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Environmental and human impacts on sediment transport of the largest Asian rivers of Russia and China

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Abstract

The paper deals with comparative summary of sediment loads and particulate trace metals (V, Cr, Co, Cu, Zn, Cd, Pb) transport in the largest Asian rivers of Russia and China. Environmental conditions and human interventions in the selected catchments (Lena, Ob, Enisey, Selenga, Kolyma, Amur, Yellow, Yangtze, Pearl) are analyzed with respect to the rate and composition of suspended sediment loads. The paper presents calculations of sediment load changes at the downstream sections of the rivers and new database of the chemical composition of suspended matter which involves all recent studies of the last decade for the sediment geochemistry. The results indicate that fluvial system and its human modifications are the most significant drivers of sediment load. Fluvial erosion in the unconfined channels exerts a significant control on the sediment load changes due to observed permafrost melting. We concluded that construction of reservoirs has the most important influence on land–ocean sediment fluxes in the largest rivers of Asia but plays relatively weak role in heavy metal composition in suspended particulate matter (SPM) due to lowest sedimentation rates of the fine clay particles, which are mostly enriched with heavy metals. The paper also presents novel mapping approaches related to cartographic recognition of the fluvial system and its human modification and sediment transfer processes in the largest Asian rivers of Russia and China, linked with a specific legend. Finally, analysis of uncertainties associated with estimating the SPM composition in the rivers was done with respect to spatial and temporal variability. It was shown that the main error occurs due to incorporation of data only from particular hydrological seasons which usually ignore high flood conditions.

Keywords Sediment transport · Heavy metals · Fluvial processes · Dams · Large rivers · Russia · China

Introduction

Many rivers are particularly exposed to problems of multiple uses, often with conflicting aims. At the global scale, river systems are altered by increased sediment and nutrient loads leading to eutrophication of river stretches, navigation and hydropower plants deteriorating ecosystem functions and further human uses leading to far reaching problems downstream. Many of river systems are modified by dams construction which became a significant driver of sediment delivery to the oceans in the global scale (Walling and Fang 2003; Cohen et al. 2014). At the same time, many regions of the World still have relatively undisturbed rivers until present time. This leads to the global spatial distinctions in patterns of water flow, water and sediment quality, fluvial processes (Alexeevsky et al. 2013), sediment transport and biodiversity. Attributing changes in all of these general topics to specific factors is challenging because multiple drivers act at different temporal and spatial scales. This leads to differences in fluvial fluxes which have a significant impact on the river system biogeochemistry (Holmes et al. 2012). In Asia, rivers originate in its central part and then cross distinctive environmental regions of Russian Federation and

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China on their way to Arctic or Pacific oceans (Karthe et al. 2015). These catchments include humid and arid lands, both most densely and rarely populated areas of the World, and in this regard could be used as a natural field laboratory to understand large-scale patterns of hydrological and land use impact of fluvial systems. Even though the rivers have been the subject of abundant studies in hydrology (Miao et al. 2010; Gao et al. 2011; Dzhamalov et al. 2012), fluvial geomorphology (Zhang et al. 2014; Chalov and Alexeevsky 2015), sedimentology and geochemistry (Liu et al. 2007; Chalov et al. 2014; Escoube et al. 2015) and water resources management (Dukhovny et al. 2013), there is lack of integrated approaches to study environmental impacts on sediment transfer processes.

The main challenge of our study is to understand and analyze the possible interactions of the multiple drivers and their individual and combined effects in the sediment transfer processes of the largest river systems of Russian and Chinese Asia. River systems and sediment patterns are analyzed in regard to various impacts from land use changes and rivers hydromorphology. The main objective of the paper is to provide comparative summary of fluvial systems and their relations to sediment patterns (sediment load long-term variability and suspended particulate matter (SPM) content) in the largest rivers of Russia and China—Lena, Ob, Enisey, Selenga, Kolyma, Amur, Yellow, Yangtze and Pearl. In particular, spatial patterns of hydrological features, fluvial processes and human interventions have been analyzed in order to explain basin-wide discrepancies of temporal changes in suspended sediment load rates and particulate modes of V, Cr, Co, Cu, Zn, Cd, Pb in river sediments. The additional aim of the study is to elaborate a mapping approach of cartographic recognition of the fluvial system and its human modification and sediment transfer processes in the largest Asian rivers of Russia and China, linked with a specific legend. The main novelty of our study is the complex representation and integrated analyses of large rivers fluvial systems, sediment rates and SPM content.

Methodology and case study area

Nine rivers from the top largest in the regions (Ob, Enisey, Selenga, Lena, Kolyma, Amur, Yellow (Huang-he), Yangtze (Chang-jiang) and Pearl (Zhu-jiang) were selected in the study. The case studies include undammed (Selenga River) and intensively dammed (Yellow and Yangtze) rivers flowing in Northward or Eastward directions, located in one country, in 2 (Amur and Selenga) and 3 (Ob and Irtysh) countries.

Sediment transfer processes (sediment load rates and composition) in the selected rivers were analyzed in regard to hydrology, land use and fluvial processes and their possible interactions. Sediment transport features were studied

based on the data for the most downstream gauging stations, which are considered as integrated measures of the sediment processes within entire basins. This approach is determined by the lack of long-term monitoring data for the sediment processes (for example on the Kolyma River there are only two gauging stations in the basin with regular measurements of suspended sediment concentrations). Therefore, detailed basin-wide assessment is not possible with the existing datasets for the Siberian rivers. Due to this, suspended sediment load datasets were analyzed for the Ob River (gauging station Salekhard), the Enisey River (gauging station Igarka), the Selenga River (gauging station raz'ezd Mostovoy), the Lena River (gauging station Kyusyur), the Kolyma River (gauging station Ust-Srednekan) and the Amur River (gauging station Bogorodskoye) (Table 1). Available published data included overviews (Dedkov and Mozzherin 1996; Dedkov and Gusarov 2006; Walling 2006; Syvitski and Kettner 2011) and regional studies for the Selenga (Chalov et al. 2014), Ob and Enisey Rivers (Magritsky 2010). The data for the Chinese rivers were obtained from literature (Gray et al. 2002; Gao et al. 2010; Wu et al. 2012; Dai and Lu 2014; Wei et al. 2016). Long-term changes in sediment transport were calculated based on relative ratio:

$$\Delta W(\%) = (W(1) - W(2))/W(1) \tag{1}$$

where $W(1)$—annual sediment yield (Mt/year), average for the reference long-term period 1, $W(2)$—annual sediment yield (Mt/year), average for the contemporary reference long-term period 2.

Average content of V, Cr, Co, Cu, Zn, Cd, Pb in suspended particulate matter (SPM) was assessed for the outlet most downstream reaches of the rivers. Both reviews (Savenko 2006; Bagard et al. 2011; Pokrovsky et al. 2015) and regional studies on the Rivers Lena (Hölemann et al. 2005), Ob (Shakhova et al. 2007), Amur (Levshina 2008; Chudaeva et al. 2011) were used. The most detailed datasets are summarized for the Yangtze, Yellow and Selenga Rivers based on novel field campaigns (Qiao et al. 2007; Chalov et al. 2014). In some cases, the data on the heavy metal composition in bottom sediments (Temerev and Savkin 2004; Chizhikova et al. 2011) and seston (Chizhikova et al. 2011) was also included into analyses. No data from Kolyma River on suspended sediment geochemistry have been found in the literature.

Estimates of elemental concentrations in river sediments were compared to the World averages of heavy metal concentrations in SPM based on data from (Savenko 2006; Viers et al. 2009). A coefficient HM to define relationship of SPM concentrations from the studied river with the World averages was calculated as:

$$\mathrm{HM}_x = \frac{C_{x\,i}}{C_{x\,\mathrm{world}}} \tag{2}$$

Table 1 Sediment load gauging stations and datasets used in the present study

River	Name of the most downstream/outlet station with sediment load measurement	Distance from the mouth, km	Basin area at the site, km^2	Observation time	Suspended sediment load, Mt/year (source)[a]	
Ob	Salekhard	287	2,950,000	1938–47, 50—present	16.0 (Surface water…, 1980)	
Enisey	Podkamennaya Tunguska	1568	1,760,000	1941–43, 56, 58—present	5.40 (Long-term data…, 1985a)	
	Igarka	697	2,440,000	1941–43, 47, 49–51, 53, 55, 56, 70–1990s	4.10 (Long-term data…, 1985a)	
Selenga	raz'ezd Mostovoy	127	440,000	1939, 41, 45, 47—present	2.20 (Long-term data…, 1986a)	
Lena	Kyusyur	211	2,430,000	1944, 60—present	21.0 (Long-term data…, 1987)	
Kolyma	Ust-Srednekan	1623	99,400	1941—present	2.78 (Long-term data…, 1985b)	
	gidrostvor Kolymskoe 1	272	526,000	1977–1990s	18.0 (Long-term data…, 1985b)	
Amur	Bogorodskoye	238	1,790,000	1965—present	20.0 (Long-term data…, 1986b)	
Yellow (Huang-he)	Lijin	104	751,900	1950—present	780 (1950–2007) (Peng et al. 2010); 707 (1950–2013) (Wei et al. 2016); 1080 (1950–1980s) (Milliman and Meade 1983; Wang et al. 2011)	
Yangtze (Chang-jiang)	Datong	511	1,705,383	1950—present	470 (Yang et al. 2011); 424 (1950–2002), 148 (2003–2010, after TGD) (Dai and Lu 2014)	
Pearl (Zhu-jiang)	Gaoyao (West (Xijiang) River)	187	351,535	1954—present	65.7 (Wu et al. 2016b); 64.5 (1954–2009) (Wu et al. 2012); 69 (1950–1980s) (Milliman and Meade 1983; Wang et al. 2011)	88.7, 29.2 (2006–2011, after LTD) (Wu et al. 2016b); 70 (1955–2000), 38.7 (2000–2010, after LTD) (Wu et al. 2016a)
	Shijiao (North (Beijiang) River)		38,363	1954—present	8.64 (Wu et al. 2016b); 5.45 (1954–2009) (Wu et al. 2012)	
	Boluo (East (Dongjiang) River)	162	25,325	1954—present	2.36 (Wu et al. 2012; 2016b)	

[a]These are reported values from the literature (the references are given in the brackets)

where x is a considered element, C—element concentration for the certain i river (C_i) or for the World average (C_{world}) (from Savenko 2006). The coefficient HM is supposed to be an appropriate indicator of environmental processes and local impacts (fluvial erosion, emissions, geochemical anomalies, etc.) to the SPM composition. It is important to note that SPM World averages are closely related to widely accepted World rock concentrations (e.g., estimated by Vinogradov 1962). For each river basin, the total trace metals concentration C_0 was calculated as:

$$C_0 = \sum_{1}^{n} C_x \tag{3}$$

where n is number of trace metals ($n = 7$).

For fluvial processes analyses, we used stream classification elaborated at the Lomonosov MSU (Alabyan and Chalov 1998) which is based on the observations in different environments of Russia—from mountains (Caucasus, Than-Shan, etc.) to flatlands (East European plane, West Siberian plain, etc.), and both at ephemeral and perennial nival belts (Chalov 2004). It contains five main fluvial processes types in the stream corridor (from high-gradient streams with rapids/falls to plain rivers) and 3 groups of channel patterns

(straight, meandering and braided) are found. All of the types are separated using variety of quantitative geomorphologic indicators (stream order, stream power, stream size and channel slopes, entrenchment ratio, sinuosity or total number of branches). Conditions of channel plan form changes differ according to the ratio of the width of the flood-prone area to the bankfull surface width of the channel. The flood-prone area is defined as the width measured at an elevation which is determined as twice the maximum bankfull depth. Unconfined channels (with wide floodplain) are characterized by high ratios of floodplain width (> 3), whereas confined (incised) channels are related to low ratios (< 1) (Alabyan and Chalov 1998). Based on distribution of confined channels, for each river confinement ratio CR (%) was calculated as length of confined channel reaches per river length:

$$CR(\%) = (\text{length of confined channel reaches})/(\text{river length}) \tag{4}$$

The assessment of channel patterns distribution was done based on the satellite imagery processing (source for the background maps—LANDSAT bands 2, 3 and 4 (U.S. Geological Survey, 2016) and digital elevation models (Shuttle Radar Topography Mission 90 m (U.S. Geological Survey 2017) survey both with data from field campaigns

(observations and measurements). For the confined and unconfined reaches distribution of straight, meandering and braided channel patterns was counted. Selected features were mapped for the territory from 20° to 80°N and from 40° to 170°E (Fig. 1) based on polyconic projections (100° central meridian). Length threshold for the selection of rivers on the map was 1000 km. We generated a fluvial processes and sediment patterns map of the largest Asian rivers draining the Northern and Eastern parts of Siberia and originating in the Central Asia. The specific legend of the general fluvial processes map includes average assessment of CR for each river basin (for the main stem of the river network), dams density and largest cities location (Fig. 1).

Additionally, we compared uncertainties associated with estimating the flux of sediments transported by rivers due to attributing data from different spatial and temporal scales based on the results for the Selenga River (Chalov et al. 2014), the Yellow River (Qiao et al. 2007) and the Yangtze River (Qiao et al. 2007). The seasonal variations of metal concentrations in the suspended sediments were examined based on the data obtained for the same point during different hydrological seasons. Uncertainties related to basin-wide variability of SPM composition were studied based on the data from the same hydrological season obtained from different locations within single catchment. Uncertainties due to sampling conditions were examined based on the cross-sectional (the same depth within one cross section at the certain sampling time) and depth-wide (through the water column at different depths) variability. For all datasets using standard procedures in Microsoft Excel 2010 average (M), variance (D, dispersion of the data around the mean), standard deviation $\sigma = \sqrt{D}$ and coefficient of variation $CV = \sigma/M$ were estimated.

Results and discussion

Environmental and human impacts on sediment transport

Estimates of channel pattern types along the main stem of the case study rivers (Fig. 1; Table 2) evidence the variable conditions of river hydromorphology. Based on the CR (%) (4), the rivers are ordered in the following sequence from confined to unconfined channels: Pearl–Lena–Yangtze–Enisey–Yellow–Amur–Kolyma–Selenga–Ob. Five of the studied rivers could be named as unconfined-dominated channels (Yellow–Amur–Kolyma–Selenga–Ob) with the confinement ratio (CR < 50%), whereas the rest (Pearl–Lena–Yangtze–Enisey) are confined-dominated channels (CR > 50%).

The construction of dams for water supply, hydropower generation and flood control is considered to be an important driver of human activities impact on sediment transfer

processes (Walling and Fang 2003). Few orders of magnitude variability of the dams density between the studied rivers (Fig. 1) should be considered in this regard. In the whole Asian part of Russia (including all studied catchments—Lena, Enisey, Amur, Kolyma, Selenga, Ob), there are only 16 large reservoirs (with the dams higher than 15 m) (Asarin et al. 2012), which is less then number of large dams in the particular Yellow River (20) or Yangtze River (35) basins (Table 3). There are 22,104 dams higher than 15 m in China (according to World dams commission reports) including the highest dam on the left tributary of the Yangtze River–the Yalong River (305 m) (Yang et al. 2011) and in total ~ 50.000 dams throughout the Yangtze River watershed. There are more than 350 large reservoirs (larger than 0.1 km^3) (Yang et al. 2011). One of the case study rivers of Russia still represents "pristine" undammed river system (the Selenga River) (dams density equals 0) (Chalov et al. 2014). All in one, the rivers can be ordered in the following sequence related to the dam density in the river catchment: Yangtze–Pearl–Yellow–Lena–Enisey–Kolyma–Ob–Amur–Selenga (Table 3).

Long-term variability of sediment load

Within river catchments of Russia, significant variability of suspended sediment load changes has been observed (Table 4). Increase in sediment load from 50% at Belegor'ye, some 700 km upstream of Salekhard (Table 1; Fig. 1) to 37% at Salekhard station has been seen in the downstream section of the Ob River (Table 4). The similar trends have been observed for the undammed Kolyma River (Ust-Srednekan) where sediment rates increased from 20 to 100 t/(km^2 year) in the second half of XX century. Reverse trends have been noticed at the outlets of the Enisey River (up to 67% decline in sediment transport in 1971–2000 compared to 1941–1956) and the Lena River (up to 16% decline during 1974–2000 compared to 1959–1966).

Multiple driver effects have been seen at the upper part of the Enisey River (tributaries of Baikal Lake). On the Selenga River during the last 30 years, there has been a substantial decline (about 50%) of annual sediment loads. In the downstream Selenga River, the decline is estimated from 67 to 34 kg/s (Chalov et al. 2014) which are in line with land use changes and a long-lasting low water period (since around 1995) (Fig. 2). A statistically significant downward trend from 903 (for the period 1941–1982) to 888 m^3/s (for the period 1983–2011) has been reported for the river. The correlation factor between water runoff and suspended sediment concentrations was 0.52 in the earlier period and 0.16 in the later period (Chalov et al. 2014). However, the main part of the estimated decline within the Russian part of the basin can almost certainly be ascribed to the crisis in the agricultural sector of the Russian economy in the end of the XX century that led to the abandonment of cultivated

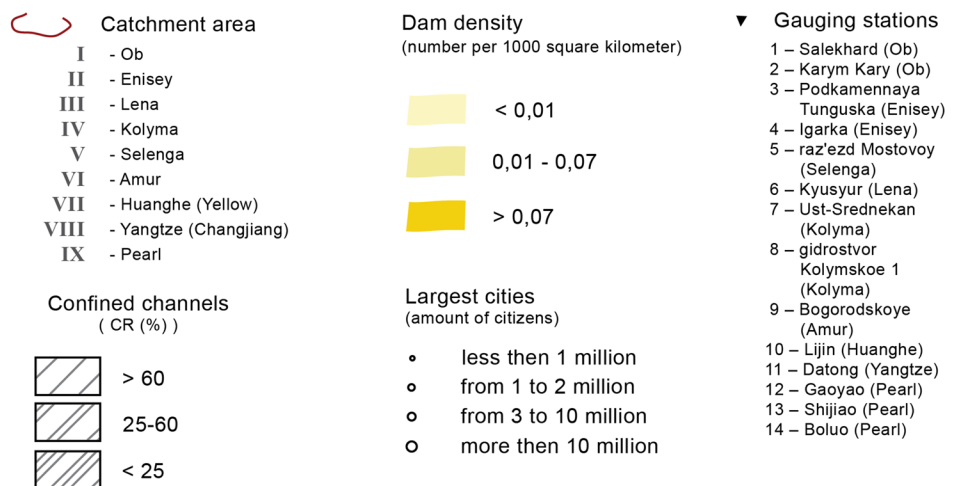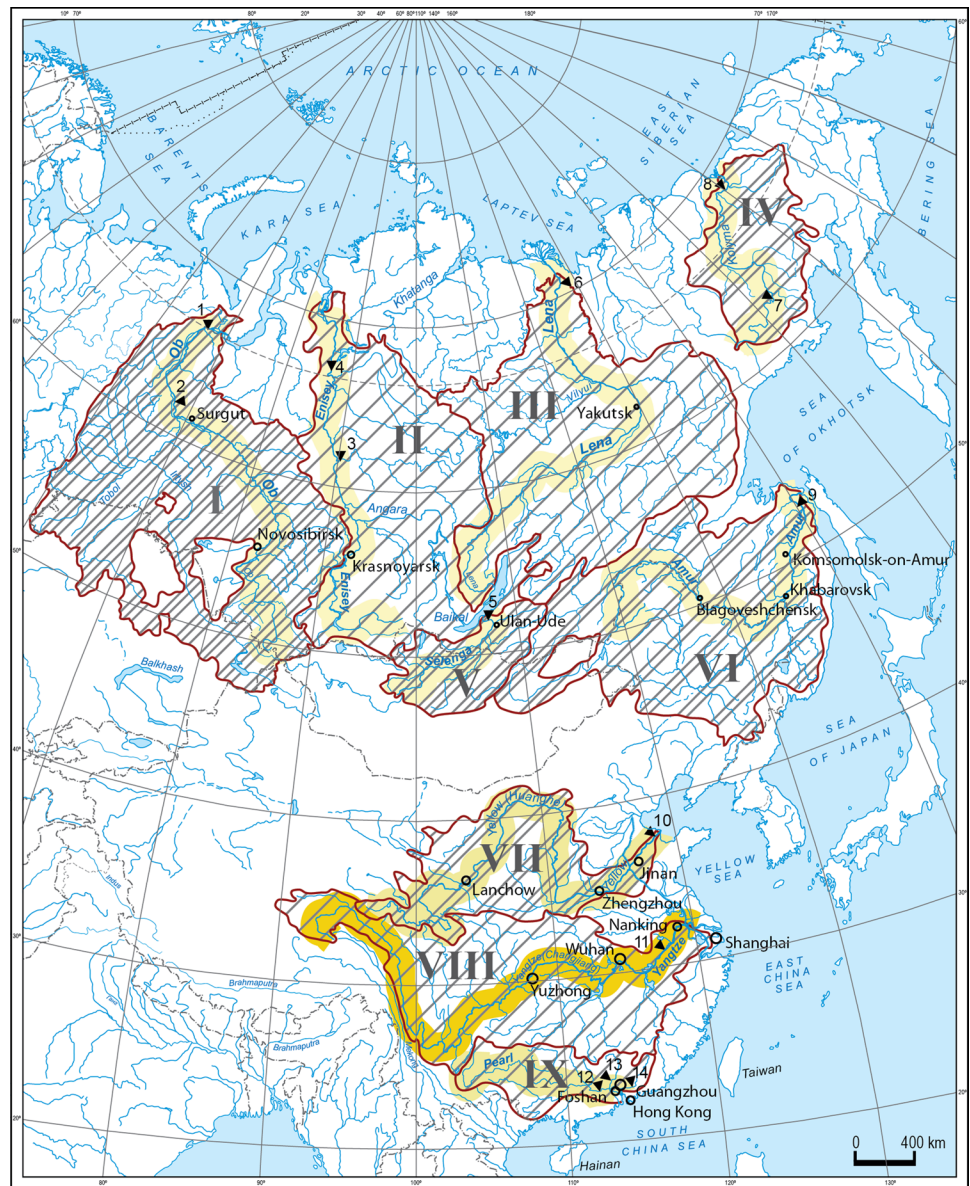**Fig. 1** Hydromorphological features and human impacts of the largest rivers of Russia and China

Catchment area
I - Ob
II - Enisey
III - Lena
IV - Kolyma
V - Selenga
VI - Amur
VII - Huanghe (Yellow)
VIII - Yangtze (Changjiang)
IX - Pearl

Confined channels
(CR (%))

> 60

25-60

< 25

Dam density
(number per 1000 square kilometer)

< 0,01

0,01 - 0,07

> 0,07

Largest cities
(amount of citizens)

·   less then 1 million
∘   from 1 to 2 million
○   from 3 to 10 million
◯   more then 10 million

▼ Gauging stations
1 – Salekhard (Ob)
2 – Karym Kary (Ob)
3 – Podkamennaya
     Tunguska (Enisey)
4 – Igarka (Enisey)
5 – raz'ezd Mostovoy
     (Selenga)
6 – Kyusyur (Lena)
7 – Ust-Srednekan
     (Kolyma)
8 – gidrostvor
     Kolymskoe 1
     (Kolyma)
9 – Bogorodskoye
     (Amur)
10 – Lijin (Huanghe)
11 – Datong (Yangtze)
12 – Gaoyao (Pearl)
13 – Shijiao (Pearl)
14 – Boluo (Pearl)

Table 2 Channel patterns distribution along the studied rivers (% from the channel length) (ordered by CR increase)

No. (by CR (%))	River	Confined			Unconfined		
		Straight	Meandering	Braided	Straight	Meandering	Braided
1	Ob	–	–	–	35	45	20
2	Selenga	–	15	–	–	54	31
3	Kolyma	4	5	13	25	45	8
4	Amur	8	9	16	9	37	21
5	Yellow	19	26	–	–	26	29
6	Enisey	31	16	11	5	6	31
7	Yangtze	35	25	–	5	17	18
8	Lena	18	12	34	15	–	21
9	Pearl	41	40	–	6	6	7

Table 3 Human drivers of the selected rivers of Russia and China

River	Dams > 15 m height		Population in river catchment		Land use (% from the catchment)	
	Number in the catchment	Dam density (per 1000 km^2 of river catchment)	Largest cities located along river main stem (humans)	Average population density (inhabitants per km^2)	Forest and natural shrubs	Agricultural lands
Lena	1	0.0004	Yakutsk (306,000)	1–3	20–80[a]	< 5
Ob	3	0.001	Novosibirsk (1,584,000), Surgut (346,500), Nizhnevartovsk (270,000).	0–25	10–60	0–80
Enisey	8	0.003	Krasnoyarsk (1,066,000)	1–10	60–80	5–20
Selenga	0	0	Ulan-Ude (430,550)	1–10	0–60	5–20
Kolyma	2	0.003	0	< 1	20–40	< 5
Amur	2	0.001	Blagoveshensk (224,335), Khabarovsk (611,100), Komsomolsk-na-Amure (251,300)	1–10	5–95	5–20
Yellow	20	0.026	Lánzhōu (3,310,000), Zhengzhou (9,190,000), Jinan (3,250,000) (8 cities with population more then 500,000)	1–200	0–10	10–20
Yangtze	35	0.18	(the largest are Yuzhong (53,210,500), Uhan (10,220,000), Nankin (8,187,800), Shanghai (24,152,700) (11 cities with population more then 500,000)	1–900	0–30	20
Pearl	9	0.02	Guangzhou (14,043,500), Foshan, (3,389,000), Hongkong (7,336,700) (8 cities with population more then 500,000)	200–600	10–30	> 30

[a]Ranges for the large regions of the catchment (North to South or upstream to downstream)

lands. Changes in land use are even more important in the Northern catchments, where decline in sediment transport rates exists under conditions of water runoff increase. In the nearby to Selenga River tributaries of Baikal Lake, 3–4 orders of magnitude decline of sediment transport has been observed since 1980, even though increase in water runoff has been noticed (Fig. 2).

The sediment load of the largest rivers in China has changed significantly since 1990s–2000s onwards. The climate change and human activities such as construction of dams, preventing of soil loss, alluvium excavation from channels, flow regulation, water consumption for agriculture have decreased river sediment flux along the main rivers of China (Gray et al. 2002; Luo et al. 2007; Gao et al. 2010; Miao et al. 2010; Wu et al. 2012; Dai and Lu 2014). For the

Yellow River sediment load at the downstream Lijin station, estimates have been ranged from 780 Mt/year (1950–2007) (Zhao et al. 2014) to 707 Mt/year (1950–2013) (Wei et al. 2016) or 1080 Mt/year from 1950 to 1980s (Wang et al. 2011) (Table 4). It has dropped to 150 Mt/year from the early 2000s due to soil conservation program, which has started in the late 1970s in the Loess plateau region, and setting into operation few reservoirs: the Liujiaxia in 1968, the Longyangxia in 1985, the Sanmenxia in 1960 and especially the Xiaolangdi in 2000. Precipitation decrease has become another important factor of sediment flux reduction (Miao et al. 2010; Wang et al. 2011; Zhao et al. 2015; Wei et al. 2016).

Sediment flux reconstruction for the Yangtze River (Wang et al. 2008) revealed that the monsoon-dominated period up to the middle of the XX century (1865–1950s) and the human-impacted period later (1950s–present) are the main time spans for the sediment load changes. The most important anthropogenic factors influenced on sediments are soil conservation and especially dams construction (Dai and Lu 2014; Yang et al. 2015). As a result ,mean sediment load to the East China Sea has decreased from ~488 Mt/year (1865–1968) (Wang et al. 2011) to 470 Mt/year (1950s—present time) (Yang et al. 2015) or 424 Mt/year (1950–2002) to 148 (2003–2010) after construction of the Three Gorges Dam (TGD) (Dai and Lu 2014) (Table 3). The sediment flux reduction at Yichang (37 km downstream from the TGD, 1800 km from the Yangtze mouth) has been even more drastic: from 530 Mt/year (1950s–1960s) to 60 Mt/year after (Yang et al. 2011).

Sediment load in the Pearl River basin has been driven by hydroclimatic factors before 1990s, whereas reservoirs impact has come later. The constructed dams have trapped 50% (Luo et al. 2007) or even 66% of sediments (Wu et al. 2014); therefore, sediment load has reduced from 85.9 Mt/year (1980s–1990s) to 29.2 Mt/year (2006–2011) (Wu et al. 2014) or according to another estimates (Lai et al. 2016) from 70 Mt/year (1955–2000) to 38.7 Mt/year (2000–2010) (Table 4).

It should be noted that the signal of reservoirs construction in sediment loads depends on the downstream location of the gauging station from the dam. It leads to increasing riverbed erosion at the downstream sections of the Ob River (with the incision rates up to 1 m), and even more significantly along Yellow, Yangtze and Pearl Rivers (Wang et al. 2008). The 2003 closing of the Three Gorges Dam (TGD) has resulted in downstream channel erosion and coarsening of bottom sediment, and erosion of the Yangtze's subaqueous delta. The downstream channel from TGD reverted from an accretion rate of ~90Mt/yr (1Mt = 1,000,000 t) between the mid-1950s and mid-1980s to an erosion rate of ~60Mt/yr after closing of the TGD. A combination of dams construction in the upper river, uncontrolled sand excavation for construction activity, which estimated as 870 Mt for 1986–2003 (Luo et al. 2007), and dredging for navigation has caused dramatically channel downcutting (Lu et al. 2007) up to 10 m during the past 10 years in the lower Pearl River.

Particulate metals features and trends

Summary of the particulate metal concentrations (supplementary 1) in the selected large rivers of Russia and China is based on the most recent dataset (Savenko 2006; Viers et al. 2009) added by the most recent studies (Wei Wen Huang et al. 1992; Hölemann et al. 2005; Levshina 2008; Yuan 2012; Hu et al. 2015). Supplementary 1 includes main information about the analytical and sampling methods used in the studies, as well as description of time frame and reaches.

Table 4 Suspended sediment transport changes of the studied rivers in the early XXI century

| River	Name of the gauging station	Most recent estimate of suspended sediment yield		$\Delta W\ (\%)^a$
		W (Mt/year)	Years (recent period/historical period) and reference	
Ob	Salekhard	15.6	1981–1992/1938–1956 (Magritsky 2010)	+37
Enisey	Igarka	4.9	1971–2000/1941–1956 (Magritsky 2010)	−62
Selenga	raz'ezd Mostovoy	1.5	1996–2016/1982–1995 (Magritsky 2010)	−50
Lena	Kyusyur	21.4	1974–2000/1959–1966 (Magritsky 2010)	−19
Kolyma	Ust-Srednekan gidrostvor Kolymskoe 1	8.3	1981–1990/1991–1997 (Magritsky 2010)	+10
Amur[b]	Bogorodskoye	–	–	–
Yellow	Lijin	150	1950–1980/2000–2013 (Wang et al. 2011; Wei et al. 2016)	−86
Yangtze	Datong	148	1865–1968/2003–2010 (Wang et al. 2011; Dai and Lu 2014)	−70
Pearl	Gaoyao (West (Xijiang) River)	38.7	2000–2010/1955–2000 (Lai et al. 2016)	−66

[a]Calculations are based on Eq. (1)

[b]No data
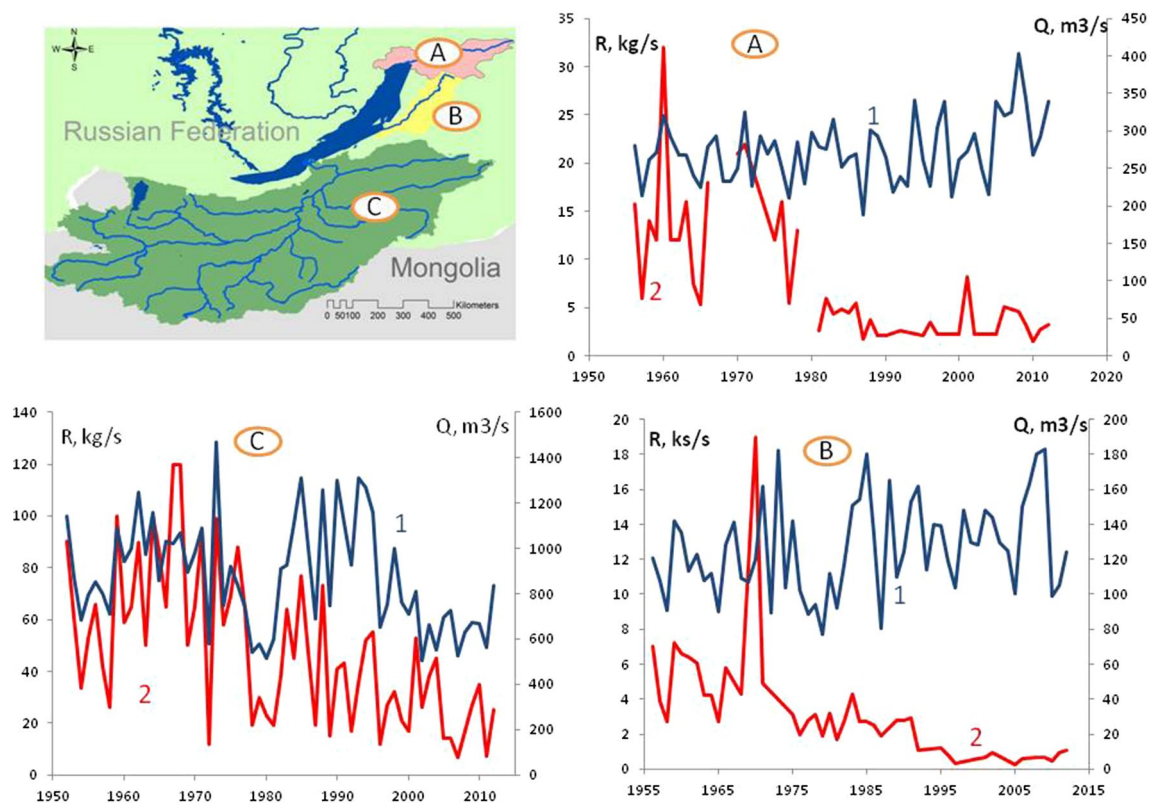
Fig. 2 Annual water Q (1) and suspended sediments R (2) discharges of the Baikal Lake tributaries [gauging station of RosHydroMet: A—Upper Angara (Verknyaa Zaimka station), B—Barguzin (Ust-Barguzin station), C—Selenga (Mostovoy station)]

Trace metals composition of suspended matter in the studied rivers is in line with average values of the reported elements in the World sediments (Savenko 2006). In decreasing order of magnitude, the average concentration are: Zn ($C_{Zn\ World}$ = 130 µg/g), V ($C_{V\ World}$ = 120 µg/g), Cr ($C_{Cr\ World}$ = 85 µg/g), Cu ($C_{Cu\ World}$ = 45 µg/g), Pb ($C_{Pb\ World}$ = 25 µg/g), ($C_{Co\ World}$ = 19 µg/g) and Cd ($C_{Cd\ World}$ = 0.5 µg/g). The exceptions were seen for the Ob, Amur, Yangtze, Selenga and Pearl Rivers due to elevated concentration of Pb with the highest reported values about 200 µg/g at the downstream of the Ob River, as well as for Enisey and Selenga rivers due to elevated concentrations of Cu—up to 181 µg/g in case of the Enisey River and > 200 µg/g for the Selenga River.

Based on the cartographic processing procedures focused on the recognition of the fluvial system and its human modification and sediment transfer processes in the largest Asian rivers of Russia and China, the fluvial processes and sediment transfer map were elaborated (Fig. 3). This map contains three information layers: (1) general fluvial processes features (unconfined channel distribution along the main stem of the river (1-CR %) which is regarded to be a significant driver of channel erosion impact on sediment transfer processes, (2) annual sediment yield and long-term sediment yield trends, (3) SPM content represented by calculated coefficient HM as a relationship of SPM concentrations from the studied river with the World averages (see Eq. 2). The mapping approach used within this study allowed a quick and descriptive delineation of the drivers of sediment transfer processes.

The total trace metal concentrations C_0 significantly varies between the studied catchments. It lays within the range of ~ 300–600 µg/g for the Chinese rivers, whereas Russian rivers are characterized by C_0 ~ 500–1200 µg/g. The highest values of C_0 have been found for the Amur River (C_0 = 1164.3 µg/g) and the lowest—for the Yellow River (C_0 = 313.6 µg/g). In decreasing order of magnitude of C_0, the rivers represent following sequence: Amur–Enisey–Selenga–Yangtze–Ob–Pearl–Lena–Yellow.

Suspended sediments of the Enisey and the Selenga River, which also belongs to Enisey catchment, were characterized by relatively higher heavy metals concentrations and especially enriched in Pb, Cu, Cd, while the suspended sediments from the Amur River were enriched in Zn. The latter might be explained by the quality of irregular infrequent observations done by (Chizhikova et al. 2011). In comparison with the World averages of metals concentration in SPM (Savenko 2006), only Yangtze and Enisey rivers

have 100% elevated concentrations of all trace metals concentrations (HM > 1) (Fig. 3). This is opposite to the Yellow River, where in all cases HM < 1 with the exception of Pb (HM_{Pb} = 1). As an average for all rivers, highest HM_x have been reported for Zn (HM_{Zn} = 2.2) and Pb (HM_{Pb} = 2.12).

Significant variability of the data for the different seasons also should be noted. Twofold differences of C_0 were documented for the Yellow and Yangtze Rivers between particular seasons (sampling campaigns at the Lijin and Datong stations, respectively, during flood and dry seasons in 2000 and 2001 (Qiao et al. 2007), between January 2009–December 2010 (Yao et al. 2015) and September 2012–October 2013 (Hu et al. 2015) for the Yellow River, and July–August 2008 (high water) and January 2009 (low water) for the Yangtze River (Yuan 2012). Up to fourfold differences have been found for the Amur River, and for the spatially distributed along the downstream part of the Selenga catchment, these differences are even much higher reaching tenfold magnitude of change (e.g., between 575 µg/g in July–August 2011 and 29.1 µg/g in June 2012).

Discussion

Hydroclimatic development and catchment properties influence sediment loads and associated particulate metals composition. Low-flow period induces decline in sediment yield over Southern (Central Asian) rivers of Russia (Karthe et al. 2014), whereas increase in water fluxes have been observed in the Northern part of Siberia and lead to opposite trends in sediment load. With the exception of Ob and Kolyma (Table 4), the 2000s decade exhibits decreasing trend in suspended sediment flux in contrast to discharge (Cohen et al. 2014) (see Fig. 3). In four cases (Chinese rivers—Yangtze, Yellow, Pearl—and the Enisey River), the decline of sediment load is attributed to sediment retention in the dams. Sediment deposition in reservoirs in particular has an impact on sediment yield fluxes to the Arctic Ocean by the Enisey River (Vörösmarty et al. 2003) due to most recent dams constructions on the Enisey and Angara Rivers. The sediment load decline in the Selenga River is related to decrease in precipitation and even earlier to the abandonment of cultivated lands in Russian part of the catchments (Chalov et al. 2014) and represent the conditions of sediment load variability in the undammed river system (Karthe et al. 2014).

Increased sediment transport rates reported for the Ob and Kolyma Rivers are related to human impacts—placer mining activities (Kolyma) (Walling and Fang 2003) and oil and coal production (Ob) (Hasholt et al. 2006) even though the lack of agriculture is observed in these catchments. Another possible explanation of the specific trends in sediment yield for Ob and Kolyma can be found in fluvial system features. Both rivers are characterized by the

lowest confinement ratios CR and thus are most sensitive to the climate warming impact on channel erosion. Increase in the winter temperatures and more intensive permafrost thaw during summer periods observed in the Arctic zone (Sazonova 2004) influence sediment load through intensive fluvial erosion of the floodplain which in turn are also added by thermal erosion process (Tananaev 2016). Along the alluvial (floodplain) banks, these processes are seen more clearly than in confined channels which usually represent rocky banks where fluvial input of sediment due to channel erosion could be neglected.

Formation of SPM concentrations is more complicated and could be hardly linked to the certain drivers using the existing databases. Significant differences of metal concentrations in sediments from the case study rivers could be ascribed to their different sediment sources and weathering processes within the catchment. The relative importance of physical weathering (releasing particles) compared with chemical weathering is also important (Carson and Kirkby 1972). The nature of transported particles depends on the climate controlling the rock weathering and soil formation over a long period (Viers et al. 2009). These impacts explain highest values of C_0 and HM values in the Selenga-Enisey River system (Table 3).

The lowest concentrations in the Yellow River are most probably related to the large amount of suspended sediments which absorb released from the upper and middle reaches heavy metals. The very important geomorphologic explanation of the low enrichments of the Yellow River sediments is related to unique elevated riverbed above the surrounding area. Therefore, the surrounding landscape cannot drain into the river nor can tributaries enter, preventing pollutants from entering the Yellow River to some extent. Also, the pollutants released from the upper and middle reaches are absorbed by the large amount of suspended sediments, precipitate and deposited as hydroxides/oxides due to the high pH values (Huang et al. 1992).

Influence of anthropogenic activities is evidenced by the fact that the majority of the rivers are strongly enriched in the Pb, Zn, Cd and Cu compared with the World averages (HM > 1.8). These elements are considered as a marker of anthropogenic activities influence (Viers et al. 2009). Particularly, according to the recent reports for the studied rivers, Pb and Zn concentrations in Yangtze sediments have increased significantly since the 1980s due to releases of waste/contaminants from human activities (Ye et al. 2012). 75% of Cd fluxes in the Yellow River are from anthropogenic sources (Hu et al. 2015) mostly related to fertilization in the upper and middle regions over the past 2 decades (Bi et al. 2014).

Large dams have a relatively low impact on SPM structure. Among the rivers with highest values of average heavy metals concentrations C_0 and HM ratio, one can see both
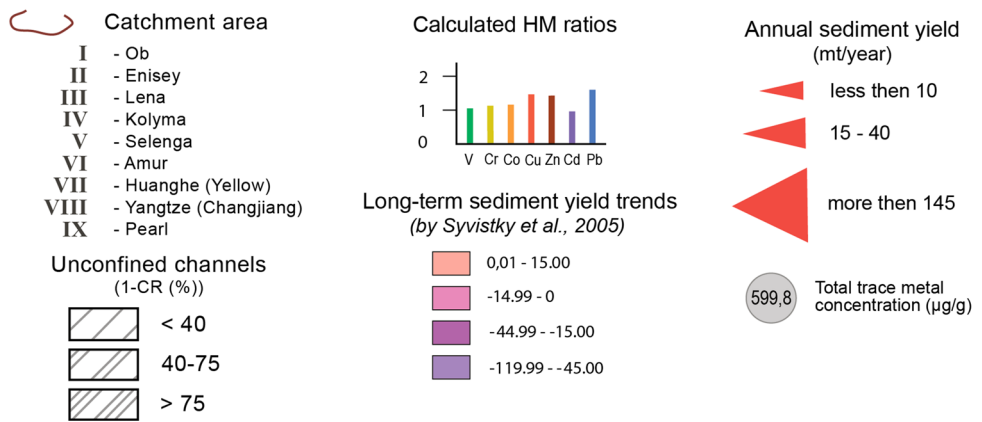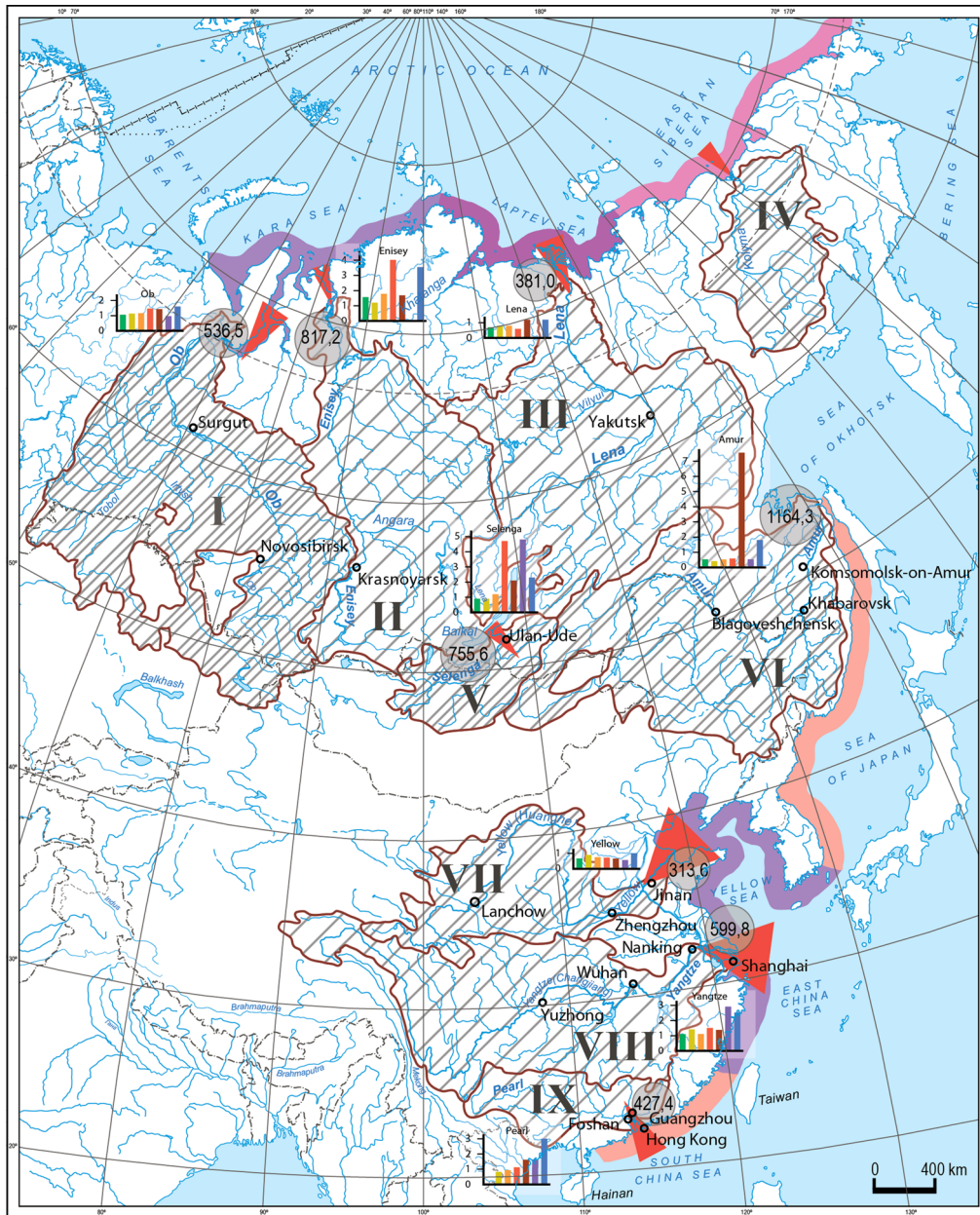
Fig. 3 Map of fluvial processes and sediment transfer processes over selected Asian large rivers of Russia and China (see Supplementary for details)

Yangtze and Selenga Rivers which represent opposite systems in hydropower development—the densest network of dams (Yangtze) and undammed river system (Selenga) (Fig. 1). This is explained by the primary deposition of coarser fractions in the reservoirs which are less subjected to heavy metals precipitation—e.g., for suspended sediments in the Yellow River, on average 78%–82% of the total heavy metal loading accumulated in the < 16 μm fraction (Yao et al. 2015). Operation of artificial floods to decrease reservoir sedimentation is another possible factor of low role of dams in SPM composition (Zhao et al. 2014).

Due to infrequent and irregular observations, the presented results and reported average values in many cases rely on single grab sediment concentration samplings. This can underestimate interseasonal variability and have an impact on the rates of the particular elements concentrations in SPM. According to recent estimates, approximately 30% of the annual fluxes of heavy metals of the Yellow River occur within the short high-water period (6% of 1 year) (Hu et al. 2015). Delivery of the sediments and heavy metals have been reported during the spring flood when active snow melting brings chemical substances including metals from the basin to the channel of the Ob River (Temerev and Savkin 2004). Examples from the Lena River indicate possible impacts of floods and elevated suspended sediment concentrations on mobilization of metals from suspended particulate matter (Hölemann et al. 2005) evidencing complicated patterns of heavy metals formation in SPM.

In our study we used both single observations (e.g., for Lena, Amur, Enisey and Ob rivers), as well as long-term regular observations (Selenga, Yangtze and Yellow rivers). Single grab measurements can reflect local conditions at the exact time of sampling campaign, whereas datasets with regular observations provide more accurate estimates of the long-term averages. These differences are clearly seen from monitoring campaign done in 2011–2013 in the Selenga River system (Fig. 4). Within spatially distributed sampling locations, range of captured heavy metals in SPM values was higher than reported World averages. In some case, these differences were orders of magnitude and were related to significant impact of short-term floods. In particular, the observed absolute metal concentrations in suspended sediments of the studied rivers in the Selenga River basin increase significantly during high-flow events in 2011 and 2013 (Fig. 4). More contaminated particle size fractions are associated with event flows (Chen et al. 2014).

Additionally, we compared seasonal (the same point sampled during different seasons), basin-wide (different point within the same hydrological season), cross-sectional (the same depth within one cross section at the certain sampling time) and depth-wide (through the water column at different depths) variations of SPM concentrations based on the results for the Selenga River (Chalov et al. 2014),

the Yellow River (Qiao et al. 2007) and the Yangtze River (Qiao et al. 2007). The results indicate that, even though the most significant variations of SPM concentrations are related to basin-wide discrepancies, the uncertainties come from seasonal changes (CV, coefficient of variation, calculated as a ratio between the mean average deviation and average concentration, for the selected metals in SPM (μg/g) (see Supplementary 2) ranged for the selected heavy metals from 0.07 to 1.79). The sampling procedures (different depths through the water column) can also contribute to relatively high uncertainties in SPM content (registered variations were up to 0.73). These evidences enable us to conclude that most of the studies on metal budgets for especially Russian rivers did not incorporate representative data from different hydrological seasons (e.g., from the spring high-flow period), therefore existing datasets underestimate the fluxes of particulate trace metals from the Siberian rivers to the ocean. Sampling techniques (e.g., depth and procedure of sampling) which vary between studies and are not regulated by single protocols also can cause uncertainties associated with estimating the flux of sediments transported by rivers.

Conclusion

The following conclusions are drawn based on study results and discussion:

1. Human impacts are the main driver of recent sediment load changes, in particular reservoir construction has probably the most important influence on land–ocean sediment fluxes. Order of magnitude difference of dams density between 0.18 and 0.026 dams per 1000 km^2 of river catchment in Chinese rivers and 0.003–0.0004 in Russian rivers explains contrasting nature of sediment load at the outlet stations—dominant role of sediment retention in Pearl, Yangtze and Yellow River, and only secondary role due to interaction with opposing directions of sediment fluxes changes. The mapping approach procedures focused on the recognition of the fluvial system and its human modification and sediment transfer processes used within this study enables to perform quick and descriptive analyses of the environmental and human impacts.

2. Links between river channel hydromorphology and sediment load trends have been studied. The river experiencing recent increase in sediment load are mostly unconfined one (Ob and Kolyma), where climate warm and associated processes of permafrost melting have been caused significant increase in erosion rates along floodplain banks. Observed sediment yield decline in confined gravel bed rivers (Enisey) is related to geomorphic conditions which cause loss of potential to restore
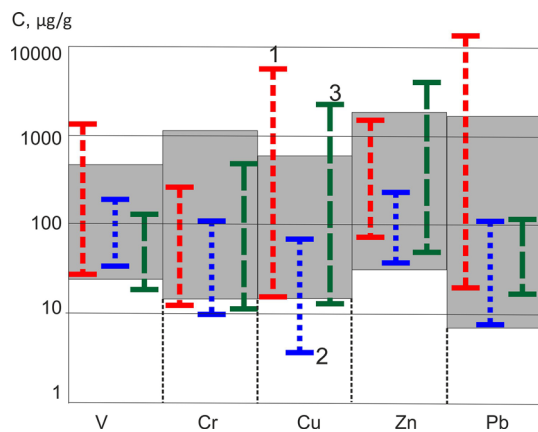
Fig. 4 Seasonal (reported) variability (max–min) of heavy metals in SPM in downstream part of the Selenga River basin (1—July–August 2011; 2—June 2012; 3—September 2013) compared to reported in the World River databases (Martin and Meybeck 1979; Savenko 2006; Viers et al. 2009) (gray boxes)

baseline sediment load conditions after reservoir construction.

3. SPM concentrations are explained by opposing impacts of sediment fluxes changes integrating geological, fluvial and anthropogenic drivers. Though metal concentrations in sediments from the case study Rivers are primarily ascribed to their different sediment sources and weathering processes within their corresponding river basin, in some cases explicit fluvial impacts can be seen. Mentioned examples include the Yellow River which represents lowest concentrations of the heavy metals in SPM among studied river. This is explained by the largest suspended sediments concentrations and unique elevated riverbed above the surrounding area prevailing sediment delivery from the catchment. We concluded that construction of reservoirs plays relatively weak role in heavy metal composition in SPM due to lowest sedimentation rates of the fine clay particles. The latter are mostly enriched with heavy metals and transported through the reservoirs without settling.

4. Interseasonal variations have the most significant impact on the concentrations of particulate heavy metals in comparison with spatial discrepancies of metals change. Most of the studies on metal budgets for the especially Russian rivers did not incorporate data from the spring high-flow period [with the exception of the Selenga River monitored since 2011 (Chalov et al. 2014)], therefore existing datasets underestimate the fluxes of particulate heavy metals from the Siberian rivers to the Ocean.

5. There is a crucial need to acquire more data not only on the elemental fluxes but also on the chemical composition of suspended particulate matter. Monitoring strat-

egy in river-related research with regard to sediment loads and content of the largest rivers should be based on integrated hydrological and geochemical approaches. Additional studies should focus on the terrestrial permafrost thaw contribution into SPM composition which is already underway and actively influencing to sediment yield turnover in fluvial networks as was mentioned for the Ob and Kolyma river basins.

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