Water level regime of the Maima River (Altai Mountains) in the context of modern climate change

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Abstract. Changes in the water level regime of the Maima River are studied in relation to observed climatic changes. The increased air temperature and decreased precipitation during the cold period leads to a decrease in the maximum flood level and a shift to later dates. A high correlation between the water level and precipitation is revealed in the period of summer and autumn low water. The trends in the mean and minimum water levels of the summer and autumn low-water periods are determined by the trends in the air temperature. Positive trends of the air temperature in the summer and autumn low-water periods contribute to the accumulation of water heat. Thus, due to the increase in the heat content of water mass and temperatures of November and December, the maximum water levels in the floods caused by sludge formation and ice jamming are becoming lower. Our analysis of the hydrological regime is based on Roshydromet monitoring data from 1940 to 2015 at a gauging station located in a village called Maima. The data on the monthly averaged air temperature and rainfall were obtained from a weather station in a village called Kyzyl-Ozek.

Keywords: Mayma River, Altai Mountains, water level, water regime, modern climate changes

1.Introduction

Modern climate changes reveal themselves in the growth of global air temperature and regional redistribution of precipitation. Being formed by the climatic processes, the rivers respond to changes in the meteorological conditions with changes in their hydrological regime. Thus, the influence of climate change in most regions of Russia in the recent decades leads to noticeable changes in the seasonal and annual runoff of the rivers, increase in the frequency of extreme hydrological events, including the extreme summer low water levels, disastrous flash floods, and snowmelt floods [1].

By the end of the 1990s, a systematic and uneven increase in the air temperature in all regions of Siberia had a higher trend than for the whole planet, and for the territory of Altai Mountains the greatest warming was observed in the winter and spring seasons [2,3]. Since the beginning of the 2000s, there has been a slowdown in the growth of average annual air temperatures; for Siberia this process is due to the formation of cold spots in winter [4]. Since 2010, the area of winter cooling has been observed in the south of Western Siberia, covering the Altai region [1]. In such conditions, study of the impact of climate change on the hydrological regime of the Altai Mountain rivers requires a special attention.

The rivers of the Mountain Altai play a key role in the formation of an overland flow in the Upper Ob basin, and in the territory of the Republic of Altai the river water resources are used to provide water to enterprises and the population, for irrigation, recreation, fishing, hydropower engineering, stormwater and wastewater disposal [5]. It is noted that the observed climatic changes lead to an increase in the winter runoff and a decrease in the spring runoff and to an increase in the frequency of extreme hydrological events of the Altai rivers [1, 6].

For better understanding of the current trends in the climate-induced changes in the hydrological regime of the rivers of the Mountain Altai, this paper proposes to consider the level regime of the Maima River for the 1940 to 2015 observational period. According to D. V. Zolotov et al. [7], the Maima river basin is characterized by unity in the conditions of flow formation and, thus, it can be a suitable model object for landscape and hydrological studies representative for the whole Altai region in the conditions of lack of hydrometeorological information. In addition, the Maima river basin is already being used as a model object for hydrometeorological research: its territory has an IMCES SB RAS autonomous remote monitoring system providing information about the environmental conditions [8]. The interest in studying Maima is also determined by the fact that this river flows through the capital of the Altai Republic – the Gorno-Altaisk city, which suffered a significant damage as a result of an extreme water level rise in May 2014.

2. Object and methods of study

Maima is a small river in the north of the Altai Republic, a right tributary of the Katun River. It originates on the ridge Iolgo southward of the Urlu-Aspak village, Maiminsky district. The catchment basin of Maima is confined to a low- and mid-mountain, moderately humid, and forest region in North Altai, 780 km^2 in area. The length of the river is 57 km, the highest point is 800 m, and the average elevation is 670 m. The tributaries of Maima are more than 20 minor rivers and streams up to 10-25 km long, with no glaciers or lakes present in the catchment. The mean annual discharge at the main-stream station (Maima village) is 8.66 m^3 / s, and the average annual water level during the snowmelt flood is 3.4 m. According to the type of water regime, Maima refers to rivers with spring snowmelt floods and summer flash floods. About 45% of the runoff is the spring runoff and 30 %, the summer runoff [9, 10]. The basin of Maima has one gauging station at the Maima main-stream (Maima village) and one long-functioning weather station, also located in the lower reaches of the basin at Kyzyl-Ozek village.

The analysis of the hydrological regime was based on the Roshydromet observational data of the Maima village gauging station from 1940 to 2015. Data on the monthly average air temperature and precipitation at the weather station in the village of Kyzyl-Ozek were obtained using the service RIHMI-WDC [11]. When calculating the correlation coefficients, the linear trend was removed from the original series. The estimation of the reliability of trends and correlation coefficients was performed for a 0.05 significance level. The following boundaries of the hydrological seasons have been adopted: the winter low water season - XI-III, the snowmelt flood - IV-VI, and the summer and autumn low water season - VII-X. The cold period is a period with negative mean annual air temperatures (November to March), and the warm period has positive temperatures (April to October).

3.Results and analysis

3.1. Air temperature and precipitation

The beginning of the period of modern climate change is considered to be 1976, and since that time the most intense increase in the air temperature has been observed, in particular, in Altai region [12]. The territory of Mountain Altai is generally characterized by a simultaneous increase in the annual air temperature, a decrease in the precipitation in winter, its increase in summer and increase in their spatial heterogeneity [6, 13]. An increase in the late and early ground frosts, extension of the ranges of maximum and minimum temperatures, as well as an increase in the aridity indicate an increase in the climate extremity [6].

Data on the air temperature and precipitation observations at the weather station in Kyzyl-Ozek are available from 1940 to 2016 [11]. According to the available data, the average long-term air temperature during the observation period is + 2.1 °C (Table 1). Minimum temperatures are observed in January, and maximum ones in July. During the period under review, the values of linear trends in all months are positive and significant in almost all months. The maximum rate of temperature increase (linear trend coefficients up to 0.66 °C per 10 years) is typical for the cold season except for January and April. The maximum precipitation was observed from June to August, and the lowest one in January and February (Table 1). No significant trends of precipitation distribution between the months were found for the observation period. When considering the amount of precipitation for the warm (April to October) and cold (November to March) periods, it was found that a significant decrease in the precipitation is only in the cold period, the coefficient of the linear trend is 6.9 mm per 10 years. Over 77 years of observations, the dynamics of annual precipitation was determined mainly by the precipitation of the warm period (correlation coefficient: 0.9).

Table 1 Average annual values of air temperature and precipitation.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Temperature, °C	-14.7	-13.7	-6.8	3.5	11.5	16.6	18.6	16.2	10.3	3.2	-6.5	-12.4	2.1
Linear trend coefficient (temperature), °C/10 years	0.18	**0.57**	**0.66**	**0.48**	0.14	0.10	**0.12**	**0.17**	**0.14**	**0.18**	**0.52**	**0.45**	**0.31**
Precipitation, mm	24	24	32	57	80	99	111	100	73	65	51	38	755

* Coefficients of linear trends which are reliable at a significance level of 0.05 are shown in bold.

To analyze the seasonal and annual dynamics of the air temperature and precipitation, their anomalies were examined with respect to the climatic norm recommended by WMO in 1961-1990. It can be seen for the air temperature series that a stable transition of the 11-year sliding average through zero has been observed since 1976 (Figure 1), which is consistent with the beginning of the period of modern climate change. Between 1976 and 2016, negative average annual temperature anomalies were observed in the mid-1980s and late 2000s to early 2010s, and they were due to a drop in the temperatures of both the warm and cold periods. The total precipitation, both for the year and for the seasons, is, on average, below the climatic norm of 1961 to 1990.

The rise in the air temperature in the cold period may be the result not only of general warming, but also of the increase in the number of days with thaws observed in the south of Western Siberia [14]. Along with the cold period warming, for the Altai Mountains there is a decrease of the duration of the stable frost period [14], which may affect the breakup and freeze-up dates of rivers. The climatic norm of 1961 to 1990 covers both the background period of 1940-1975 and the period of modern climate change since 1976, and so the trend of changes in the meteorological parameters with respect to the climate norm may be less expressed than with respect to the background period. For example, the increase in the air temperature in 1976 - 2016 relative to the annual climatic norm in the warm and cold periods is 0.8 °C, 0.7 °C, and 1 °C, respectively, and relative to the background period it is 1.4 °C, 0.9 °C, and 2.2 °C, respectively. The precipitation relative to the climatic norm for the year, in the warm and cold periods decreased by 19.1 mm, 4.9 mm, and 10.9 mm, respectively, and relative to the background period it decreased by 37.2 mm, 6.2 mm, and 32.2 mm, respectively.

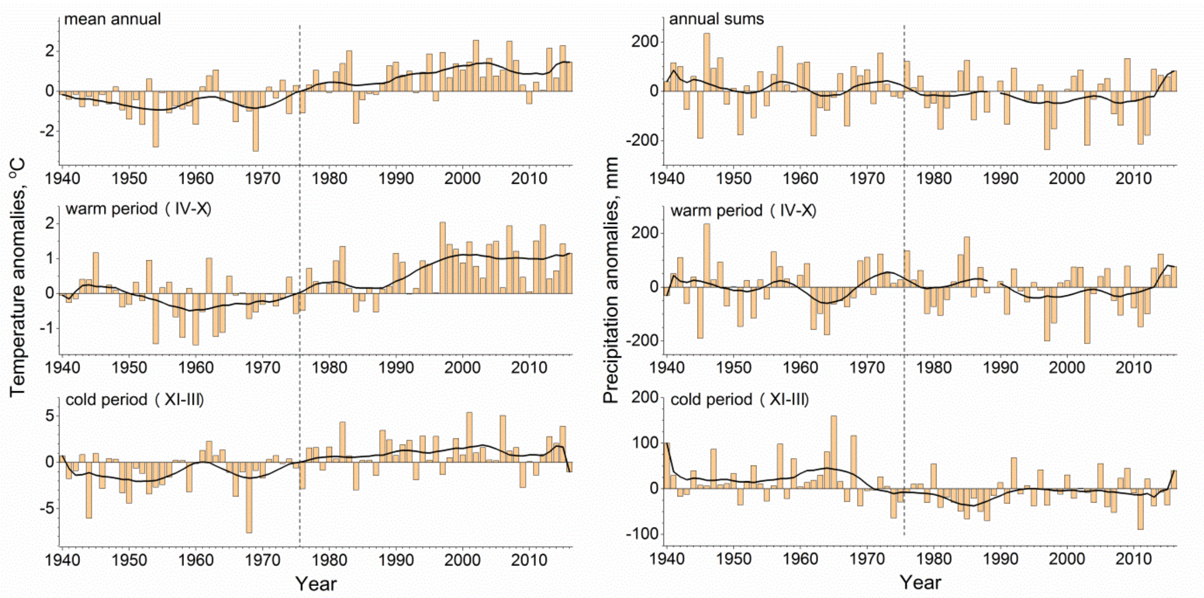

Figure 1. Annual and seasonal anomalies of mean temperature and total precipitation relative to the climate norm of 1961 to 1990, smoothed by 11-year sliding average.

3.2. Maximum water level in the snowmelt flood

The maximum water level in the snowmelt flood is determined by the moisture reserves in the snow deposits at the beginning of snow melting, the index of autumn wetness, the liquid precipitation in the snowmelt period, the severity of winter, and other parameters. According to V.P. Galakhov [15], the overwhelming part of the flood volume of the Maima River is formed by snow melting in the catchment area. Analysis of the dynamics of the annual course of the water level for the entire period of observations showed that the average spring rise in the water level begins in March, and the decrease of the flood is recorded in June; the average date of the flood peak is April, 17. Trends in the changes of the maximum water level, the date of its occurrence, the air temperature and precipitation of the cold period become apparent in the approximation of the observations series by the 3rd degree polynomial (Figure 2).

Figure 2 shows that since the beginning of the modern climate change (1976) the maximum of high water has been decreasing with an increase in the recent years (Figure 2a). Thus, the average maximum flood level in 1940 - 1975 was 333 cm, and in 1976 - 2015 it was 297 cm, i.e. the average changes were 36 cm. A similar trend is observed in the precipitation in the cold period, while the temperature in the cold period has an opposite trend (Figure 2b). The increase in the air temperatures and the number of thaw days during the cold period contributes to a decrease in the depth of soil freezing and early water yield from the snow deposits. This leads to spreading of the groundwater forming the surface runoff. As a result, the snow deposits towards the beginning of the spring snowmelt are reduced, and taking into account the decrease in the amount of precipitation in the cold period this creates conditions for a decrease in the maximum flood levels. The correlation coefficients of the maximum flood level series with the series of air temperature and precipitation in the cold period are low but significant. The highest correlation between the flood levels and temperature is observed in January to March with a correlation coefficient of 0.37. For precipitation, the correlation coefficient is 0.31. It is obvious that the main contribution to the formation of the maximum flood level is made by the snow cover water storage at the beginning of the snowmelt, however, the consistency of the trends of the considered parameters indicates their high interdependence in the long term.

The lowest flood maximums are typical for 1980 - 2000; in this period the maximum levels (Figure 2a) were observed mainly in the second half of April and in early May. With a low amount of precipitation in the cold period in 1989, 1990, 1994, and 2014, the late occurrence of maximum levels is associated with the intense liquid precipitation. For example, the extremely high flood level observed at the end of May in 2014 was caused by a two-month mean rainfall in the foothills of Altai during one week [16]. The late dates of the maximums not caused by the rainfalls are probably associated with a lower depth of soil freezing during the winter period and their faster thawing in the spring. Under such conditions, there is an intensive seepage of the melt water deep into the soil, resulting in a decrease in the proportion of the slope runoff and the rate of water flow into the river. Thus, the date of the flood maximum is shifted to a later date.

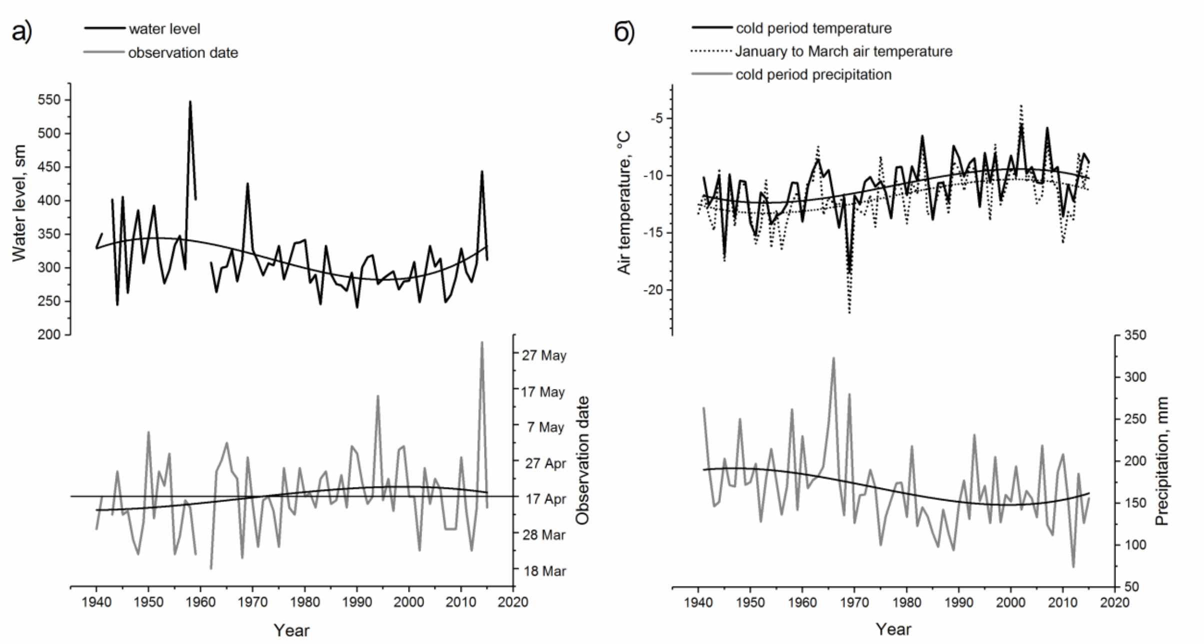

Figure 2. Variations of the maximum flood level and its dates (a); air temperature and precipitation in the cold period of the year (XI-III) (b); with a 3rd degree polynomial approximation.

3.3. Minimum level of summer and autumn low water season

The period of summer and autumn low water season for the Maima River is characterized by a minimal annual value of the water level. During this period Maima has mainly groundwater and precipitation feed. Therefore, the correlation between the water level and precipitation in the summer and autumn low water season is obvious. An increase in the air temperature, in turn, affects the free-water surface evaporation, which may result in a decrease in the water mass and, consequently, in the water level [17]. Approximation of the studied observation series of the water level and meteorological parameters by a 3rd degree polynomial shows that the trends of the minimum and average water level and the trend of average air temperature are opposite (Figure 3). At the same time, there are no obvious trends in the amount of precipitation. Nevertheless, there is a strong correlation between the series of precipitation and the average water level in the summer and autumn low water season (the correlation coefficient for the entire observation period is 0.73). A significant correlation between the water level and the air temperature is only in 1976 - 2015 with a correlation coefficient of -0.6.

In the period of modern climate change, the dates of the summer and autumn minimum shifted to earlier ones: in 1940 - 1975 the minimum water level was observed mainly in August to October, and in 1976 – 2015 in July to September. It should be noted that the increase in the air temperature in the warm period affects the biological regime of Maima. For example, an intensive growth of grass in the riverbed was observed in 1994 - 1995, 1998, and 2000 - 2001 as a result of favourable temperature conditions. This fact indicates an increase in the heat content of the water mass in the summer and autumn low water season.

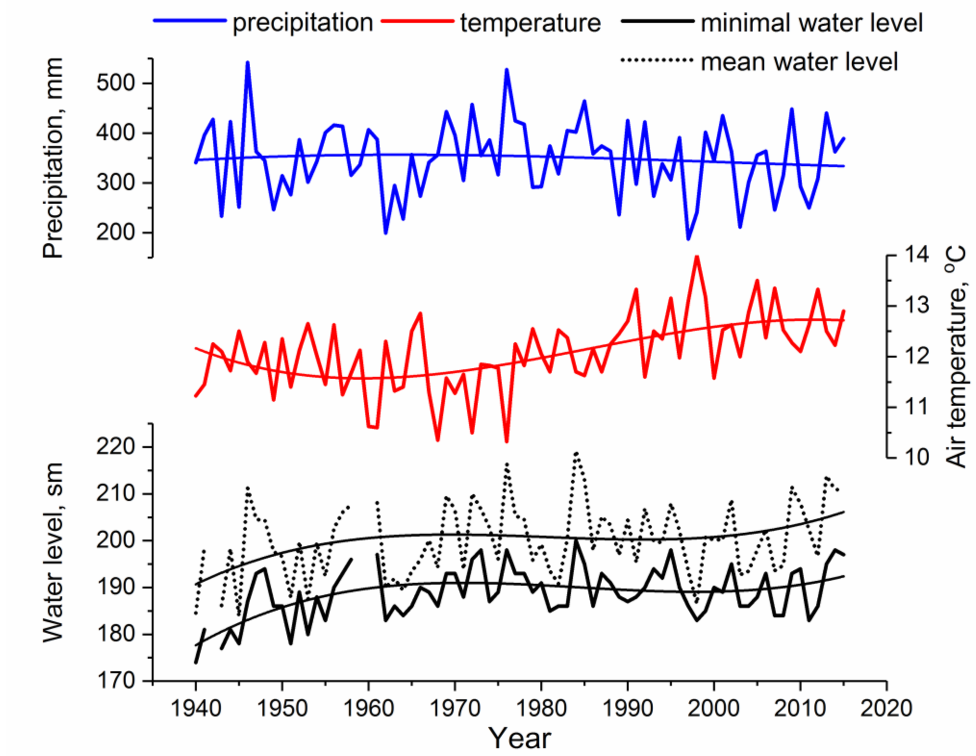

Figure 3. Variations of the mean and minimal water level, air temperature, and precipitation in summer and autumn runoff low; with a 3rd degree polynomial approximation.

3.3. Maximum winter level

The beginning of the freeze-up period for most Altai Mountain rivers is characterized by the formation of ground- and needle-ice – sludge [6,10]. The sludge is formed from supercooled water under intensive turbulent mixing typical for mountainous rivers with fast currents and rock bedding. Ice slush and ice jams on the rivers of Altai Mountains often cause a considerable rise of the water level [10]. For the Maima River the winter level rise caused by ice slush and ice jams is observed mainly in November and December, and in some cases it exceeds the mean annual snowmelt flood level (313 cm). Figure 4 shows the variations in the maximum and mean water levels, as well as the average air temperature in November and December. Values of the water levels exceeding the mean annual maximum of the high water are observed in 1946 - 1947, 1957, 1965, 1974, and 1976, and they are caused by the ice jam at the beginning of ice formation with a fast drop in the air temperature. Since 1976 winter water levels exceeding the mean annual flood maximum are not observed; on the contrary, there is a steady trend towards their decrease with a linear trend coefficient of 14 cm per 10 years. On average, the maximum water level in November and December in 1940 - 1975 was 268 cm, and in 1976 - 2015 it was 257 cm, i.e. it decreased by 11 cm for the period of the current climate change. However, despite the decrease in the maximum winter level, the Maima River is characterized by an increase in the winter runoff [17]. This is due to less soil freezing in softer winters and snow melting in frequent thaw periods, providing additional snow feed.

It should be noted that despite the warming slowdown in the 2000s and the decrease in the temperatures of the cold period in the late 2000s and early 2010s, the average temperature of November and December has a stable positive trend (Figure 4). The increase in the air temperature leads to a decrease of the maximum and mean water levels in November and December. Thus, the correlation coefficient between the series of November and December mean water levels and the air temperatures for the entire period of observations is -0.35, while in 1976 - 2015 the correlation coefficient increases to -0.55. The intensity of ice slush formation is also determined by the heat content of the water mass accumulated during the summer and autumn low water season. The correlation coefficient of the water levels in November and December and the air temperature of the summer and autumn low water season for the entire period of observations is -0.39 with an increase to -0.44 in 1976 - 2015.

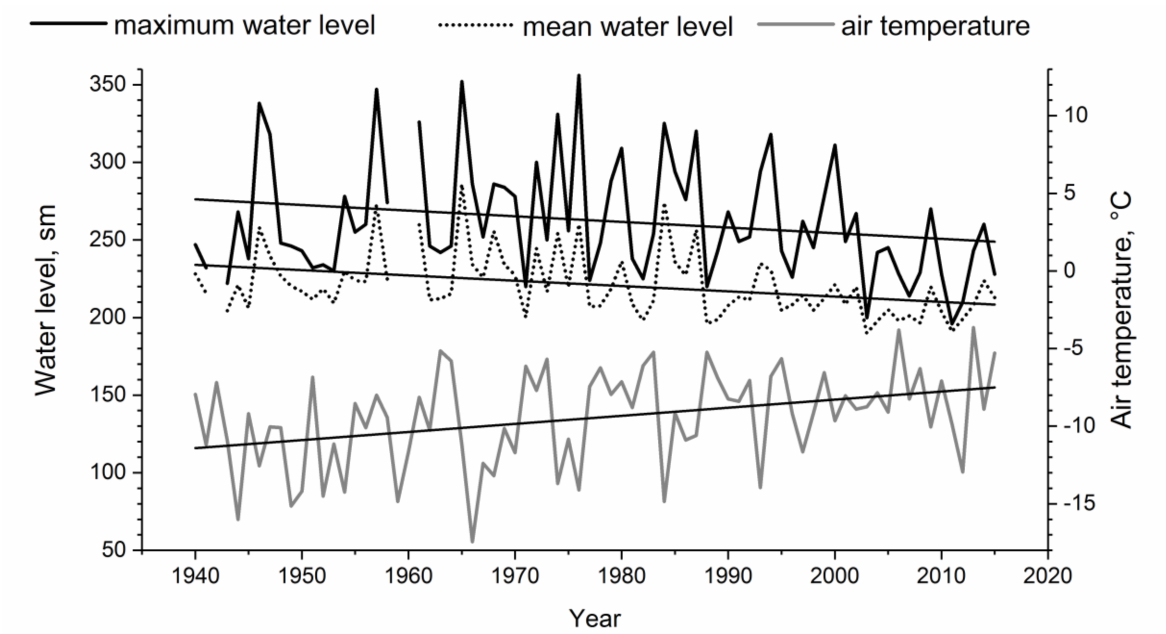

Figure 4. Variations of maximum and mean water levels and average air temperature in November and December, with linear trends.

4.Conclusions

Analysis of the Maima water level changes, air temperatures, and rainfall in the catchment area has revealed that:

- The trends in the maximum snowmelt flood level during the period of instrumental observations are determined by the trends in air temperature and precipitation of the cold period. These parameters, although they are not the main factors determining the maximum of snowmelt flood, affect its trend (the correlation coefficients of the level and the temperature and precipitation are -0.37 and 0.31, respectively). Thus, the 36-cm decrease in the mean snowmelt flood level in 1976 - 2015 in comparison with 1940-1975 is due to both the decrease in the amount of frozen precipitation and warming of winters which results in the earlier snow melting and in the decrease of the depth of soil freezing. In this case some part of the snowmelt water forms the winter runoff, and some part of it seeps into the thawed soil, which ensures a longer water yield and a lower snowmelt flood level.
- In the period of summer and autumn low water season the Maima River is characterized by a high dependence of the water level on the amount of precipitation (the correlation coefficient is 0.73). However, the trends of mean and minimum level of summer and autumn low water season are determined by the trends of air temperature during this period. A significant correlation between the water level and air temperature (the correlation coefficient is -0.6) appears only in 1976 - 2015, which indicates an increase in the contribution of evaporation to the formation of summer and autumn low water season levels in the period of climate warming.
- The rise in the water level in November and December caused by the ice slush formation and ice jams depends on both the temperature of November and December and the temperature of

the summer and autumn low water season, which is an indicator of the water mass heat content (the correlation coefficients are 0.35 and -0.39, respectively). In 1976 - 2015, the contribution of November and December temperatures to the formation of the maximum winter level in comparison with the contribution of summer and autumn low water season temperatures increases (the correlation coefficients are 0.55 and -0.44, respectively). Thus, the general increase in air temperatures is followed by a decrease in the maximum winter water levels, which indicates a less intensive ice slush formation.

References

[1] The Second Roshydromet Assessment Report on Climate Change and its Consequences in the Russian Federation. *Roshydromet Climate Centre* Electronic resource: http://cc.voeikovmgo.ru/ru/publikatsii/2016-03-21-16-23-52 (retrieved 06/2018)
[2] Ippolitov I I, Zadde G O and Kabanov M V 2003 The regional peculiarities of recent climatic ecologic changes in Siberia *Tomsk State University Journal* 3(IV) 174-78
[3] Suchova M G and Modina T D 2007 Modern change the temperature of the air and precipitation on Altai, as manifestation of the Regional change the climate *The world of science, culture and education* 2 14-8
[4] Ippolitov I I, Loginov S V, Kharyutkina E V and Moraru E I 2014 Climate variability over the Asian territory of Russia in 1975–2012 *Geography and Natural Resources* 4 13–21
[5] Report on the state and protection of the environment of the Altai Republic in 2016 *Official website of the Altai Republic* Electronic resource: http://www.altai-republic.ru/society/doklad_nature_2016.pdf (retrieved 06/2018)
[6] *Geography of Siberia in the early 21st century* vol 5 *Western Siberia* 2016 ed Vinokurov Yu I and Krasnoyarova B A (Novosibirsk: Academic publishing «Geo») p 447
[7] Zolotov D V, Lubenets L F and Chernykh D V 2012 Landscape factors of runoff formation in the Mayma river basin (North and North-East Altai) *The world of science, culture and education* 2 360-69
[8] Zuev V V, Kurakov C A and Uymanova V A 2017 Combined monitoring of weather-climate and hydrological regime of Mayma river basin (Mountain Altay): first results *Polzunovsky vestnik* 3 70–5
[9] Puzanov A V, Robertus Iu V, Liubimov R V and Kivatskaia A V 2015 Hydrological and hydro chemical aspects of surface runoff in the Maima river basin (the Altai Republic) *Regional Environmental Issues* 1 49–55
[10] Resources of surface waters of the USSR 1969 Altai and Western Siberia Issue 1 Mountain Altai and Upper Irtysh Part 1 ed Semenova V A (Leningrad: Hydrometeorological Publishing House) vol 15 p 316
[11] Bulygina O N, Razuvaev V N and Aleksandrova T M 2013 Description of the data set of daily air temperature and precipitation at meteorological stations of Russia and the former USSR (TTTR) (*Electronic resource* http://meteo.ru/data/162-temperature-precipitation **(**retrieved 05/2018))
[12] Kharlamova N F 2013 *Estimation and forecast of modern climate changes in the Altai region: monograph* (Barnaul: ASU) p 156
[13] Shmakin A B *et al* 2012 The climate of the Altai-Sayan ecoregion, its modern and possible future changes *Regional environmental response to global changes in North-Eastern and Central Asia: Proceedings of the International Scientific Conference (Irkutsk, 7-21 Sept. 2012)* Irkutsk IHP SB RAS **1** 112–17
[14] Mirvis V M and Guseva I P 2007 *Changes in the regime of thaws in the territory of Russia* (St. Petersburg: FGBI «MGO») vol 556 pp 101–15
[15] Galakhov V P 2015 Conditions for formation of flood on small mountain river (the Maima river basin as a case study) *Bulletin of the Altay Branch of the Russian Geographical Society* 3(38) Barnaul 35-40

[16] Zinoviev A T, Koshelev K B, Dyachenko A V and Kolomeitsev A A 2015 Extreme Rainfall and Flood Event of 2014 in the Upper ob River Basin: Causes, Prediction and Field Observations *Water Sector of Russia: problems, technologies, management* 6 93-104
[17] Paromov V V 2012 Intra-annual flow regime of rivers of the Altai-Sayan mountain region, in the context of climate change *Water and environmental problems of Siberia and Central Asia: Proc. All-Russian scientific. Conf. with international participation, dedicated to 25th anniversary of the Institute of Water and Ecological Problems SB RAS (Barnaul, 20-24 Aug. 2012)* Barnaul **1** - Formation of land water resources under natural and anthropogenic impact 121–125