basic) and from 1988 to 2020 (estimated).

From the materials of "Meteorological Monthly" (1967–1987) and "Hydrological yearbook" (1967–1987), we analyzed the dependence of maximum water levels near

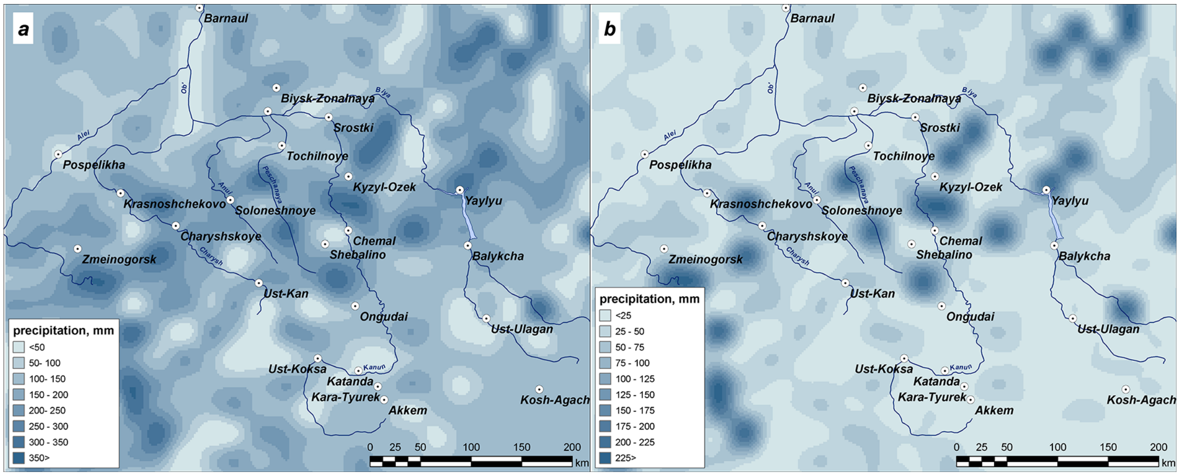

Figure 3: Total precipitation for the winter period (XI-III) in the Upper Ob basin: a – a snowy year (1969); b – a snowless year (2012).

Barnaul on precipitation amounts for the cold period in the mountainous watershed (Katun River basin) calculated with the use of the orographic correction. The coefficient of determination $R^2 2 = 0.71$ is evidence of their close relationship (Figure 5, see equation at the top).

The equation for forecasting maximum levels has the form:

$$H_{max} = 2.3881 \times X + 372.77 \tag{1}$$

where H_{max} – the maximum water level, X – the total precipitation for the winter period (XI-III).

The dependence application to the period 1990s – 2000s suggests that the maximum observed levels were much lower than the calculated ones in some years (Figure 5, see equation at the bottom).

The dependence in Figure 4 does not include the year 2014. The maximum level of 702 cm (corresponding to 3% probability) in 2014 was caused by a catastrophic rain flood superimposed on the second flood wave in late May-early June. In this case, it is hardly possible to determine the maximum snowmelt-induced level. We also excluded from the dependence the year 2012 with its extremely low water content and maximum stage of 285 cm (the difference between the calculated and actually observed levels made up 180 cm). It should be noted that in other years, starting from 1936 (the onset of "Hydrological yearbook" publication), maximum water stages exceeded the mark 439 cm above gauge zero. The reason for insufficient water in 2012 calls for a special consideration.

5 Effect of soil freezing on maximum water stages

In our previous works, devoted to forecasting the volumes and maximum levels of the Charysh River [7, 9], we discussed a significant influence of the absorption capacity of soils (primarily their freezing) on volumes and maximum levels of floods. On average,

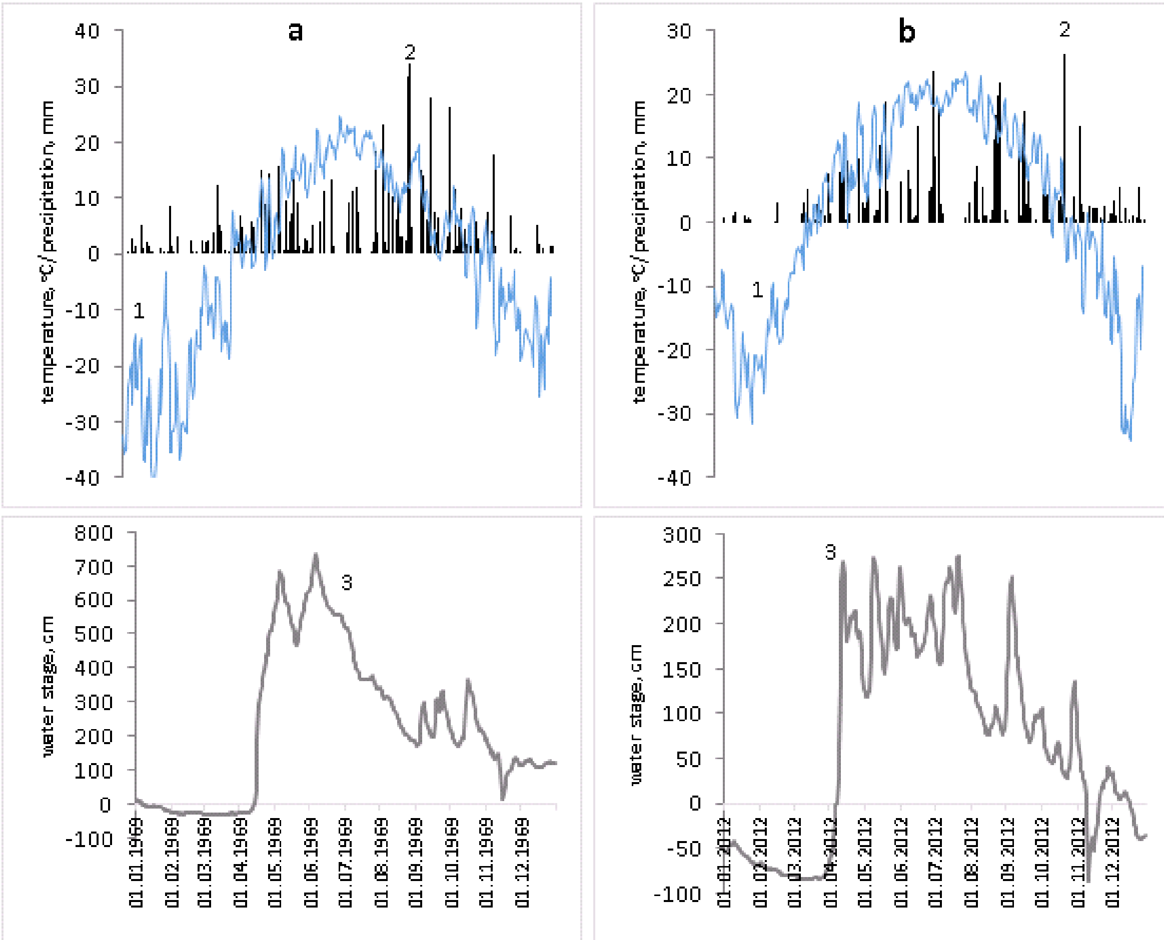

Figure 4: Complex graphs of hydrometeorological elements: a – 1969 (high water content), b – 2012 (low water content). 1 – average daily temperature, 2 – total precipitation (Kyzyl-Ozek w.s.), 3 – water level, cm above gauge zero (the Ob River-Barnaul g.s.).

the depth of soil freezing in the region reaches 80 cm, in snowless sites – up to 2 m or more [11]. Soil freezing is most intensive at the beginning of winter. Among main factors determining this indicator are weather conditions at the initial stage of the snow cover formation in foothills and flat parts of the watershed. If snow depth, formed prior to significant frosts' onset (average daily temperature below 10°C for several days), exceeds 20–25 cm, then it prevents from severe freezing of soils. In this case, large losses of meltwater due to absorption by soils are noted in spring. At the same time, maximum flood levels become 100 cm [7] and runoff depth 50–100 mm lower [9] than in the years when weather conditions contribute to soil freezing. With allowance made for this qualitative characteristic, one can improve flood prediction on the Charysh River [7].

Obviously, the soil state plays a decisive role not only in the Charysh River basin. Since the low-mountain rivers (Alei, Charysh, Anui, Peschanaya, Lebed) form the Ob floodplain at the beginning of the flood period, the maximum possible levels near the city of Barnaul also depend on the conditions in the beginning of snow accumulation

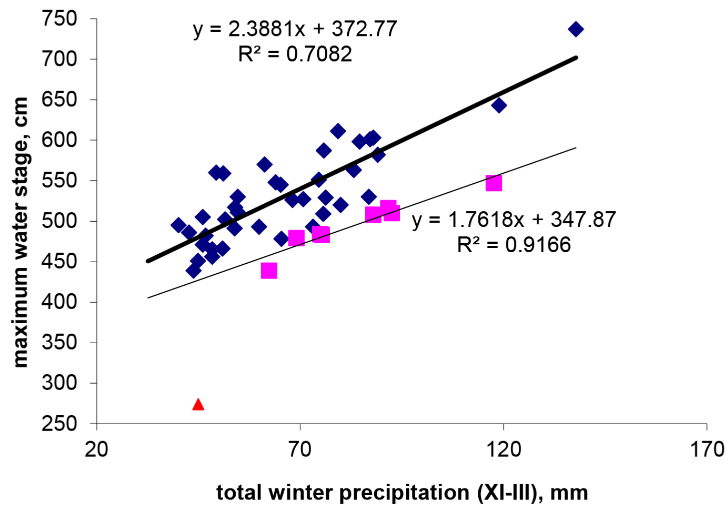

Figure 5: Dependence of maximum levels of the Ob River near Barnaul on precipitation for the cold period (XI-III) in 1966–2020. “Squares” display the years 1994-1995, 1996-1997, 2005-2006, 2012-2013, 2016-2017 and 2019-2020. A “triangle” shows 2012.

in the above-mentioned basins. Analysis of complex graphs of hydrometeorological elements showed that during the study period (1967–2020) the establishment (before severe frosts) of snow cover higher than 20–25 cm was observed during 7 years characterized by weak soil freezing, i.e.in 1994, 1996, 2011, 2012, 2013, 2017, and 2020.

The influence of a soil freezing factor is most pronounced in the snowy years. For example, in 2012–2013 and 2016–2017, the difference between the calculated (by equation 1) and the actually observed maximum levels was more than 1 meter. It is known that snow cover thickness is the most important factor determining the depth of soil freezing in winter, being sometimes more significant than air temperature [12]. Falling out of the bulk of solid precipitation amounts at the beginning of winter increases the influence of this factor [13].To assess the effect of soil freezing on water levels in the Ob River, let us consider the «calculation error» , i.e. the difference between the real and predicted maximum snowmelt-induced stage (derived from equation 1) and winter precipitation amount, which indirectly characterizes snow cover depth (Table 2, Figure 6).

The relationship is characterized by the coefficient of determination $R^2 = 0.84$. The maximum stage resulting from the catastrophic flood of 2014 was not included in our calculations. In 2012, the extremely low level of flooding was obviously caused not only by weak soil freezing, but also by preceding extremely low-water summer-autumn and winter low-water periods. The minimum level in the history of observations – -96 cm above gauge zero– was observed in November 11, 2011. In March 2012, it reached – 85 cm (60–70 cm lower than usual) thereby indicating a very weak autumn-winter moistening of the watershed, which contributed to considerable losses of meltwater runoff during the snowmelt period. Pre-winter moistening of the basin, along with a depth of freezing, was the most important factor determining the water absorption capacity in the basin [14,15]. Since this factor was not taken into account in the model at this study stage, the year 2012 was excluded from the calculations of the correction (Figure 6).

Table 2: Maximum levels in years with weak soil freezing and lack of floodplain inundation near Barnaul

Year	Date	Maximum observed level H_{max},cm	Forecasted maximum level,H_{max}, cm	Forecast error ΔH, m	Total precipitation of the cold period in the Katun basin, mm
1994-95	20.05	508	583	0.75	88
1996-97	18.04	479	538	0.59	69
2002-03	04.05	484	552	0.68	75
2012-13	02-03.05	493	590	0.97	93
2016-17	24.05	547	653	1.06	118
2019-20	07.05	516	592	0.76	92

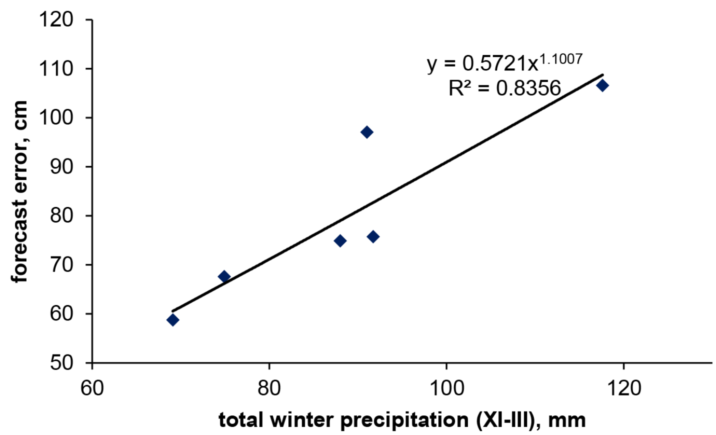

Figure 6: Relationship between the real and calculated snowmelt-induced stage and winter precipitation amount.

When calculating maximum water levels of the Ob River near Barnaul, the correction is estimated within 0.6 - 1.1 m (depending on precipitation amounts during the cold period) in the case of a stable snow cover (exceeding 20-25 cm) formed before the onset of significant frosts.

Conclusions

Thus, the use of the orographic correction makes it possible to reliably estimate the amount of winter precipitation in the basin of a large river (Upper Ob) with a complex orography. The relationship between maximum level of the Ob and winter precipitation is characterized by the coefficient of determination $R^2 = 0.71$. The established dependence can be used for a medium-term forecasting of dangerous hydrological phenomena caused by snowmelt at the city of Barnaul.

In some years, when a stable snow cover of 20–25 cm is formed before the onset of frosts and significant soil freezing, the increase in losses of meltwater runoff due to absorption should be allowed in maximum level calculations. This requires the correction of 0.6–1.1 m, depending on the total winter precipitation. The presented physical-statistical model does not take into account the influence of liquid precipitation during flood recession and can be used in medium-term forecasts provided that the meteorological conditions of the flood period are close to the long-term average. During flooding, maximum snowmelt-induced levels must be adjusted with due regard for weather conditions. In the future, when assessing the capacity of water absorption by soils, it is reasonable to introduce a predictor characterizing the pre-winter moistening of the basin.

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Samoilova S.Yu.,
Institute for Water and Environmental Problems, Siberian Branch of the Russian Academy of Sciences (IWEP SB RAS),
1, Molodezhnaya St., 656038 Barnaul, Altai Krai, Russian Federation,
Email: bastet@iwep.ru

Mardasova E.V.,
Institute for Water and Environmental Problems, Siberian Branch of the Russian Academy of Sciences (IWEP SB RAS),
1, Molodezhnaya St., 656038 Barnaul, Altai Krai, Russian Federation,
Email: mardasova_ev@mail.ru

Kolomeytsev A.A.,
Institute for Water and Environmental Problems, Siberian Branch of the Russian Academy of Sciences (IWEP SB RAS),
1, Molodezhnaya St., 656038 Barnaul, Altai Krai, Russian Federation,
Email: kolomeycev@iwep.ru

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