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River Sedimentation

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Impact of placer mining on suspended sediments in rivers of the Kamchatka Peninsula (Russian Federation) and the Selenga River basin (Mongolia) and its modeling

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ABSTRACT: The impact of placer mining on suspended sediment concentration (*SSC*) variability is discussed for rivers of North Kamchatka (Russia) and the Selenga river basin (Mongolia) taking into account a discharge of sewage. It is shown that with a constant input of anthropogenic particles in the river a seasonal surpass over *SSC* baseline downstream of a placer mining is about 1.6–8.8 times, depending on the river size and water phase. Mathematical algorithm for calculation of suspended particles transport along the river reaches situated downstream of anthropogenic sediment source is proposed; the efficiency was tested on studied phenomena within the accuracy of 6–31%.

1 INTRODUCTION

Placer mining are associated with river valleys. Its opencast mining by ore washing leads to significant input of sediment suspension in river flows, modifications of natural sediment load and its regime, change of hydraulic conditions of suspension transport or stream transporting capacity (Knighton 1998, Krishnaswamy et al. 2006, Macklin et al. 2006, Syvitski & Kettner 2011, Wantzen & Mol 2013). Most of these regions are situated in remote, sparsely populated areas, where the stream gauging network is underdeveloped, thus wise the study of placer mining impact remains challenging (Chalov et al. 2015b, Makhinov & Makhinova 2006). The lack of full-rate hydrometeorological data complicates a large-scale modeling and the estimation of anthropogenic impact on the environment in general.

The authors carried out studies in following remote areas: in the Vyvenka river basin (North of the Kamchatka peninsula, Russia) near the placer platina mining “Levtyrinyvayam” and in the Selenga river basin (Mongolia) near the placer gold mining “Zaamar Goldfield” and “Boroo Gold”. The objective of this study was the estimation of placer mining impact on *SSC* change in river systems and a development of general mathematical model that describes and predicts a distribution of suspended matter downstream of the anthropogenic sediment source for scarce monitoring conditions.

2 METHODS AND STUDY AREA

The fieldwork was carried out in the Selenga and the Vyvenka river basins near the placer mining. The fieldwork included the annual monitoring from late spring up to beginning of autumn over the period 2009–2014 in the North of Kamchatka tundra areas. The studied streams were minor rivers the Levtyrinyvayam and the Penist’iy, and the mine site was closed and partly reclamated near the latter. The length of the Levtyrinyvayam L is 49 km, the basin area $F = 212\,\text{km}^2$, the length of the Penist’iy $L = 6.4\,\text{km}$, $F = 20\,\text{km}^2$.

For the Selenga basin the steppe landscape is common, the fieldwork was carried out here in summer 2011–2014 (Chalov et al. 2015b) on the Tuul river ($L = 704\,\text{km}$, $F = 49,840\,\text{km}^2$) and the Boroo minor river ($L = 100\,\text{km}$, $F = 1970\,\text{km}^2$). A river discharge was measured on minor rivers with a current meter ISP-1, on larger rivers with ADCP. Turbidity measurements were performed with turbidimeter Hach 2100P. A suspension sediment concentration was assessed by filtering with preliminary weighted membranes “Millipore” with 47 mm diameter and 0.45 μm pore size. Mineral particles size distribution was determined with a laser particle sizer Fritsch Analysette 22.

The formula for suspended particles longitudinal distribution was found using methods of mathematical analysis. Suspended matter transport modeling was performed with Mathcad 14.0 software.

3 RESULTS AND DISCUSSION

3.1 *The impact of placer mining on suspended sediment concentration in river waters*

For the river basin where an open-cast mining is carried out, a modification of suspended sediment load W_R along the river is related to the mineral particles input from the natural and disturbed ground of water collection. Together with mineral particles naturally transferred in river waters in the upstream areas W_{Rnat}, other suspended particles are added downstream due to the stream diversion channel erosion W_{Rchan}, the slope erosion W_{Rsl}, the infiltration from technological reservoirs and silt-detention basins W_{Rfil} and the discharge of treated sewage W_{Rsew}:

$$W_{Rnat} + W_{Rchan} + W_{Rsl} + W_{Rfil} + W_{Rsew} - W_{Rac} = W_R \tag{1}$$

The majority of left-side terms in equation (1) make W_R increase along the river flow. Only a term W_{Rac} determining the amount of accumulated suspended particles has an opposite sense for W_R. The term W_R is larger for the river reach situated downstream from the open-cast mining area than for the upstream.

Within the boundaries of platina mine site in the North of Kamchatka, the main load appears now in the Levtyrinyvayam river valley, where the fine-grain recovered reserves are stored. This leads to an increase in *SSC* by 3.3 times (Fig. 1, Table 1). As a result, a mean grain size of suspended particles decreases by 50 times up to 0.010 mm; 99% of these particles have an anthropogenic genesis. During the river flood period the *SSC* in this area increases by 30 times and more compared to low flow *SSC*. Downstream, the diversion channel comes into a natural channel, water run-off falls because of the water spreading over the valley plain, this invokes a decrease in stream transporting capacity and a partial accumulation of suspended matter. This process is especially intensive for the river reaches where the flow speed is minimum. In these areas a mean grain size of bed load is 0.085 mm, 73% of particles are received from the mining company territory.

In low flow conditions the *SSC* of the Penist'iy river downstream from the area of mining works exceeds the baseline values by 3.3 times even after the mine reclamation (Fig. 1, Table 1). A mean grain size of suspended particles is 0.037 mm. About 90% of particles enter the flow in consequence of eroding of non-working silt-detention basins and draining of industry-related terrains. After inflow of the Penist'iy river to a main river the rate of particles from anthropogenic source declines up to 80%. Channel particles appear in sediment suspension composition (more than 20%), and the *SSC* decreases by 1.8 times. Therefore, the anthropogenic *SSC* that is formed by fine particles does not reduce along minor rivers to their mouth.

Downstream of the placer gold mining in the Tuul and the Boroo valleys (the Selenga basin, Mongolia) the pattern of *SSC* raises in river waters is different from that one caused by waste-water discharge from mining company (Chalov 2014, Chalov et al. 2012, 2013, 2015a, b, Thorslund et al. 2012). The most significant impact of mining work on *SSC* is noticed in the Tuul's downstream near "Zaamar Goldfield" mining. Suspended particles concentration in water during the active phase of gold mining reaches 472 g/m^3 (Tulokhonov 1996). Our data have shown that downstream from this mining during the summer river flood the *SSC* increases almost by three times (from baseline $SSC_b = 107$ g/m^3 to 289 g/m^3)

Table 1. The *SSC* longitudinal changing downstream of the placer mining.

River	Water stage	SSC_b	SSC in the site g/m^3 km			SSC_{max}/ SSC_b	L km
L_i/L		0	0.24	0.35–0.77	1		
Tuul	Flood	107	108	289	184	2.7	127
	Low flow	84.8	100	136	77.1	1.6	
Boroo	Flood	24.3	n/d	n/d	212	8.8	64
	Low flow	39.2	n/d	n/d	64.2	1.6	
Levty-riny-vayam	Low flow	7.01	7.07	21.8	23.2	3.3	3.3
Penist'iy	Low flow	6.51	4.77	20.5	21.4	3.3	8.9

* SSC_b – baseline *SSC*, SSC_{max} – the largest measured *SSC* along the river due to mining impact, L_i – distance from a site to the end of the reach, L – length of the reach, n/d – no data available.

(Table 1, Fig. 1). The excess of suspended particles in river water decreases by 1.6 times (from maximal $SSC_{max} = 289$ g/m^3 to 184 g/m^3) closer to the river mouth because of coarse fraction accumulation. For the summer low flow period the *SSC* in river water increases by 1.6 times (from $SSC_b = 84.8$ g/m^3 to 136 g/m^3) due to the mining impact, and then decreases by 1.8 times (from $SSC_{max} = 136$ g/m^3 to 77.1 g/m^3) close to the river mouth. In the Boroo river downstream from the gold mining site the *SSC* increases by 1.6 times (up to 64.2 g/m^3) during the low flow period (Table 1). During the river flood period the rate of anthropogenic modification of *SSC* is even higher – 8.8 times. The ratio of maximum contemporary *SSC* to baseline *SSC* is found within the range of 2.7–8.8 (flood period) and 1.6–3.3 (low flow period) for all studied rivers passing through the placer mining districts (Table 1).

Hence, the Table 1 shows the *SSC* longitudinal changing along the minor rivers in the Selenga basin, in the North of Kamchatka and for the Tuul river downstream from the placer mining. The relation L_i/L demonstrates the position of a site at the river, where L_i – distance from the site to the end of the reach, L – length of the reach along the river from the mining upstream to the river mouth at the river flow. The SSC_{max} is always the largest measured *SSC* at the river stream. It was measured at the mouths ($L_i/L = 1$) for the minor rivers and at the mining area where $L_i/L = 0.35 - 0.77$ for the Tuul river (Fig. 1).

A mean suspended particles grain size in the Tuul river downstream from the Zaamar decreases from 0.058 to 0.022 mm during the flood period, and from 0.045 to 0.024 mm during the low flow period. The use of dredging machines in the Tuul channel leads to an increase of fine particles concentration in river

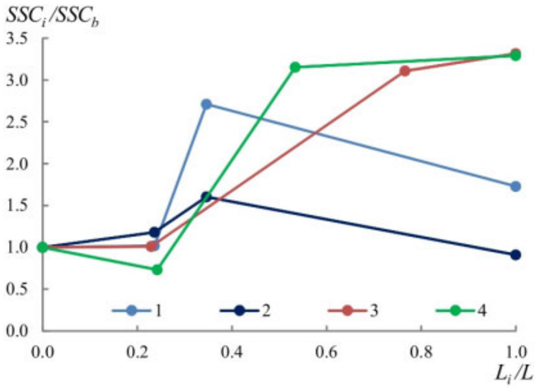

Figure 1. The *SSC* longitudinal changing downstream of the placer mining in the Tuul river (1 – flood, 2 – low water), in the Levtyrinyvayam river (3) and the Penist'iy river (4) during low water (SSC_i – *SSC* in a site, SSC_b – baseline *SSC*, L_i – distance from a site to the end of the reach, L – length of the reach).

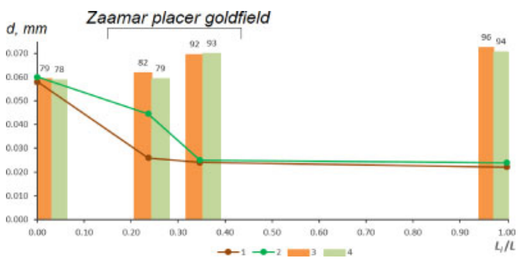

Figure 2. The changing of mean grain size d (1, 2) and fine particles concentration (%) (3, 4) in the Tuul river during flood (1, 3) and low water (2, 4) (L_i – distance from a site to the end of the reach, L–length of the reach).

waters up to 90% and more, depending on water stage (Fig. 2).

3.2 *Mathematical modeling of longitudinal transport of suspended matter for river reaches situated downstream of anthropogenic objects*

Numerous models describing sediment transport exist: MIKE, HEC-RAS, TELEMAC, DELFT, GSTAR, STREAM, SEDZLJ, ISIS etc. They have different spatial and temporal scales; and a choice and description of main processes for sediment regime can vary from one model to another. The final choice of the model depends on a balance between the importance of every process and the possibility to describe it in details, the estimated accuracy, the availability of data, the boundary conditions, the model verification and the number of calculations (Lick 2009, Westrich & Förstner 2007). Most of existing model demand detailed hydrometric data. In general, these models are based on empirical and half-empirical equations for sediments transport (Engelund & Hansen 1967, Copeland & Thomas 1989, Laursen 1958, Toffaleti 1968, Yang 1973, 1984), some of them calculate suspended and stream sediment load together (Ackers & White 1973).

A solution of equation of turbulent diffusion for suspended particles is obtained to describe the distribution of suspended particles (Makkaveev 1931, Graf 1984):

$$\frac{\partial SSC}{\partial t} = \frac{A}{\rho}\left(\frac{\partial^2 SSC}{\partial x^2} + \frac{\partial^2 SSC}{\partial y^2} + \frac{\partial^2 SSC}{\partial z^2}\right) - \left(v\frac{\partial SSC}{\partial x} + u\frac{\partial SSC}{\partial y} + w\frac{\partial SSC}{\partial z}\right) - \omega\frac{\partial SSC}{\partial y}, \quad (2)$$

where A – turbulent exchange coefficient, u, v, w – components of local velocity vector, x, y, z – longitudinal, vertical (with a zero on water surface, increasing downwards) and cross-section spatial axes, ω – particle fall velocity.

The analytical solution for equation (2) of turbulent diffusion for suspended particles was obtained under some assumptions and taking into account the rate of *SSC* along the flow depth. The assumptions are:

1) depth, width and velocity of the flow are constant for the studied reach;
2) there is no other source for suspended sediment discharge;
3) the sediment concentration regime is steady ($\partial SSC/\partial t = 0$);
4) cross-section and vertical components of velocity can be neglected: $w = u = 0$.

The flow width and depth averaging was performed to describe the *SSC* along the flow stream. Finally, a linear partial differential equation of the first order can be solved using the Makkaveev equation of vertical *SSC* distribution as a boundary condition (Makkaveev 1931, Karaushev 1977).

$$SSC/SSC_{bottom} = \exp\left(-\frac{2mC\omega}{gV}(1-\frac{y}{h})\right), \quad (3)$$

where SSC_{bottom} – bottom *SSC*, m – the Bazen-Bussinesk coefficient, C – the Chezy-coefficient, g – the acceleration of gravity, V – the average stream flow, h – the total depth.

The final equation is:

$$SSC(x) = SSC_0 \exp\left(-\frac{2mC}{gh}\left(\frac{\omega}{V}\right)^2 x\right), \quad (4)$$

where SSC_0 – the *SSC* in the initial cross section.

As far as sediment suspension particles have different size and thus are transported from the initial cross section on different distances, the calculation of longitudinal *SSC* transport with the equation (4) has to be done separately for particles i of the fraction that

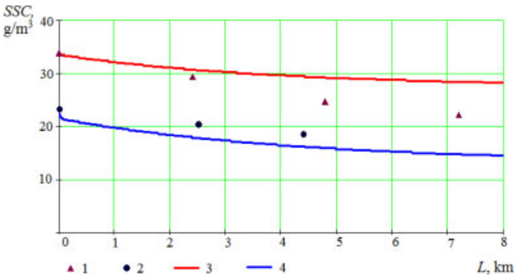

Figure 3. The real SSC (1, 2) and the modeled SSC (3, 4) along the Levtyrinyvayam river for the conditions of best performance of industrial object (1, 3) and reduced platina production (2, 4).

forms a partial SSC: $ssc_i = SSC_{\alpha_i}/100$, where α_i – the fraction grain size composition (%):

$$SSC = \sum_{i=1}^{n} ssc_i , \qquad (5)$$

where n is a number of fractions.

Proposed mathematical model of suspended particles distribution in the river flow demonstrates an exponential decrease of SSC with moving away from initial cross-section. The model can be used for the river reach situated downstream from the source of large amount of suspended matter.

Several efficiency tests were performed for the equation of turbulent diffusion for suspended particles with a longitudinal distribution of the cross section averaged SSC. The tests were carried out in the downstream from anthropogenic sediment source areas.

Calculated for the conditions of best performance of industrial object, the modeled SSC decreases over the length of Levtyrinyvayam river up to 5.4 g/m^3 near the control cross-section, which corresponds well to the absolute accuracy $\Delta SSC = 6.3$ g/m^3 and ratio error $\delta = 29\%$. Under conditions of reduced platina production, the SSC decreases more drastically because of silt and sand particles additional contribution (25% more); in this case the calculation is more accurate: $\Delta SSC = -2.1$ g/m^3, $\delta = -11\%$ (Fig. 3).

The streams continue eroding of former silt-detention basins even after reclamation of platina mine district in the Penist'iy river valley. As a result, there is an additional input of silt-loam particles in the river flow. The estimated SSC decreases downstream from disturbed ground by 7.1 g/m^3, which exceeds the real data on 18% or 2.0 g/m^3.

The SSC for the Tuul river was calculated for flood and low flow conditions. The estimations correspond well to the real data for a high streamflow: $\delta = -6\%$, $\Delta SSC = -8$ g/m^3. This means that the gold mining on the Zaamar field is a main source of sediment load during the river flood period in studied area. With a low streamflow the SSC estimation had less accuracy: near the final cross section it was higher by 24.1 g/m^3 than real data, $\delta = -31\%$, which can be explained by existence of other source of sediment suspension in the studied area of the Tuul river, e.g. channel erosion.

4 CONCLUSION

To sum up, placer mining operations leads to an increase of the SSC and additional input of fine particles in river waters. These processes are amplified during the river flood. During this period the excess of SSC with anthropogenic genesis is 8.8 times higher than the baseline values for minor rivers in the Selenga basin, and 3.3 times higher in the North of Kamchatka. For the Tuul river the increase of SSC depends on the water phase and reaches 1.6–2.7 times over the baseline. Downstream from the mining the SSC does not change along the stream of minor rivers because of the high concentration of dust, silt and clay in river waters, which forms a sediment transfer stream. Along the flow of the Tuul closer to its mouth the anthropogenic SSC decreases by 1.7 times independently from the stream flow state.

The model analytical solution of cross section averaged SSC demonstrates the accuracy in a range of 6–31%.

A solution of the longitudinal SSC transport equation for the unsteady state is a subject of further research.

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