RESEARCH PAPER

INFLUENCE OF THE LARGE FLOOD ON THE ELEMENT COMPOSITION OF FLUVISOLS IN THE AMUR RIVER VALLEY

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ABSTRACT. Floodplain soils function as long-lasting stock or source of different substances, including pollutants. The main factor determining biochemical processes in fluvisols is flooding. Global climate change, which is causing more frequent and massive floods, is urging us to assess the potential environmental risks and create appropriate environmental management strategies. This study was performed to estimate the impact of a heavy flood on the total content of major elements and both total and mobile trace elements in fluvisols of one of the longest rivers in the world, the Amur. The study was conducted in field conditions by sampling from the same soil profiles before and after the flood. As a result, 10 major and 42 trace elements were distinguished. Major-element composition was determined with X-ray fluorescent method, trace-element composition - with the inductive coupled plasma mass spectroscopy. Maximum decrease of concentration was determined for CaO, MnO, P2O5 (up to 60%) and Sr, Cd, Ba, Tl and Pb (up to 40%). Significant increase was in concentration of Ni, Cu, and Mo (up to 160%). Among mobile trace elements, increase was observed in concentration of Sc, Ni and Th (up to 400%). With the correlation analysis, it was also established that the main causes of changes in elemental composition of the soils were decrease of pH, development of redox environment and washing out of organic matter. The main factor determining the influence of the flood on fluvisols was floodplain relief, which affected the length of the inundation, flood water velocity and the way allochthonic matter retained.

KEY WORDS: catastrophic flood, fluvisols, major elements, trace elements, Amur River

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INTRODUCTION

Floodplains and fluvisols perform the function of natural drainage system in global circulation of matter since they transport major and trace elements from land to rivers, and further to seas and oceans (Zocatelli et al. 2013). Part of the migrating matter is retained in different geochemical barriers within of fluvial soils in the floodplain area, which provides their high biological efficiency and fertility (Wei & Jin-liang 2002). However, fluvisols may be subjected to heavy contamination in presence of high element contents within catchment area, of geogenic or anthropogenic origin (Förstner et al. 2004; Lair et al. 2009). Subsequently, the soils might cause pollution of the downstream areas due to remobilization, transportation and redistribution of elements (Förstner et al. 2004; Hilscherova et al. 2007). One of the main factors regulating distribution and retention of major and trace elements in fluvial soils are floods (Day et al. 1988; Zerling et al. 2006). Flood waters bring silt deposits, which vary in chemical composition and in texture (Gerrard 1987). They also feed ground waters, which determine transport of major and trace elements in soils of floodplains (Pirastru & Niedda 2013). Flood waters influence the processes of soil formation by changing redox potential (Eh), soil reaction and microbial activity, which significantly affects mobility of elements (Abgottspon et al. 2015; Shrestha et al. 2014). The frequency and capacity of floods have recently increased, which probably caused by global climate change (Oriola & Chibuike 2016; Wölz et al. 2009). Growing events of extreme flood occurrence increases necessity to assess their impact on the element composition of soils and estimate possible environmental risks.

The main problem impeding the study of flood impact on floodplain soils is in little possibility to predict floods as well as their capacity and length (Silvestro et al. 2017). Consequently, most of the existing results showing the influence of long-lasting inundations on soil properties and their elemental composition have been obtained in laboratory or on model experiments (Abgottspon et al. 2015; Frohne et al. 2014; Unger et al. 2009). However, these results do not reflect in situ processes due to heterogeneity in time and area of content of major and trace elements in floodplains (Schulz-Zunkel et al. 2013). The latter is attributed to strong variability of biochemical and soil-forming processes occurring in floodplains (Lair et al. 2009; Tockner et al. 2016). Furthermore, most scientific works dealing with the content and behavior of major and trace elements in fluvisols take into consideration narrow range of elements (Antić-Mladenović et al. 2016; Martin 2015), whereas, analysis of wide range of elements would allow us to distinguish associations of elements prone to accumulation or losses and, as a result, to forecast the flood consequences in the future.

In 2013, the severest in the last 120 years inundation struck the Amur River basin situated on the border of Russia and China (Makhonov & Liu Shuguag 2013; Verbitskaya 2015; Sokolova 2015). However, it was difficult to estimate the consequences of the flood for the floodplain soils due to lack of research of the fluvial soils in the area. Studies of elemental composition of fluvisols have mostly been conducted in the tributaries of the Amur, and even those were not numerous (Makhonov & Makhonova 2017; Martynov 2015; Sorokina & Zarubina 2013; Sorokina & Gusev 2014; Sorokina & Gusev 2018; Wang 2015). The only study of elemental composition of fluvisols was performed in the middle reach of the Amur River, Russian side, in 2011. Short time period between the 2011 research and the flood gave us a unique opportunity to analyze the flood consequences. Therefore, the objective of our study was to assess the impact of the severe 2013 flood on elemental composition of the fluvisols of the Amur floodplain based on comparative analysis of the soil composition before and after the flood. We also investigated the changes in relationships of different element fractions and properties of the fluvisols after the flood. We also investigated the changes in relationships of different element fractions and properties of the fluvisols after the flood. The research expands understanding of the natural procedures of element migration in fluvisols and contributes to study of soil formation processes which occur in the Amur floodplain. One of the largest rivers in the world, which has important environmental significance for Russia and China and is experiencing anthropogenic impact (Ermoshin et al. 2013).

MATERIALS AND METHODS

Study site and the properties of the soils under research

The site of study locates along the middle reach of the Amur River in Amur region, Russian Far East (Fig. 1). The River starts at the Mongolian Plateau and flows into the Sea of Okhotsk reaching the length of 4,440 km and the catchment area of 1,855 km^2. The River mostly has rain nourishment which comprises significant 70%. The region has monsoon climate which means that precipitation is unequal during the year. During warm period precipitation may reach 80% of annual volume which causes significant fluctuation of the river flow. Within the middle reach of the Amur River, sum of annual precipitation is 900 mm. Mean temperature during the year is 0°C, absolute temperature minimum is -45°C ranging 45–70°C during the year. The period of mean temperature over 0°C is 165-195 days, over 10°C – 120-130 days (Muranova 1966).

The study area is a floodplain area up to 10 km wide, up to 5 km long and up to 14 meters high. Soil studies were conducted in 2011 and 2014, during which 31 soil profile were set, of which samples were taken from genetic horizons. According to the results of the work, a soil map was compiled (Fig. 2). The flood in 2013 made it possible to assess its impact on various aspects of the process of soil formation, including the elemental composition of alluvial soils. For this, three soil profiles were reestablished with sampling from the same horizons. Despite the fact that most of the studied floodplain was flooded (Fig. 3), repeated sections were laid only within the riverbed floodplain. The choice of these sections is due to the fact that they are located in the zone of the longest flooding and the strongest hydromechanical impact, which is confirmed by published data (Makhonov 2017).

The hydrological characterization of the study area was performed according to the nearest hydrological post provided by the Amur Center for Hydrology and Environmental Monitoring (table 1). The post is located in the Poyarkovo village, 60 km upstream. Based on these data, in 2011 and 2012 the studied floodplain was not flooded. In 2013, the maximum level of water rise was 7.3 meters, as a result, a column of water up to 3 meters stood above the soil located within the coastal rampart. The period of direct flooding of the floodplain lasted from July 27 to September 2, which amounted to 38 days. Flooding of hydromorphic alluvial soils by groundwater was recorded even in 2014.The soil samples were classified according to the World Reference Base for soil resources (WRB 2014). We identified Haplic Fluvisols, Umbric Fluvisols and Umbric Fluvisols (HypoGleyic).

Analytical investigations

The properties of the fluvisols and their major-elemental composition were analysed in the analytical centre of mineralogy-geochemical research Institute of Geology and Nature Management FEB RAS. Granulometric composition was determined with pipette-sampling technique, organic matter was measured with wet combustion method, pH was determined with potentiometric method, cation-exchange capacity was represented by scope of calcium and magnesium, aluminum and hydrogen cations (CEC). All the analyses were conducted in accordance with generally accepted methods (Pansu 2006). Major-elemental composition was determined with X-ray fluorescent method on the spectrometer XRF-1800 Simadzu (Japan).

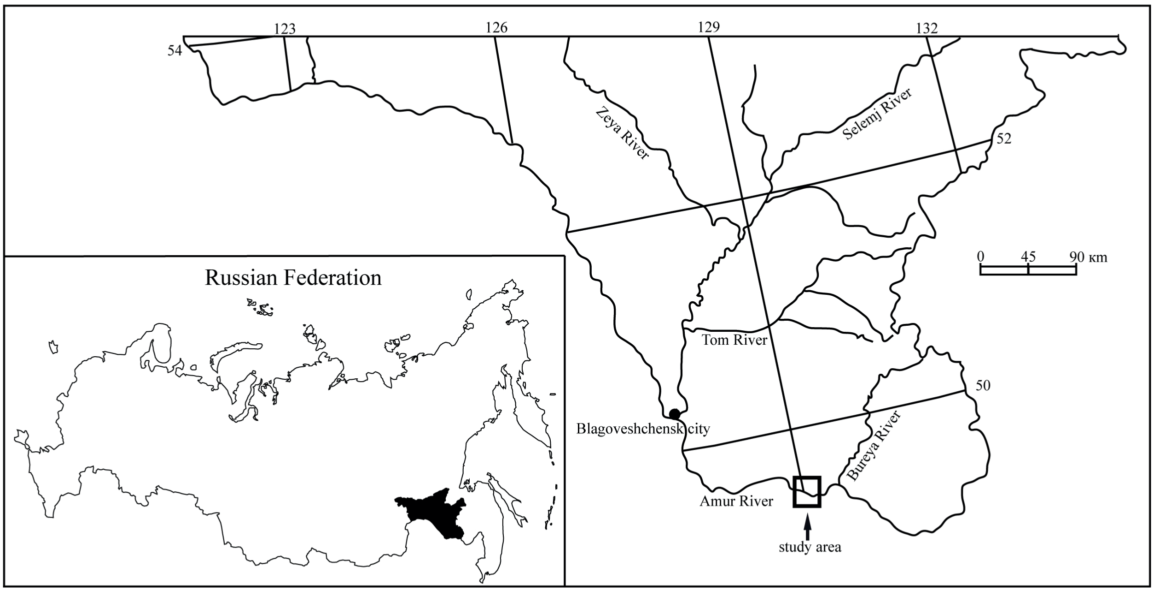

Fig. 1. Location of the study area on the territory of the Amur Region

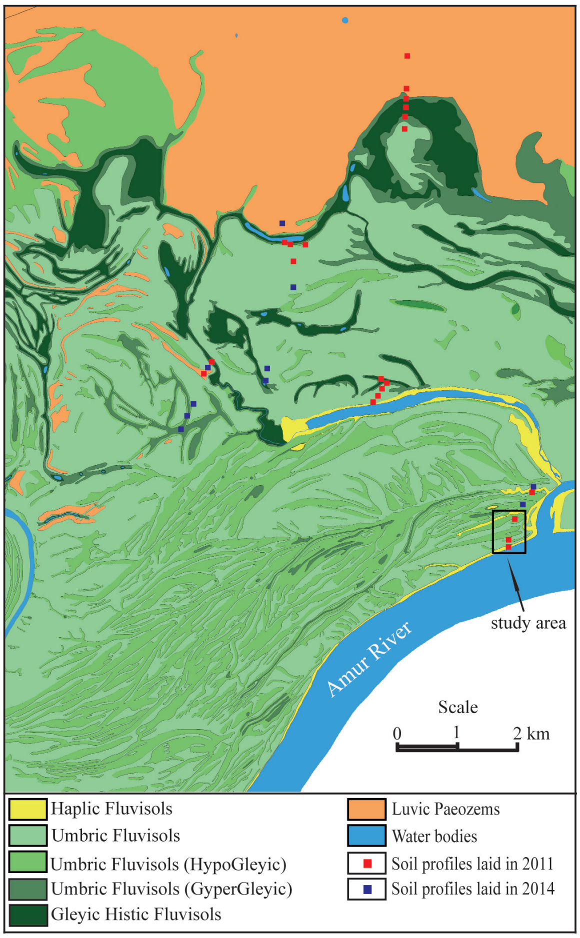

Fig. 2. A soil map of a part of the floodplain of the middle course of the Amur River based on materials from expeditions 2011 and 2014

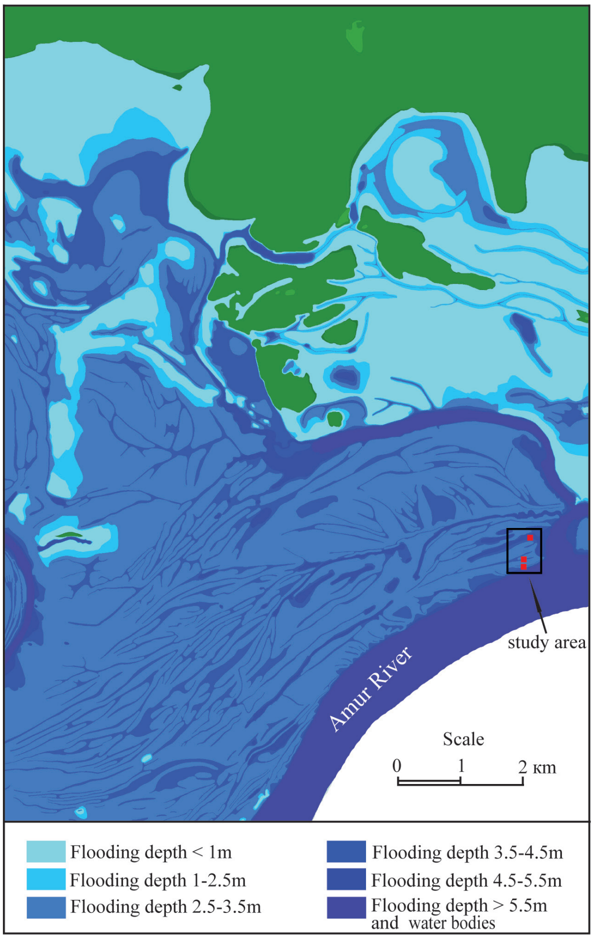

Fig. 3. Flooding model when the water level in the Amur River rises by 7 meters

Table 1. Potential technologies for extracting, generating and storing renewable energy at closed mines

	Water edge in the Amur River (cm)	The maximum level of water rise in the Amur River, relative to the edge (cm)			The height of the river bank of the shore, relative to the edge (cm)
		years			
		2011	2012	2013	
Poyarkovo village	104.0	279	285	729	476
Study area	98.4	285	291	735	460

Determination of total and mobile forms of trace elements (Zn, Cu, Cd, Pb, Be, Sc, V, Cr, Ga, As, Zr, Nb, Hf, Ta, Sr, Ba, Li, Co, Ni, Rb, Y, Mo, Sn, Sc, W, Tl, Th, U, La, Ce, Pr, Eu, Nd, Sm, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) was carried out in the accredited analytical centre of Far Eastern Geological Institute FEB RAS (the accreditation certificate number is RA.RU.518986). Total content of trace elements was determined applying acid digestion method in mixture of acids HF, HNO3, and HCLO4 at ratio 2,5:1:0,5. Extraction of mobile trace elements was conducted with ammonium acetate buffer at pH 4.8. The soil solutions were mineralized in microwave oven MARS-5 (CEM Corporation, USA). Analysis of wide range of elements was performed with the inductive coupled plasma mass spectroscopy Agilent 7700x (Agilent Technologies, Japan). Source data on major and trace elements contents are given in Appendix A.

Statistical analysis

The influence of the flood on the content of major and trace elements is introduced in percentage ratio of the content of the elements after the flood to the content of the elements before the flood. To visualize the ratio we applied k-means clustering. The number of clusters was chosen in advance by using hierarchical approach (Ward's method, Manhattan distance) at a distance of 4 steps. The length of each step was 20 for major elements, 50 for total trace elements and 100 for mobile trace elements.

To determine relationships between soil properties, major and trace elements Pearson's correlation analysis was applied. Before the analysis, the variables with abnormal distribution were standardized. The found correlation coefficients were averaged according to k-means clustering. The number of clusters was chosen in advance by using hierarchical approach at a distance of 1 step with the length 10. For all calculations software STATISTICA v.7.0 was used. To create a soil map and hydrological model software «Panorama 2011» was used.

RESULTS

The properties of fluvisols before and after the flood

Profile №1 (P1). Haplic Fluvisols (Epiarenic). Soil profile (N49°.24′08.38″ E129°12′16.15″) was set up on the foot of levee close to towpath. After the flood, the soil got slightly firmer, and humus horizon got darker.

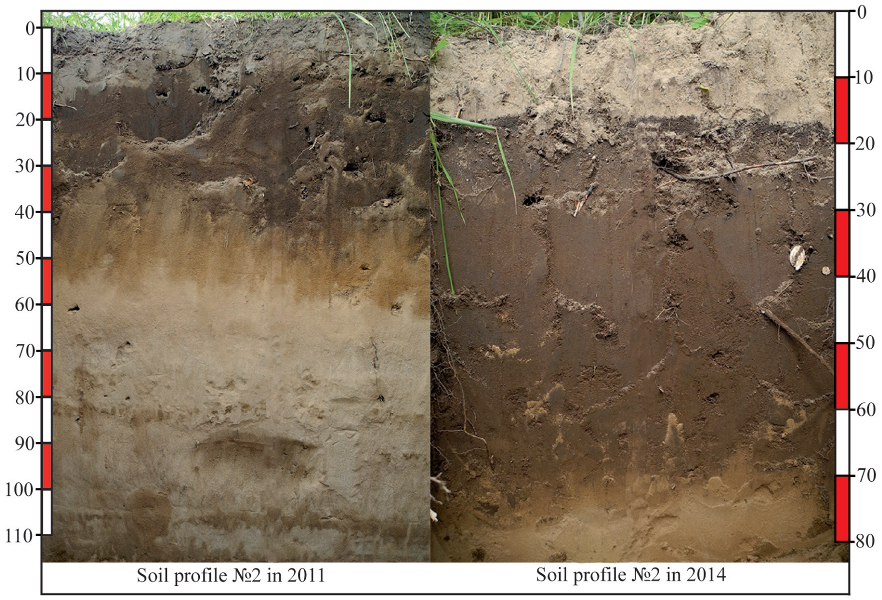

Fig. 4. Change in the morphological appearance of profile №2 after the flood

Profile №2 (P2). Haplic Fluvisols (Epiarenic). Soil profile (N49°24′08. 85″ E129°12′15.72″) was set up on the top of levee. After the flood, the soil was covered by sandy alluvia deposition 30 cm. The latter indicates significant water flow force in the area during the flood (Fig. 4).

Profile №3 (P3). Haplic Fluvisols (HypoGleyic). Soil profile (N49°24′23.70″ E129°12′19.62″) was set up in the depression of the floodplain on the bottom of a dry creek distancing 500 m from the river. After the flood, organic horizon was partially washed out, and mixed with bottom silt particles. Such morphological changes indicate high water flow velocity at the beginning of the flood. Later, the area was long inundated by waters.

After the flood, we observed decrease of soil pH and decrease of organic matter content in all studied soils. In profile 1 and 2 silt and clay contents decreased (Table 2).

Changes of major and trace element content after the flood

In terms of major-element composition, the content of elements belonging to C1 did not change much in P1 and P2, whereas in P3 the elements accumulated in upper horizon and were washed out in lower horizon (Fig. 5). Content of the elements belonging to C3 lessened in all soils, especially in P3. Content of the elements belonging to C2 differed widely in all soils though it increased in organic horizons.

Total content of trace element in P1 and P3 mostly rose after the flood (Fig. 6) though it lessened or did not change in P2 Trace elements in P1 and P3 mainly accumulated in lower horizons. Among the trace elements maximum increase in content is characterized by Ni, Cu and Mo, whereas maximum dispersion for Sr, Cd, Ba, Pb and Tl.

Content of mobile trace elements belonging to C2, C3 and C4 increased significantly in organic horizons, especially in P1 and P3. Content of elements belonging to C1 decreased almost in all studied soils (Fig. 7). Most accumulation was typical for Sc, Ni and Th.

Analysis of correlation coefficients of soil properties, major and trace elements before and after the flood

Total concentrations of trace element were divided into four clusters according to correlation coefficient (R) before the flood (Fig. 8). Clusters 2 and 4, which encompassed greater part of elements, had similar values of R. The elements had strong positive R to aluminum and magnesium oxides and to exchange cations of calcium and magnesium, characterizing cation exchange capacity (CEC). Elements belonging to C1 showed strong R to clay particles, CEC, manganese oxide, phosphorous oxide and calcium oxide. However, Sr and Ba belonging to C3 significantly differed from other trace elements (Fig. 8), i.e. they had significant negative R to clay particles, CEC, organic matter, aluminum and magnesium oxides, but they had positive R only to potassium oxide. Significant correlations to pH and iron oxides were not revealed in trace elements.

After the flood, almost all elements united into a single cluster according to their R (Fig. 9) with the exception of Sr and Ba, whose R mirrored values of other elements. Besides, all trace elements belonging to C2 had strong correlation to clay particles, CEC, carbon, hydrogen cations, aluminum cations and aluminum and magnesium oxides.

Clusters based on relations between the content of mobile trace elements, major elements and soil properties before the flood can be divided into two groups (Fig. 10). Elements belonging to clusters 1 and 4 appeared to have strong correlation to organic matter, clay particles and also positive R to manganese and calcium oxides and pH. Clusters 2 and 3 had strong correlation to aluminum and sodium oxides, but negative R to calcium, manganese, phosphorous oxides and pH.

After the flood, mobile trace elements grouped into 3 clusters, and variation of R values between variables decreased (Fig. 11). All mobile trace elements had positive, Rs to clay particles, organic matter, CEC and oxides of aluminum, iron, magnesium and phosphorous. Elements belonging to C1 had near zero R to pH and calcium oxide though C2 and C3 elements had perfect negative R to pH and calcium oxide.

DISCUSSION

It is considered to be that floods enrich fluvisols with different elements and substances (Saint-Laurent et al. 2014; Wei & Jin-liang 2002). On the other hand, there are results suggesting that floods can generate negative conditions for soil formation due to destruction of organic horizon and remobilization of organic, silt and clay particles (Saint-Laurent et al. 2010), major and trace elements (Izquierdo et al. 2012; Schulz-Zunkel et al. 2015). Our research is consistent to both assumptions to be correct as inundations wash out some elements but retain others.

Analysis of the flood impact on the content of major elements

Long-lasting inundation did not have any considerable impact on the content of Si, Al, Mg, Na or K since difference in their content was less than 10% from those values before the flood (Fig. 2). The mentioned elements being part of river

Table 2. Properties of alluvial soils before and after the flood

Profiles	Layers	Depth (cm)	Clay (%)	pH KCl	total C (%)	Ca+Mg, (mg-eq)	H+Al (mg-eq)	Clay (%)	pH KCl	total C (%)	Ca+Mg (mg-eq)	H+Al (mg-eq)
			Before flood					After flood				
P1	A	0-5	6	6.2	1	5.33	0.03	4	5.2	0.6	2.58	0.02
	C	10-15	4	5.9	0.03	0.58	0.02	3	4.8	0.06	1.84	0.01
P2	A1	0-5	8	5.4	1.3	5.94	0.06	7	5.0	0.9	5.39	0.03
	A2	20-25	12	4.1	0.9	4.31	0.49	8	4.0	0.8	4.53	0.60
	C	40-45	15	3.9	0.6	2.43	1.00	10	4.3	0.07	1.47	0.16
P3	A	0-5	20	7.3	11.3	16.49	0.04	22	4.5	5.3	17.15	0.87
	Cgi1	15-20	12	4.7	2.3	13.51	0.18	13	3.8	1.9	9.44	4.22
	Cgi2	40-45	13	4.3	1.7	9.37	0.53	14	3.9	1.8	6.98	3.11

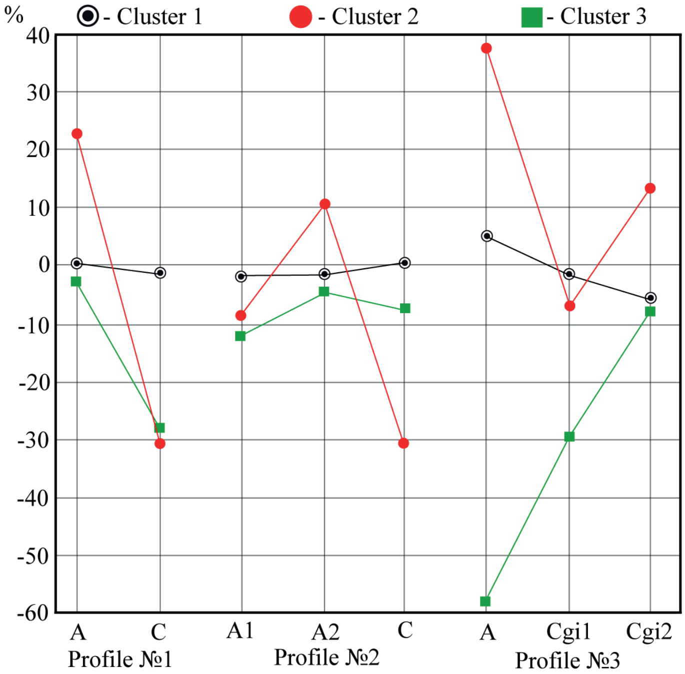

Fig. 5. Graph of average changes in the content of major elements after flooding, %:
C1: SiO_2, Al_2O_3, MgO, Na_2O, K_2O;
C2: TiO, Fe_2O_3;
C3: MnO, CaO, P_2O_5

deposits retaining in channel-near floodplain were mostly presented in the form of primary minerals. As primary minerals are big in size, infiltration of their oxides down the soil profile is insignificant.

Content of Mn, Ca and P oxides decreased after the flood (Fig. 2). The latter may be attributed to destruction of the upper horizons and washing out of fine particles, like in partially eroded organic horizon P3, where reduction of the elements was the severest after the flood. Besides, the decrease of the element content may be a result of redox regime change.

Long stay of flood waters favors development of redox processes (Ponnamperuma 1984). In P1 and P2, which are situated in floodplain depression, and consequently, stayed longest under the water after the flood, significant reduction of calcium oxide was observed. The latter is consistent with the reports concerning strong leaching of calcium oxides in humid conditions due to water saturation (Orlov & Bezuglova 2000). Most phosphorous in young fluvisols is concentrated in the form of primary minerals (Zehetner et al. 2008), which are not subjected to substantial influence of changes of soil properties, and are only exposed to physical loss caused by washing out of soils. Floods may have negative influence on the content of non-mineral form of phosphorous due to reduction of sorption capacity of phosphorous under hydration conditions (Lair et al. 2009). Manganese exists in the form of primary minerals as well, but Mn+2 is prone to leaching by river waters (Sharma et al. 2016).

Iron and titanium oxides accumulated in upper horizons of P1 and P3 and were washed out in lower horizons though in P2 they retained in the middle part of the soil profile (Fig. 2). Therefore, iron and titanium oxides moving with allochthonic matter were present in smaller particles, which were able to get inside the soil profile and retain in upper horizon. In mineral horizons iron and titanium compounds were leached down the profile. Titanium is not a mobile element, and it mostly exists in the form of primary minerals (uddevallite or rutile) resistant to erosion (Cornu et al. 1999). Although titanium oxides can sometimes be mobile, in our case, physical displacement may have occurred due to washing out of soil profile by flood water. Iron oxides behaved the same way, which indicated that they were also presented in mineral form in the fluvisols. In redox environment, which accompanies inundation of soils,

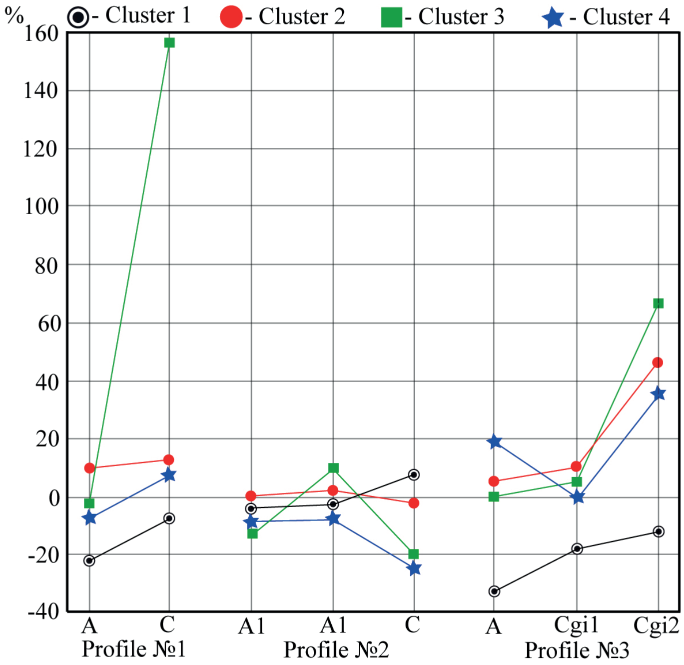

Fig. 6. Graph of average changes in the content of trace elements after flooding, %:
C1: Sr, Cd, Ba, Tl, Pb;
C2: Be, Sc, Zn, Y, REE;
C3: Ni, Cu, Mo;
C4: Li, V, Cr, Co, Ga, As, Rb, Zr, Nb, Sn, Cs, Hf, Ta, W, Th, U

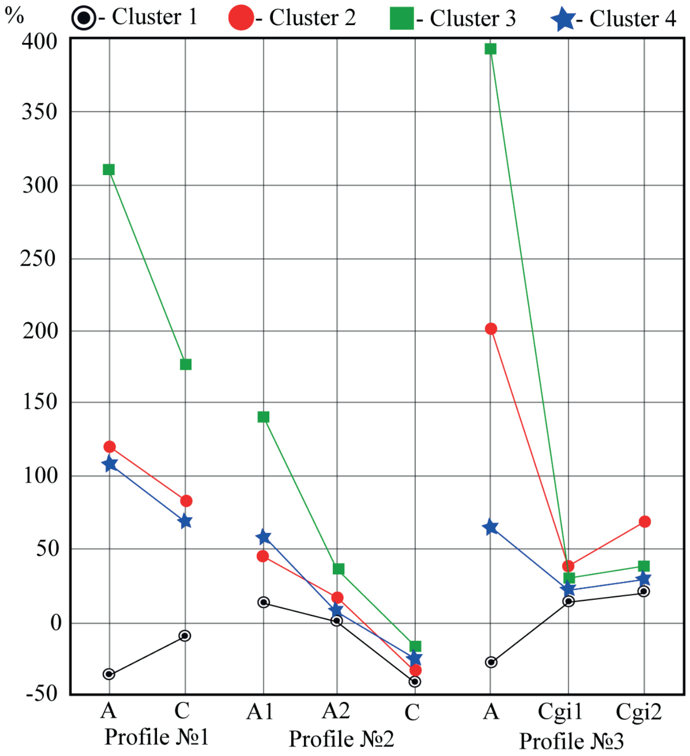

Fig. 7. Graph of average changes in the content of mobile trace elements after flooding, %:
C1: Li, Cr, Co, Zn, Rb, Sr, Mo, Cd, Cs, Ba, W, Tl;
C2: Be, Cu, Hf, U, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu;
C3: Sc, Ni, Th;
C4: V, Ga, As, Y, Zr, Pb, La

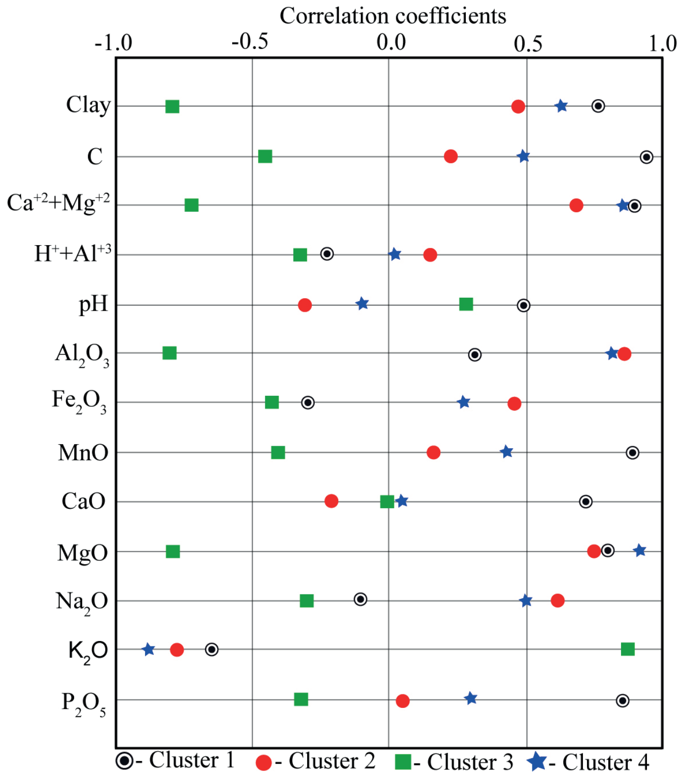

Fig. 8. Graph of average coefficients of correlation between the content of the total trace elements, major elements and properties of soils before the flood:
C1: Zn, Cu, Cd, Pb;
C2: Be, Sc, V, Cr, Ga, As, Zr, Nb, Hf, Ta, Eu;
C3: Sr, Ba;
C4: Li, Co, Ni, Rb, Y, Mo, Sn, Sc, W, Tl, Th, U, La, Ce, Pr, Nd, Sm, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu

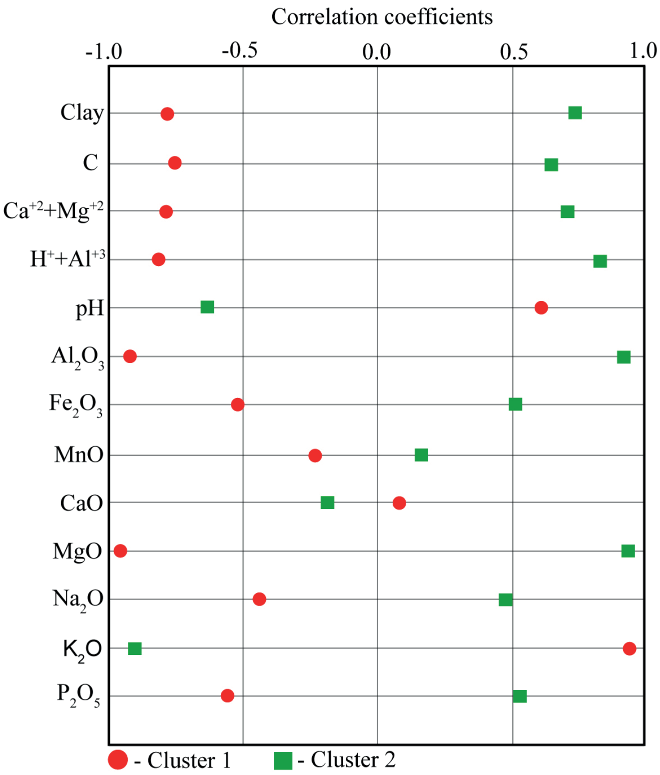

Fig. 9. Graph of average coefficients of correlation between the content of the total trace elements, major elements and properties of soils after the flood:
C1: Sr, Ba;
C2: All other elements

iron oxides disintegrate and mobilize (Vodyanitsky 2010) due to high acidity, being, consequently, intensively washed out by flood waters.

The most substantial changes of major element composition were observed in P3, which was inundated for longer period of time due to its location on the bottom of a dry creek. Minimum changes occurred in major element composition of P2, which located on the top of levee and was the first to come out of flood waters. As the location was on the way of the flood waters entering the floodplain, the soil was covered by a thick layer of alluvia, which preserved the soil from washing out and significant changes in element composition. Hence, length of inundation and water flow velocity were the main factors determining the influence of flood on element composition of fluvisols. In turns, the impact of water flow was affected by floodplain landscape, which goes in line with supposition that floodplain relief is the key pedogenic factor in fluvial soil formation (Du Laing 2009).

Analysis of the flood impact on total content of trace elements

Flood caused rise of trace elements content in P1 and P3. In lower horizons elements belonging to clusters 2, 3 and 4 mainly accumulated, whereas in upper horizons their content did not change or rose insignificantly (Fig. 3). The maximum rise in content of Ni, Cu and Mo was observed, which could be explained by great content of the elements in allochthonic matter. Our conclusion is consistent with the data about greater concentrations of the elements in bottom sediments (Sorokina & Zarubina 2011). Elements belonging to C1 were washed out of all the soil horizons, but most intensively out of upper horizons. Reduction of the content of C1 elements and insignificant accumulation of C2, C3 and C4 elements in organic horizon can be attributed to influence of redox potential. Changes of redox potential are faster and bigger in organic horizons of redundantly wet soils than in mineral horizons. Decrease of Eh during the flood results in drastic rise of acidity (Shaheen et al. 2016). In such conditions trace elements are washed out of soils or displaced down the soil profile. The latter is supported by the data (Antić-Mladenović et al. 2016; Kuznetsov et al. 2017; Shaheen et al. 2014) on high mobility of Sr, Cd and Pb at low pH as well as numerous studies of the influence of redox potential on accumulation of trace elements (Cao et al. 2001; Frohne et al. 2011; Schulz-Zunkel et al. 2015). In organic horizon of P2 the content of the most trace elements did not change (Fig. 3). In the lower horizon both processes, washing out and accumulation, were observed. There were some differences in accumulation of trace elements between fluvisols, which could be explained by longer inundation of P1 and P3, eventually, leading to greater amount of allochthonic matter. In P2, sedimentary cover of alluvia impeded arrival of new elements. However, the location of the soil in the area of high dynamics of water flow caused intensive washing through the soil, and afterward, decreases in concentration of most elements, especially in sandy horizon.

The flood did not have much influence on the relationships between soil properties, content of major elements and total trace elements (Fig. 5, 6). Before the flood, content of trace elements was mostly dependent on mineral composition of the soils (Fig. 5). That is indicated by positive correlation to Al and Mg oxides, which, in youth fluvisols, exist in the form of the substances having strong sorption potential (Du Laing et al. 2009), namely: primary aluminosilicates and secondary clay minerals (Scriabina 2011). Organic matter also did not have much influence on total content of trace elements, which might have been caused by youth of the studied soils. The only

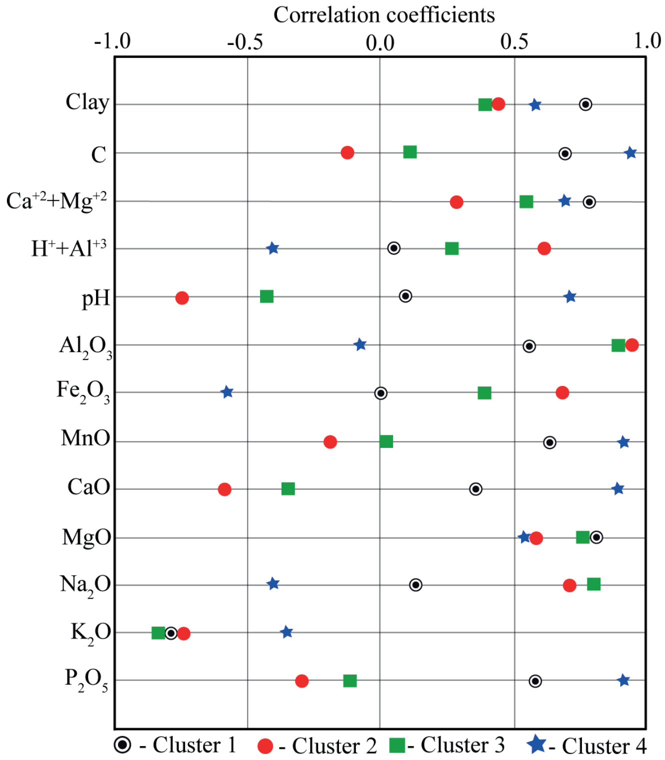

Fig. 10. Graph of average coefficients of correlation between the content of the mobile trace elements, major elements and properties of soils before the flood:

C1: Rb, Ba, W, Tl, Pb;
C2: Be, Sc, Cr, Ga, Y, Hf, Th, REE
C3: Co, Ni, Cu, Zr, Cs, U;
C4: Li, V, Zn, As, Sr, Mo, Cd

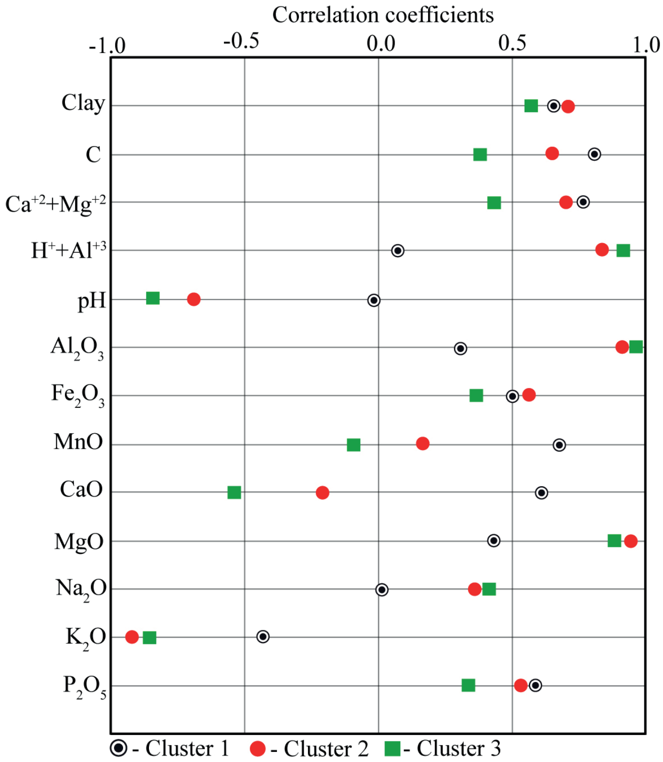

Fig. 11. Graph of average coefficients of correlation between the content of the mobile trace elements, major elements and properties of soils after the flood:

C1: Li, V, Ni, Zn, As, Sr, Mo, Cd, W;
C2: Be, Cr, Co, Rb, Zr, Ba, Hf, Pb;
C3: Sc, Cu, Ga, Y, Cs, Ti, Th, U, REE

elements bound to carbon of organic matter were Zn, Cu, Cd and Pb. The elements standing apart were Sr and Ba as they had positive R only to potassium oxides (Fig. 5). The behavior of Ba was dependent on its association to potassium in rocks and its frequent existence in alkaline feldspars and biotites (Kabata-Pendias 2011). Sr can display similar behavior, as it is geochemically isomorphic with Ba and is contained in great amount in plagioclases and feldspars (Ivanov 1994). On the bases of origin of Sr and Ba and lack of positive or negative Rs to soil properties, we may presume that Sr and Ba mainly exist in the composition of primary minerals or that they are absorbed by the minerals. After the flood the relationships between trace elements, major elements and soil properties changed insignificantly though reduction of diversity of Rs was observed (Fig. 6). All trace elements, apart from Sr and Ba, had near values of R to major-element composition and soil properties. The latter indicated reduction of spacial variability of fluvial soil properties after the flood.

Thus, the flood caused increase of the concentration of most trace elements, except Sr, Cd, Ba, Tl and Pb. Accumulation of elements mainly occurred in lower horizons, whereas composition of upper horizons did not change much due to rise of acidity and development of reduction environment during inundation. Also, the flood developed the conditions in fluvisols which make all trace elements, except Sr and Ba, show similar behavior in relation to soil properties.

Analysis of the flood impact on the content of mobile trace elements

Mobile fractions of trace elements are very dynamic and their content in soils can change in a short period of time (Kovda 1973). As a result, it is hard to estimate the influence a flood has on them. However, mobile trace elements strongly react to changes of soil properties, so their content allows us to identify the processes occurring in soils after inundations. After the flood, most analyzed mobile trace elements accumulated on organic horizons (Fig. 4), whereas total content of trace elements did not change significantly. The main factor of mobility of trace elements both in soils and soil solutions is pH (Zeng et al. 2011). Thus, increase of content of mobile trace elements belonging to C2, C3 and C4, as well as decreasing of content of C1 elements (Fig. 4) was dependent on increase of acidity. The reason for decrease of the content of C1 elements in Fig. 4 was in positive correlation of the elements to pH and CaO (Fig. 7). This the elements stayed mobile in neutral or slightly acidic pH, whereas strengthening of acidity after the flood caused their immobilization. The latter is proved by Rs of the trace elements to pH close to 0 after the flood (Fig. 8).

Content of mobile trace elements also depended on their selective sorption. Unlike total content of trace elements, part of mobile trace elements (C1 and C4) was accumulated by organic matter, but the other part (C2 and C3) was accumulated by soil minerals (Fig. 7). Trace elements adsorbed by organic matter had linkage to contents of manganese, phosphorous and calcium oxides. While comparing element composition of C1 (Fig. 4) and element composition of C2 and C3 (Fig. 7), we noticed that content of elements adsorbed by organic matter reduced after the flood. That was assumptive consequence of decrease of the content of organic matter, or oxides, which bind with the trace elements. After the flood differences of selective sorption by the components of the soils of mobile trace elements became less pronounced (Fig. 8). Therefore, the flood caused homogenization of relationships between the content of mobile trace elements and soil properties. However, the process was weaker than that of total content of trace elements.

All things considered, the flood caused immobilization of Li, Cr, Co, Zn, Rb, Sr, Mo, Cd, Cs, Ba, W and Tl in fluvisols as a result of increase of acidity, reduction of organic matter content and of content of calcium, manganese and phosphorous oxides.

Other trace elements which were mainly connected with mineral composition of soils mobilized in the conditions of high acidity. The flood had stronger influence on mobility of trace elements in organic horizons, which was caused by development of reduction environment in the horizons during the flood and, as a result, higher acidity of organic horizons compared to mineral ones.

CONCLUSION

Our study of the influence of the severe flood on element composition of fluvisols in the middle reach of the Amur River demonstrated that main influence revealed in enhancement of the fluvisols acidity, washing out of organic and silt fractions and retention of allochthonic matter. As a result of these processes, the content of calcium, manganese and phosphorous oxides decreased in major-element composition. Concurrently, in trace-element composition, washing out of Sr, Cd, Ba, Tl and Pb occurred. Besides, immobilization of mobile Li, Cr, Co, Zn, Rb, Sr, Mo, Cd, Cs, Ba, W and Tl was observed. After the flood, total content of Ni, Cu, Mo and mobile forms of Sc, Ni, Th accumulated. The consequences of the flood mostly depended on floodplain landscape, which made topography the key soil-forming factor in development of element composition of fluvisols. Content of other major and trace element altered insignificantly. The attained results contribute to fundamental knowledge of flood consequences for fluvisols and floodplain landscapes in general, and are critical to study of geochemical processes in one of the longest rivers of the world, the Amur. ■

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APPENDIX

Table A.1. Content major elements in alluvial soils before and after flood

Major elements	Content major elements, %							
	Profile 1		Profile 2			Profile 3		
	A	C	A1	A2	C	A	Cgi1	Cgi2
Before flood								
Si_2O	72.54	72.44	69.2	69.97	68.85	64.19	66.38	67.99
TiO_2	0.77	0.83	1.02	1.01	1.07	0.81	0.99	0.77
Al_2O_3	11.59	10.77	12.47	13.14	13.92	13.1	15.82	15.93
Fe_2O_3	4.58	5.43	6.69	6.79	7.17	4.76	7.17	6.26
MnO	0.13	0.14	0.18	0.18	0.12	0.38	0.18	0.14
CaO	3.17	2.96	2.9	2.11	1.91	6.47	1.78	1.57
MgO	0.6	0.58	0.72	0.71	0.74	1.21	1.16	1.14
Na_2O	1.7	1.53	1.56	1.54	1.57	1.36	2.02	2.17
K_2O	3.98	4.72	4.14	3.52	3.61	2.96	2.96	2.76
P_2O_5	0.32	0.21	0.32	0.26	0.32	0.77	0.24	0.26
After flood								
Si_2O	71.48	75.4	70.72	68.83	72.63	66.72	66.8	64.99
TiO_2	0.95	0.56	0.92	1.11	0.75	1.01	0.94	1.02
Al_2O_3	11.22	10.06	12.16	13.57	11.61	14.77	17.31	16.97
Fe_2O_3	5.61	3.85	6.21	7.57	4.93	7.15	6.56	5.89
MnO	0.14	0.1	0.16	0.16	0.13	0.21	0.1	0.14
CaO	3.18	2.56	2.72	1.99	2.1	1.94	1.07	1.09
MgO	0.57	0.48	0.67	0.72	0.56	0.98	1.12	1.04
Na_2O	1.74	1.7	1.6	1.39	1.8	1.74	1.99	1.78
K_2O	4.31	4.89	3.95	3.5	4.45	2.96	2.59	2.68
P_2O_5	0.27	0.12	0.26	0.27	0.19	0.31	0.23	0.28

Table A.2. Content of the total and mobile form of trace elements in alluvial soils before flood

Trace element	Content trace element, mg/kg															
	Profile 1				Profile 2						Profile 3					
	A		C		A1		A2		C		A		Cgi1		Cgi2	
	total	mobile	total	mobile	total	mobile	total	mobile	total	mobile	total	mobile	total	mobile	total	mobile
Li	16.2	0.048	11.7	0.028	22.0	0.064	22.2	0.051	22.6	0.041	37.0	0.581	44.0	0.116	33.7	0.108
Be	1.5	0.030	1.3	0.039	1.8	0.055	1.8	0.132	1.8	0.136	1.9	0.047	2.4	0.189	2.1	0.193
Sc	5.4	0.007	3.0	0.015	6.6	0.018	6.1	0.066	5.9	0.084	7.6	0.017	10.9	0.134	8.7	0.173
V	48.3	0.037	27	0.027	60.0	0.024	56.7	0.016	56.5	0.020	69.3	0.155	99.6	0.037	84.0	0.032
Cr	36.0	0.085	13	0.230	31.4	0.336	29.6	0.427	27.6	0.519	38.1	0.334	56.7	0.653	43.1	0.720
Co	6.5	0.172	3.9	0.151	8.4	0.191	8.7	0.224	8.8	0.209	11.6	0.316	15.3	0.459	13.7	0.560
Ni	11.5	0.078	6.7	0.059	15.0	0.093	15.7	0.237	14.5	0.097	27	0.345	28.3	0.642	22.9	0.687
Cu	7.1	0.003	3.1	0.042	10.8	0.024	10.7	0.082	8.9	0.036	37.2	0.065	25.0	0.310	20.0	0.305
Zn	49.5	2,759	21.4	0.178	57.9	0.604	51.1	0.165	49.3	0.079	168.1	9,285	101.1	0.582	78.8	0.676
Ga	15.0	0.006	13.0	0.007	17.3	0.011	16.5	0.044	16.7	0.049	15.6	0.025	22.3	0.064	19.6	0.064
As	5.3	0.105	4.9	0.086	7.6	0.064	7.7	0.056	8.1	0.077	10.1	0.719	14.7	0.125	14.6	0.117

Rb	91.8	0.270	85.2	0.032	98.9	0.197	94.2	0.526	93.2	0.557	101.7	2,822	114	1,469	103.8	1,603
Sr	418.1	14,978	428.8	4,951	396.6	9,957	356.7	10,842	341.4	7,196	295.8	72,258	261.2	19,058	316.8	13,387
Y	11.0	0.138	7.8	0.175	12.8	0.275	12.2	1,178	10.5	1,211	17.0	0.575	19.5	1,775	16.0	1,799
Zr	40.1	0.017	17.4	0.020	38.1	0.023	42.8	0.048	43.1	0.051	50.9	0.053	75.5	0.105	63.9	0.131
Nb	6.8	0.000	4.4	0.000	7.9	0.000	7.5	0.000	7.6	0.000	7.2	0.000	9.9	0.000	7.5	0.000
Mo	0.4	0.003	0.3	0.005	0.5	0.003	0.5	0.004	0.5	0.000	1.0	0.008	1.4	0.003	1.1	0.001
Cd	0.2	0.043	0.1	0.006	0.1	0.017	0.1	0.007	0.1	0.003	1.1	0.164	0.2	0.013	0.1	0.017
Sn	1.3	0.000	0.7	0.000	1.5	0.000	1.4	0.000	1.4	0.000	2.2	0.000	2.5	0.000	2.0	0.000
Cs	2.3	0.008	1.5	0.002	3.0	0.006	3.4	0.053	3.3	0.062	5.6	0.042	6.9	0.088	5.2	0.097
Ba	973.0	26.92	1,103.0	12.68	915.0	28.88	858.0	51,700	850	30,700	835.3	81.22	792.2	66.23	891	61.51
Hf	1.2	0.001	0.6	0.001	1.2	0.001	1.4	0.002	1.3	0.002	1.5	0.001	2.2	0.004	1.7	0.004
Ta	0.5	0.000	0.4	0.000	0.6	0.000	0.5	0.000	0.6	0.000	0.5	0.000	0.7	0.000	0.5	0.000
W	0.6	0.001	0.4	0.000	0.9	0.002	1.2	0.002	1.0	0.001	1.4	0.002	1.7	0.001	1.3	0.001
Tl	0.5	0.003	0.5	0.001	0.5	0.002	0.5	0.005	0.5	0.005	0.6	0.017	0.6	0.011	0.6	0.010
Pb	19.2	0.372	16.3	0.177	20.5	0.286	18.7	0.431	19.1	0.600	39.2	0.786	25.2	0.793	25.3	0.816
Th	4.2	0.012	3.5	0.028	5.5	0.034	6.1	0.131	6.0	0.142	8.3	0.033	11.1	0.239	9.0	0.237
U	1.2	0.099	0.8	0.129	1.6	0.172	1.7	0.321	1.8	0.324	3.2	0.224	4.2	0.889	3.6	0.861
La	21.7	0.178	12.8	0.275	28.6	0.383	25.3	1,570	27.3	1,776	35.5	0.690	37.2	2,027	33.4	1,991
Ce	47.5	0.297	28.8	0.28	61.3	0.630	52.7	2,916	59.2	3,158	68.6	1,206	77.7	4,370	70.2	4,420
Pr	5.2	0.039	3.4	0.060	6.8	0.088	5.7	0.387	5.9	0.423	7.2	0.151	8.2	0.521	7.4	0.514
Nd	19.2	0.169	12.9	0.244	24.9	0.372	20.6	1,648	20.9	1,778	26.5	0.666	29.8	2,268	27.5	2.22
Sm	3.4	0.036	2.4	0.049	4.2	0.079	3.6	0.329	3.5	0.349	4.8	0.132	5.6	0.472	4.9	0.459
Eu	0.8	0.007	0.7	0.010	0.9	0.015	0.8	0.063	0.8	0.068	0.9	0.025	1.1	0.088	1.1	0.086
Gd	2.6	0.034	1.9	0.045	3.2	0.072	2.9	0.298	2.7	0.316	4.3	0.121	4.7	0.421	4.2	0.410
Tb	0.4	0.005	0.3	0.006	0.5	0.010	0.5	0.044	0.4	0.047	0.6	0.017	0.7	0.063	0.6	0.062
Dy	2.1	0.024	1.5	0.033	2.6	0.050	2.4	0.219	2.1	0.236	3.3	0.086	3.8	0.32	3.1	0.319
Ho	0.4	0.004	0.3	0.006	0.5	0.009	0.5	0.040	0.4	0.043	0.6	0.016	0.8	0.059	0.6	0.06
Er	1.1	0.011	0.8	0.016	1.4	0.022	1.3	0.101	1.2	0.107	1.8	0.039	2.2	0.148	1.8	0.153
Tm	0.2	0.001	0.1	0.002	0.2	0.002	0.2	0.012	0.0	0.012	0.3	0.004	0.3	0.017	0.3	0.018
Yb	1.1	0.006	0.8	0.011	1.3	0.014	1.2	0.066	1.1	0.069	1.6	0.022	1.9	0.097	1.6	0.103
Lu	0.2	0.001	0.1	0.002	0.2	0.002	0.2	0.010	0.2	0.010	0.2	0.003	0.3	0.014	0.2	0.016

Table A.3. Content of the total and mobile form of trace elements in alluvial soils after flood

Trace element	Content trace element, mg/kg															
	Profile 1				Profile 2						Profile 3					
	A		C		A1		A2		C		A		Cgi1		Cgi2	
	total	mobile	total	mobile	total	mobile	total	mobile	total	mobile	total	mobile	total	mobile	total	mobile
Li	15.3	0.055	12.1	0.040	19.5	0.042	23.3	0.051	14.8	0.034	37.2	0.086	48.5	0.070	49.9	0.054
Be	1.6	0.06	1.6	0.033	1.7	0.085	2.0	0.161	1.6	0.056	2.1	0.175	2.7	0.251	2.9	0.269
Sc	6.8	0.028	4.1	0.048	8.1	0.037	7.8	0.075	6.8	0.078	12.4	0.095	14.9	0.213	15.8	0.242
V	49.6	0.094	30.6	0.038	56.5	0.036	56.5	0.017	45.1	0.020	93.4	0.188	105.3	0.031	116.3	0.024
Cr	28.1	0.107	16.2	0.033	33.9	0.145	32.9	0.324	24.7	0.070	56.4	0.665	65.3	1,084	68.4	0.956
Co	6.5	0.125	4.6	0.046	8.1	0.076	8.9	0.284	7.2	0.064	13.8	0.264	15.1	0.332	17.5	0.258
Ni	11.0	0.371	13.4	0.151	13.4	0.293	19.4	0.443	12.2	0.054	27.2	1,099	31.3	0.457	32.1	0.59

Cu	6.5	0.037	8.3	0.125	7.7	0.021	13.4	0.069	8.0	0.078	25.6	0.255	26.0	0.255	28.4	0.468
Zn	41.3	1,334	31.8	0.570	47.5	0.387	57.4	0.139	41.8	0.133	102.7	4,105	102	0.515	102.3	0.393
Ga	14.9	0.013	14.1	0.016	16.5	0.016	16.8	0.049	15.8	0.026	20.4	0.047	23.8	0.092	24.2	0.109
As	6.0	0.257	4.4	0.106	6.7	0.078	7.4	0.054	4.9	0.048	13.5	0.462	11.5	0.110	22.1	0.139
Rb	87.0	0.116	96.4	0.007	93.9	0.314	95.3	0.561	94.9	0.287	113.5	1,162	110.2	1,914	110.6	1,884
Sr	375.5	8,279	382.9	3,168	376.8	10,941	323.4	12,825	391.9	3,676	226.1	22.84	206.1	9,592	202.4	10,251
Y	11.5	0.294	8.5	0.317	13.8	0.380	12.5	1,342	11.8	0.725	18.4	1,213	21.7	2,262	25.7	2,818
Zr	37.6	0.024	25.7	0.019	42.9	0.028	42.1	0.022	31.6	0.022	68.6	0.101	77.9	0.123	85.0	0.14
Nb	6.5	0.000	4.6	0.000	6.3	0.000	6.3	0.000	5.9	0.000	9.1	0.000	10.4	0.000	10.1	0.000
Mo	0.4	0.001	0.9	0.001	0.5	0.001	0.4	0.001	0.3	0.001	1.3	0.003	1.4	0.001	2.4	0.002
Cd	0.1	0.025	0.1	0.007	0.1	0.013	0.1	0.004	0.1	0.002	0.2	0.077	0.1	0.016	0.1	0.014
Sn	1.1	0.000	0.8	0.000	1.3	0.000	1.3	0.000	1.2	0.000	2.3	0.000	2.4	0.000	2.5	0.000
Cs	2.2	0.005	1.9	0.001	2.8	0.017	3.5	0.053	2.0	0.014	6.4	0.042	7.3	0.181	7.6	0.211
Ba	844.1	22.36	904.0	12,270	829.6	38.85	865.5	60.41	906.4	11.27	700.9	77.94	705.2	66.49	691.7	62.28
Hf	1.0	0.001	0.7	0.001	1.4	0.001	1.1	0.001	0.9	0.001	1.8	0.004	2.0	0.005	2.2	0.006
Ta	0.4	0.000	0.3	0.000	0.4	0.004	0.4	0.005	0.4	0.001	0.6	0.002	0.7	0.001	0.7	0.001
W	0.7	0.002	0.4	0.001	0.8	0.003	0.9	0.006	0.7	0.002	1.5	0.012	1.6	0.030	1.8	0.032
Tl	0.4	0.753	0.5	0.365	0.5	0.770	0.5	0.73	0.5	0.237	0.6	1,319	0.6	1,400	0.6	1,076
Pb	15.6	0.043	14.7	0.071	17.2	0.069	17.7	0.146	21.7	0.059	22.2	0.199	23.3	0.356	24.7	0.403
Th	4.0	0.198	3.5	0.112	5.2	0.292	6.1	0.407	4.7	0.186	9.4	0.758	11.4	1,286	12.4	1,649
U	1.2	0.395	0.9	0.553	1.5	0.590	1.5	1,881	1.2	1,853	3.0	1,475	4.2	2,898	5.0	3,568
La	25.8	0.769	15.3	1,029	27.0	0.942	28	3,048	21.1	1,029	33.5	3,124	40.2	6,502	47.1	7,758
Ce	54.4	0.093	32.3	0.128	55.7	0.137	53.9	0.451	46.6	0.332	69.4	0.371	83.5	0.753	97.1	0.909
Pr	6.2	0.387	3.9	0.474	6.3	0.530	5.8	1,903	4.9	1,212	7.6	1,609	8.9	3,210	10.5	3,877
Nd	22.1	0.082	14.2	0.091	23.0	0.110	20.0	0.376	17.9	0.196	27.2	0.335	32.4	0.695	38.2	0.827
Sm	3.7	0.016	2.6	0.016	4.1	0.022	3.5	0.073	3.3	0.037	5.1	0.066	6.7	0.127	7.1	0.15
Eu	1.0	0.075	0.8	0.08	1.1	0.102	0.9	0.344	0.9	0.169	1.1	0.323	1.3	0.624	1.5	0.738
Gd	3.3	0.011	2.3	0.012	3.7	0.015	3.35	0.051	3.0	0.027	4.7	0.046	5.6	0.089	6.6	0.112
Tb	0.4	0.055	0.3	0.059	0.5	0.073	0.4	0.255	0.4	0.138	0.6	0.233	0.8	0.474	0.9	0.573
Dy	2.1	0.010	1.6	0.011	2.5	0.013	2.2	0.047	2.2	0.024	3.3	0.044	4.0	0.084	4.7	0.102
Ho	0.4	0.025	0.3	0.029	0.5	0.032	0.4	0.118	0.4	0.060	0.6	0.109	0.8	0.210	0.9	0.256
Er	1.2	0.003	0.9	0.003	1.4	0.004	1.3	0.013	1.2	0.007	1.8	0.012	2.2	0.024	2.6	0.029
Tm	0.2	0.017	0.1	0.021	0.2	0.021	0.2	0.076	0.2	0.037	0.3	0.072	0.3	0.137	0.4	0.167
Yb	1.0	0.002	0.7	0.003	1.3	0.003	1.1	0.011	1.1	0.005	1.7	0.011	1.9	0.020	2.3	0.025
Lu	0.2	0.000	0.1	0.000	0.2	0.004	0.2	0.005	0.2	0.001	0.2	0.002	0.3	0.001	0.3	0.001