Long-term dynamics of maximum flood water levels in the middle course of the Ob River

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Abstract. Results of statistical analysis of the long-time series of flood maximum water levels in the Ob River middle course (West Siberia, Russia) are presented. Most time series are statistically non-homogeneous at the 5 % level of significance. In most cases, there is a violation of homogeneity in 1959 due to the Novosibirsk HPP flow regulation, but there might be also some natural change. The extremely low maximum levels of 2012 are the “outliers” from probability distribution functions at 5% significance level. In the modern period (after 1959), some downward tendencies in maximum water level change over the middle course of the Ob River cause decrease in the area, depth and duration of floodplain inundation.

1. Introduction
The snowmelt flood period is one of the most important hydrologic seasons of Siberian rivers [1]. Maximum river water levels determine a flood situation on river banks, floodplain inundation conditions and parameters. High hazardous floods cause intensification of fluvial processes, river banks erosion, damage for settlements, engineering constructions and people living in riparian zones. The Ob River and its large lowland tributaries have wide floodplains, the flooding of which affects the rates of gas exchange of river water with the atmosphere, including greenhouse gases emission, which in turn influences the characteristics of climate change. The Ob floodplain is an important source of carbon input into the Arctic Ocean [2]; moreover, it is a unique ecosystem producing a great variety of habitats, species and organic material.

Many studies report changes in water flow of great Siberian rivers and their tributaries [3] including maximum flood water discharges in the Ob basin [4, 5]. The influence of dams, permafrost thaw, fires was considered, “naturalized” water discharge time series at the basin outlet reconstructed and the upward temporal trends in annual and winter stream water discharges estimated [3, 6]. Maximum water levels formation in the rivers of Tom and Irtysh, large tributaries of the Ob, under the flow regulation and influence of ice jams were studied [7–12]. Nevertheless, the changes in maximum flood water levels in the Ob River, especially taking account observations during the last 15 years are considerably understudied.

The goal of the work is to analyze the main characteristic features of the variability of the long-term annual spring–summer flood maximum water levels at nine gauge stations in the middle course of the Ob River, mainly within the Tomsk administrative region, West Siberian Lowland, Russia (Table 1). It is needed for detecting: (1) the limits of statistically homogeneous (stationary) periods in the long-term time series of maximum water levels, (2) tendencies in the observed levels change over time, and (3) estimating the maximum water levels of low probability of exceedance within the studied reach. Based on the study outcomes, it would be possible to analyze changes in the floodplain inundation rates and regime.
2. The study area

The Ob is the third largest northward flowing river in Siberia (Figure 1). Its headwaters are located in the Altai Mountains. The river originates from the confluence of the large mountain rivers of Biya and Katun near the city of Barnaul, drains a total area of $3 \times 10^6$ km$^2$ and contributes about 400 km$^3$ of the annual flow to the Arctic Ocean. The Ob River within the 1,000 km long study reach has polyzonal water regime integrating peculiarities of water runoff formation in all crossed landscape zones. Siberian rivers are characterized by the presence of a high and long spring to summer snowmelt flood and autumn rain floods; a winter low flow period lasts about six months. Maximum water levels in the middle course of the Ob are related to the passage of the spring–summer flood water flow peak, i.e. to maximum water discharges. The intra–annual distribution of water flow in large transit rivers differs considerably from the flow distribution in medium-size rivers.

![Figure 1. Study area and gauge stations in the middle course of the Ob River](image)

The first flood wave in the Ob River coming from the mountainous part of the basin merges with the floods of lowland tributary rivers and in most cases produces the highest water discharges at Novosibirsk. High water flows of the Tom River at Tomsk have several peaks, the first of which is close in magnitude to the maximum of the Ob at Novosibirsk and passes almost at the same time. As a result of the superposition of these waves, the maximum flow rates of the Ob flood in the area downstream the mouth of the Tom are formed. The Chulym River and other tributaries increase the volume and duration of the flood, and the flood wave is also flattening. The intra-annual distribution of river flow downstream of Novosibirsk is influenced by the Novosibirsk HPP flow regulation since 1959.

Maximum water levels at the downstream gauge stations usually are observed during the ice drift and sometimes caused by ice jams in the river. In most cases, e.g. 65 % of peaks at the settlement of Nikolskoye, 75 % at Molchanovo and 60 % at Kolpashevo, the extremes are related to the first flood wave after the ice break-up. In Nikolskoye and Molchanovo, it occurs likely due to the great water inflow from the Tom River, the flow of which is formed in the mountains of Kuznetsk Alatau and is not controlled by dams. Downstream of Kolpashevo, at Kargasok and Aleksandrovskoye gauge stations, an even smaller number of maxima (no more than 15 %) are associated with ice phenomena. At those locations, the highs are often associated with the third flood wave, which can combine with the second one and takes place in the middle-to-late June.
3. Materials and methods

The Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) has gauged water levels of the Ob River at several locations listed in Table 1. The long-term records for the period up to 2016 have been obtained from open sources and used for the analysis. Long-term water discharge observation data are available only at Kolpashevo and Aleksandrovskoe.

The analysis was performed using the integral curves of the yearly maximum water levels, as well as statistical tests for the homogeneity: a Student’s t-test for means and Fischer’s F-test for variances taking into account the skewness of maximum level series and Pearson’s autocorrelation. In the case of a certain time series statistical homogeneity over observation periods at the significance level 5%, the high water levels of low probability of exceedance were predicted, the values of which then would be used to determine the boundaries (and depth) of inundation of the Ob floodplain in corresponding areas in the modern period. The calculations were performed in accordance with the recommendations of the Code of Practice 33-101-2003 [13], mainly using the software package "HydroCalc" [14].

Statistical homogeneity analysis was carried out in the following sequence:

1. according to the criteria of Smirnov–Grubbs and Dixon, years with sharply deviating extreme values (outliers) of maximum water levels were revealed. Such outliers at most gauge stations correspond to a very low flood of 2012 [15];

2. each observed time-series was then divided into two parts: (a) from the beginning of observations up to the year from the period and (b) the period from the year up to 2016. The boundary year between two periods in time series was set in increments of one year near the change-point of corresponding integral curve, constructed for a maximum water level time series. Then the sample variances and averages of two parts of each time series were tested for homogeneity according to the Fisher’s and Student’s criteria. In most cases, the change-point corresponds to 1959;

3. all the series of observations for the period 1959–2016 (with maximum water levels 2012 or without them, according to the results of the analysis at step 1) was divided into two approximately equal portions and tested for non-stationarity using criteria of homogeneity of sample variances (the Fisher test) and sample averages (the Student test) at the significance level of 5%;

4. in the case of confirmation of the homogeneity hypothesis of sample variances (Fisher's criterion) and averages (Student's criterion) empirical probability distributions of flood maximum levels were obtained for all gauge stations and then based on the extrapolation of probability distributions the water levels of low probability exceedance might be determined.

| Gauge Station       | Distance from the Ob R mouth, km | Period of observations | Recent stationary period |
|---------------------|----------------------------------|------------------------|-------------------------|
| 1 Kruglikovo*       | 2829                             | 1894–2016              | 1959-2016               |
| 2 Pobeda            | 2722                             | 1966–2016              | 1966-2016               |
| 3 Nikolskoe         | 2634                             | 1978–2016              | 1978-2016               |
| 4 Molchanovo*       | 2557                             | 1932–1987              | 1959-2016**             |
| 5 Mogochino         | 2518                             | 1948–1987              | 1959-1916**             |
| 6 Kolpashevo*       | 2422                             | 1914–2016              | 1959-2016**             |
| 7 Kargasok          | 2180                             | 1935–2016              | 1959-2016**             |
| 8 Prokhorkino       | 2024                             | 1960–1997              | 1960-2016**             |
| 9 Aleksandrovskoe*  | 1830                             | 1935–2016              | 1971-2016**             |

* Basic Gauge Stations with long-term observations

**Observations of 2012 were excluded as outliers
4. Results
Extremely low flood peaks were observed in 2012 over almost the entire territory of Western Siberia during a high-water season. It was likely caused by the abnormally low precipitation rates in the autumn 2011 and subsequent winter 2011–2012 [12, 15]. There was the reason why the peak level observations of 2012 were excluded from further computations in accordance with the results of the analysis based on the Smirnov–Grubbs and Dixon criteria for each particular gauge station.

The violation of statistical homogeneity since 1959 (the beginning of seasonal regulation of the Ob water flow by the Novosibirsk HPP and reservoir) is characteristic for all studied series of observations including the Kolpashevo gauge station. Apparently, this violation was produced not only by the runoff control through the reservoir annual filling during floods from the upper part of the Ob basin but also due to the increased local erosion of the river bottom just downstream of the dam (which contributed to the local "landing" of water levels), as well as the increased water withdrawals in the city of Novosibirsk in later years. Such a disturbance of homogeneity downstream of the mouth of the river Tom could also be associated with the termination of ice jams formation in the Tom and gravel mining from the Tom river bed, resulted in a decreasing trend in maximum flood water levels in Tomsk since the late 1950s.

In addition to the anthropogenic causes for the decrease in water levels along the entire length of the Ob study reach, the natural factors in the form of the flood flow decrease for the rivers running in the Altai foothills and the rivers of Tom and Chulym [4] are also important. Study of the average monthly water discharge in May (the month in which the maximum discharges occur at most gauges) shows a downward tendency not only in the 1960s, but also over the next two decades (Figure 2) [16]. Only in the 1990s there was some stabilization of the average monthly water discharge in May and even some growth in the 2000s.

![Figure 2. Long-term dynamics of May monthly average water discharge Q in the Ob River at Kolpashevo and Aleksandrovskoe (with Prokhorkino) in May over the period 1942–2015](image)

Decrease in both the maximum flood water discharges and water levels also affected the depths and duration of floodplain inundation. Particularly noticeable reduction in floodplain inundation was observed in 1980–1990. Records of flood water levels at the Molchanovo gauge station show that over the period 1980–1990 the floodplain was flooded (above the level of 870 cm at which water enters the floodplain), only four times, and in two cases water flooded fragments of the floodplain for only one to two days (Figure 3).
5. Conclusions

Most long-term time series of maximum flood water levels over the study reach should be considered as statistically non-homogeneous at the 5% level of significance.

In most cases, for various reasons, there is a violation of homogeneity in 1959. This is the year when the Novosibirsk HPP was brought into operation. Apparently, there are also natural reasons because the 1959 violation might be traced up to the Kargasok gauge station located at more than 800 km downstream of the reservoir.

The extremely low maximum water levels of 2012 are “outliers” in the statistical analysis at a significance level of 5% and can be traced at Molchanovo and downstream in the entire considered section of the river.

In the modern period (after 1959), some downward tendencies in maximum water levels in the middle course of the Ob River under study that are also observed cause some reduction in the area, depth and duration of floodplain inundation.
The results of this study are currently used in the development of a neural network for predicting water levels in settlements as part of the Flood module of the Tomsk Region Geoportal. This module uses large-scale landscape and soil maps [17–19] and highly detailed digital elevation models of river valleys [20], which allows getting 3D-models of the current situation with flooding in on-line mode.

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