Impact of Large Floods on Water Resources and Infrastructure of Urban Areas in the Amur River Region

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Abstract. This article considers the impact of rainfall floods of the Amur river on the distribution of suspended sediments and the content of heavy metals in the watercourse. It presents measurement data of these parameters for equal flood rise and fall flows. The authors found out that factors like a high proportion of watercourse width to its depth, the presence of large tributaries, and the branching of the river course have the strongest impact on the heterogeneity of the distribution of terrigenous and chemical substances across the length and width of the river. They also identified the key impacts of large floods that transform the river course and have negative effects on the reliability and conditions of waterworks within urban territories.

1. Introduction

The steams with unsteady water regimes, such as the rivers in Eastern Asia, frequent floods are important factors of transporting terrigenous material and chemical pollutants. The uneven flow of various substances to the lower reaches of large rivers increases significantly in the monsoon climate areas. Under such natural conditions, floods may develop rapidly due to intensive precipitation. As a result, the pollutants accumulated in the river basin over a long time are flushed into the river.

Large rivers have wide courses, which explains the significant heterogeneity of substance distribution in water across the watercourse profile. During large floods, alluvial plains go underwater, which complicates the currents and creates various conditions for transporting and accumulating terrigenous material and chemical pollutants. Branching typical of large rivers also facilitates the uneven distribution of various substances across the width of the watercourse.

During the floods, river courses may alter significantly, which can have adverse consequences for their economic use. The problem of river bed instability and active alternation in branching areas is especially relevant in urban territories.

The content of various chemical substances in the waters of the river Amur and their multiyear dynamics have been studied in detail [1-3, et al.]. Floods are a specific phase of the water regime, and their influence on the terrigenous and chemical flow-off remains insufficiently researched especially those associated with specific hydrological factors typical of branching watercourses.

The purpose of this research was to assess the influence of rainfall floods on the water quality conditions in the Amur watercourse during summers and autumns based on the analysis of a number of hydrochemical parameters and the resilience of waterworks.
Unlike the results obtained by the state monitoring service, detailed research of the distribution of various pollutants in the riverbed help ascertain its unevenness, which is crucial for the accurate evaluation of the flow-off volumes of various components and the environmental conditions of large rivers.

2. Materials and methods
The research was conducted in the lower reaches of the Amur river during summer and autumn medium-scale floods. The highest water flow observed was 12-20 thousand m$^3$/s. Floods usually lasted for over two months: from mid-July up to the first third of October. The most detailed research was carried out during the flood of 2003. Water sampling was performed during the rise (July 16th) and fall (September 26th) of the water level at a similar flow value (15,200 and 16,000 m$^3$/s respectively).

Near Khabarovsk, water was sampled upstream of the city at a 100-meter interval across the entire width of the course (1,700 m). At each of the verticals, samples were taken from the near-surface levels.

To assess the influence of a large tributary on the spread of various substances across the width of the river during the flood, samples were taken from the Amur creek at a location 15 km upstream from Khabarovsk and 12 km downstream from the river Ussuri junction.

The heavy metal analysis was carried out in the regional laboratory for analytical control of the Federal State Territorial Data Bank for natural resources and environmental protection in the Far Eastern Federal District. Water turbidity was measured at the laboratory of the Institute of Water and Environmental Problems of FEB RAS.

The assessment of waterwork conditions in the course of the Amur river under the impact of disastrous floods of 2013 and 2019 was carried out based on the analysis of changes in morphological and morphometric parameters of the river bed before and after the flood through satellite photographs and direct field observations.

3. Results and discussion
A key factor conditioning significant heterogeneity in the distribution of suspended and dissolved substances in the watercourse is a large proportion of the river width to its depth, which is 250-300 for the Amur. Under such conditions, the mixing of waters is complicated, and the uneven distribution of various substances across the course persists for a significant distance. This phenomenon is clearly evident below the inflow of large tributaries and when large drains enter the river from big cities, especially those located on one of the banks, and during large accidents accompanied by the mass discharge of pollutants into the river.

Another important factor in the uneven content of various substances in the watercourse is the morphological features of riverbeds. The beds of large rivers in their lower reaches are usually characterized by complex branching [4]. For the Amur, the number of branches can sometimes reach 10-12, and their length up to several dozens of kilometers. For example, the length of the Amur creek near Khabarovsk is 60 km, and the length of the Staryi Amur creek near Mariinskoye is 80 km. Branches help retain the heterogeneity of pollutions across the watercourse for a significant distance.

The phenomenon of directed accumulation is a key factor in the transporting of terrigenous material and it is typical of the lower reaches of many of the world's largest rivers, including the Amur, Yangtze, Amazon, etc [5]. It conditions frequent and intensive redistribution of sediment flow-off between branches and facilitates the accumulation of large amounts of sediments in the alluvial plains that act as the source of secondary pollution of the river.

3.1. Suspended sediment flow-off
Throughout the year, the flow-off of suspended sediments in the Amur river is extremely uneven. It reaches its maximum during the open surface period. During springs and summers (April to September), the sediment flow-off reaches 87% of the annual value, and it can rise up to 91% in some years. This is due to the fact that alluvial sediments quickly get eroded during high floods. The highest
turbidity of water is observed during high floods of the Amur and its largest tributaries [6]. During the low-flood years, the content of suspended substances in the water is low due to the weaker erosion of the alluvial sediments.

The turbidity of water in the cross-section profile of the watercourse upstream of Khabarovsk is very uneven: during the flood rise, it varies between 26 and 221 mg/dm$^3$ at a water flow of 11,700 m$^3$ and reaches the top values near the right bank. This distribution is explained by the influence of a large tributary, the Sungari river, that enters the Amur on the right 270 km upstream. During the flood fall, the turbidity of water at the flow of 12,900 m$^3$/s was distributed more evenly and varied between 29 mg/dm$^3$ and 86 mg/dm$^3$ with top values also observed near the right bank. The average water turbidity during the flood rise is 2-3 times higher than during the fall at approximately equal water flow values (Table 1).

|                | Khabarovsk | Amur creek | Sikachi-Alyan | Komsomolsk-on-Amur |
|----------------|------------|------------|---------------|--------------------|
| Flood rise     | 158.1      | 91.5       | 101.2         | 100.4              |
| Flood fall     | 51.8       | 38.3       | 38.1          | 44.7               |

During high floods, alluvial plains submerge under water entirely, which leads to the accumulation of huge amounts of sediments in them and alluvial lakes [7]. During the flood of 2013, wide, 70-500 meter long ledges were formed along the banks in the areas where there was a powerful water flow entering the alluvial plain. These ledges consisted of fine and close sands of up to 1.2 m thick near the bank. Further on to the alluvial plain, the thickness of sand sediments gradually decreased. Sand sediments are replaced by 1-2 cm sandy clay 100-150 m away from the shoulder of the alluvial plain. The thickness of loamy silt deposits in the interiors of alluvial islands was 0.2-1.0 mm.

The tributaries of the Amur river influence the turbidity of its water to a great degree. For example, during the low-water season in the summer of 1998, water turbidity upstream of the junction of the Amur and the Sungari varied between 20 and 40 g/m$^3$. At the same time, the Sungari, the largest tributary of the Amur, was flooding. Water turbidity in the Amur downstream of the Sungari junction was 417 g/m$^3$ [6]. During the summer flood of 2009, these parameters were 50 and 700-800 g/m$^3$ respectively.

Along the Amur river from Khabarovsk to its lower reaches, the content of suspended substances generally declines. It is caused by the reduction of the current velocity due to the increase in the useful flow area and the features of directed sediment accumulation. The data obtained from field observations during various phases of the water regime show that water turbidity reduces downstream by 30-35% on average [8].

![Figure 1](image-url). The changes in water turbidity in the Amur river over the length (left) and width (right) of its course.
Large tributaries also condition the significant differences in water turbidity values across the width of the Amur. Near the Khabarovsk railroad bridge over the Amur, there is an influx of turbidity-free water from the Zeya and Bureya reservoirs along the left bank. The increased turbidity of water in the middle of the river is due to the high turbidity of the Sungari, a large tributary, and a narrow stretch of clear water along the right bank is due to the influx of turbidity-free waters of the river Ussuri.

3.2. Heavy metal distribution
The distribution of heavy metals in the cross-section of large rivers is very uneven, which can also be explained by unfavorable conditions for the mixing of waters in wide and shallow courses. When pollutants from tributaries enter the river, their increased content can be observed for several hundreds of kilometers. The detailed analysis of the distribution of nitrobenzene from the Sungari river across the width of the Amur after the accident at a chemical plant in Jilin (China) of 2005 showed that the pollutant was completely dissolved in the Amur 550 km downstream [9].

The content of various substances in the cross-section of the water stream is characterized by significant fluctuations. The analysis of heavy metal distribution across the width of the Amur river near Khabarovsk showed that the unevenness value measured at the proportion of maximum and minimum content of the component varies between 1.3-3.5 (Table 2).

| Table 2. Heavy metal content across the width of the Amur river during the flood of 2003, mg/dm$^3$ |
|-----------------------------------------------|
| Measurement data | Zn | Cu | Pb | Ni |
| Homogeneity index | 0.029-0.101 | 0.003-0.009 | 0.003-0.006 | 0.003-0.004 |
|                   | 3.5 | 3.0 | 2.0 | 1.3 |

The content of heavy metals in the water was measured during different flood phases. The content of heavy metals in the Amur near Khabarovsk was as follows: during the rise, there was less zinc and copper in the water than during the fall (1.5 and 2.0 times respectively), and the pattern for lead and nickel was the opposite (2.5 and 18.0 times respectively) (Table 3).

| Table 3. The average content of heavy metals in the waters of the Amur river during the flood of 2003, mg/dm$^3$ |
|-----------------------------------------------|
| Flood rise | Zn | Cu | Pb | Ni |
| Flood fall  | 0.0403 | 0.0029 | 0.0103 | 0.0552 |
|             | 0.0654 | 0.0062 | 0.0040 | 0.0032 |

3.3. Impact on waterworks
The most drastic transformations of multibranch parts of the Amur course occur during large floods. In the recent decade, there were two such floods in the Amur region, in 2013 and 2019. These conditioned a significant transformation of the river course and the redistribution of the water flow between the branches [10].

Large accumulative formations in the multibranch river course during floods and their constant downstream displacement has a negative impact on the infrastructure of settlements. The safe operation of water intakes, bridges, motorways, and railroads located in the alluvial plains is often threatened. A good example is the lack of discharge facilities in railroad and motorway embankments on the left bank alluvial plain near Khabarovsk. It caused a significant rise in the water level in the city during the catastrophic Amur flood in 2013.

River course evolution near large cities like Khabarovsk and Komsomolsk-on-Amur is negative for the local population and economic activity. In 2005-2006, large waterworks (overflow dams) were constructed near Khabarovsk in Pemzenskaya and Beshenaya creeks to prevent unwanted redistribution of the water flow, and 5 km long bank protection dams were built in the sections of the
Amur with intensive lateral erosion. These dams are implemented as piles of rocks without extra bindings.

Their operation showed that the rockfill method is not effective enough in ensuring the resilience of bank protection. Overflow dams consisting of large rocks are constantly destroyed during floods and spring ice-gangs thus requiring regular restoration.

![Figure 2. The erosion of the bank protection dam on the Amur river near Khabarovsk during the flood of 2013.](image)

The unsteady watercourse regime in multibranch sections of the Amur river is characterized by redistribution of the water flow between the branches, intensive erosion of banks, and bank infrastructure. Currently, the problem of technological stabilization of the Amur course is becoming more pressing to mitigate the adverse consequences of watercourse deformations, preserve the existing conditions of natural resource exploitation near the city, and ensure stable water supply to Khabarovsk.

4. Conclusions
The significant differences in the conditions and the degree of pollution of the Amur river water can be explained by hydrological and hydromorphological parameters of the river. The factors like the high proportion of watercourse width to its depth, the presence of large tributaries, and the branching of the river course have the strongest impact on the heterogeneity of the distribution of terrigenous and chemical substances across the length and width of the river.

During the rise of rainfall flood, watercourses receive a large amount of suspended and other chemical substances washed off from the land surface in the river basin. During the flood fall, the content of pollutants at similar water flow values is significantly lower. The spatial heterogeneity of pollutant distribution in different sections of the river complicates the efficient and valid environmental monitoring of the Amur river.
To evaluate the risks associated with adverse consequences of river course evolution near Khabarovsk and Komsomolsk-on-Amur, it is necessary to constantly monitor the respective watercourse processes and the condition of the existing waterworks.

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