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# Extreme spatial variability in riverine sediment load inputs due to soil loss in surface mining areas of the Lake Baikal basin

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ABSTRACT

Surface mining can contribute to increasing riverine loads of potentially metal-enriched sediments. However, the related human disturbances and natural processes reflect a great complexity, which hinders quantitative understanding. We here consider the Zaamar Goldfield in Mongolia, one of the world's largest placer mining sites, located in the Tuul River basin (upper Lake Baikal basin). A main study aim is to investigate relations between patterns of increased sediment loads along the Tuul River and the (spatially variable) area coverage of active or recently abandoned placer mines in the river vicinity. Specifically, we compare observed loads derived from nested catchment areas with the output from spatially distributed soil erosion modelling. Results showed that riverine sediment loads in mining areas reflect soil losses both from soil erosion and direct human impacts (e.g. waste water discharge), which are two to three orders of magnitude higher than the input from natural areas dominated by soil erosion alone. Notably, the sediment load contributions from the mining areas were insensitive to changes in hydrometeorological conditions, whereas contributions from natural areas were much lower during drier periods (as expected when governed by soil erosion by water). Accordingly, the relative contribution to the total sediment load (*TSL*) of metal-enriched soil from mining areas is likely to be particularly pronounced (with estimated values of about 80% of *TSL*) under drier hydrometeorological conditions. This is consistent with observations of considerably elevated metal concentrations under low flow conditions and implies that if annual average discharge continues to decrease in the Tuul River as well as the entire Selenga River system, increased metal concentrations may be one of the consequences.



## 1. Introduction

Anthropogenic changes in natural landscapes are increasing globally, which has direct impacts on hydrological processes (Vitousek et al., 1997; Foley et al., 2005; Jarsjö et al., 2012; Jaramillo and Destouni, 2014). Among other things, these changes may alter fluvial sediment transport conditions. For instance, construction of dams and reservoirs significantly reduces sediment loads to the seas (Walling and Fang, 2003; Syvitski et al., 2005; Yang et al., 2006). In contrast, agricultural practices, deforestation and surface mining can accelerate natural soil erosion, which increases sediment loading of rivers (Walling, 2006; Chalov, 2014; Jaramillo et al., 2015; Jarsjö et al., 2017). Ultimately, the sediment loads in rivers spatially integrate information about soil loss from basin scale fluvial systems (Stock et al., 2006). Therefore, sediment load is an approximation of net soil loss from the basin (Whitelock and Loughran, 1994).

Data on heterogeneity in variables that shape gross erosion and deposition patterns in basins (e.g. soil classes, vegetation cover and topography; Helming et al., 2005; Boix-Fayos et al., 2006; Delmas et al., 2012) can aid in identifying areas of high soil erosion and associated sediment delivery (Imeson and Prinsen, 2004; Puigdefábregas, 2005). This is important for management of land and terrestrial pollutants (Wu et al., 2007; Kleeberg et al., 2008; Alder et al. 2015; Jarsjö et al., in review). Furthermore, quantitative understanding of how different human activities affect soil loss is needed for assessing impacts on riverine sediment loads and transport of sediment associated contaminants (Walling, 1983; de Vente et al., 2007) as well as in projections of future trends in sediment and pollution transport through basins (Walling and Webb, 1996; James, 2013; Fischer et al., 2016).

Various models have been developed to take into account the heterogeneity of variables related to soil erosion by water (de Vente et al., 2013). Spatially distributed empirical models have shown to be useful in identifying high erosion areas and their connectivity to river

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networks (Ferro and Minacapilli, 1995; Van Rompaey et al., 2001; de Vente et al., 2008; Wilkinson et al., 2009). In these models, human impacts are primarily represented indirectly, through associated changes in the natural soil erosion variables such as loss of vegetation cover or changes in topography. Such changes can for instance be caused by disposal of tailings and waste material heaps in mining areas (e.g. Jaramillo, 2007; Kim et al., 2012; Haregeweyn et al., 2013). However, anthropogenic changes in natural landscapes generally reflect a great complexity of human activities, some of which result in additional soil losses that are not accounted for in the empirical soil erosion models. Examples include mining practices related to washing of excavated sediments and tailing dam breaches that cause erratic discharges of turbid waste water (Gilbert, 1917; Hudson-Edwards et al., 2001; Chalov, 2014) as well as by diversions of natural channels that enhance bed erosion (Kondolf, 1997; Chalov et al., 2015b).

Observations in areas heavily disturbed by surface mining have shown that they can be associated with riverine sediment inputs that are orders of magnitude higher than what can be explained by model simulations of soil erosion by water (Jarsjö et al., 2017; Thorslund et al., 2016). A general question is then if and to which extent there is a relation between area (extent) of surface mining and magnitude of riverine sediment input. Such a relation would, for instance, be useful in assessing impacts of different land use development scenarios on river water characteristics.

A working hypothesis for the present analyses is that it is possible to relate gradients in riverine sediment flows to the various degree of anthropogenic disturbance (specifically area coverage of surface mines) next to the river. We specifically aim at (i) determining if one can observe systematic differences in the sediment loading (i.e. degree of sediment flow increase along rivers) depending on the area coverage of surface mining and natural regions next to the river (and how large or small these differences can be) and (ii) relating such different contributions from natural and mining areas to corresponding soil erosion model estimates to investigate predictive capabilities in natural areas (base-line conditions) and mining disturbed areas. Our case study area is a downstream part of the Tuul River basins (Mongolia) which is situated in the headwaters of the Selenga River basin, the main tributary to Lake Baikal (UNESCO World Heritage site). The lower part of the studied Tuul River basin has been by affected by the developing alluvial surface mining (placer mining) industry since the early 1990s.

## 2. Materials and methods

### 2.1. Site description

The Tuul River basin is located in Mongolia, in the headwaters of the Selenga River basin, which is the main tributary of Lake Baikal (Fig. 1), a UNESCO World Heritage Site. Over 80% of the Tuul River basin is steppe, mostly used for pasture. Other land cover categories include forests (7%), hay and croplands (3%) and urban areas (1%). The upper part of Tuul River passes the most populated area in Mongolia, the city of Ulaanbaatar (1.1 million inhabitants, 95% of the Tuul River basin's population; MEGD, 2012). After approximately 720 km the Tuul River flows into the Orkhon River. Here we specifically focus on the Zaamar Goldfield, which is located in the lower part of the Tuul River basin (green area, Fig. 1A), extending down to 60 km from the Tuul-Orkhon confluence. The region that contributes to the flow of the Tuul River at Zaamar has an area of approximately 55,000 km$^2$ and covers a large part of the entire Tuul River basin (red border, Fig. 1A). In total, about 60 km of the river runs through areas impacted by placer gold mining. The mining was initiated in the early 1990s and takes place mainly on the floodplain, terraces of the main stream and alluvial fans of its tributaries. Excavation and disposal of the gold-bearing material as well as negligent management of the mining wastewater and settling ponds have resulted in an altered sediment transport dynamics of the region (Chalov et al., 2015a). Furthermore, most of the mining organizations in the Zaamar Goldfield have activities that do not comply with requirements regarding land rehabilitation (MEGD, 2012). According to a detailed

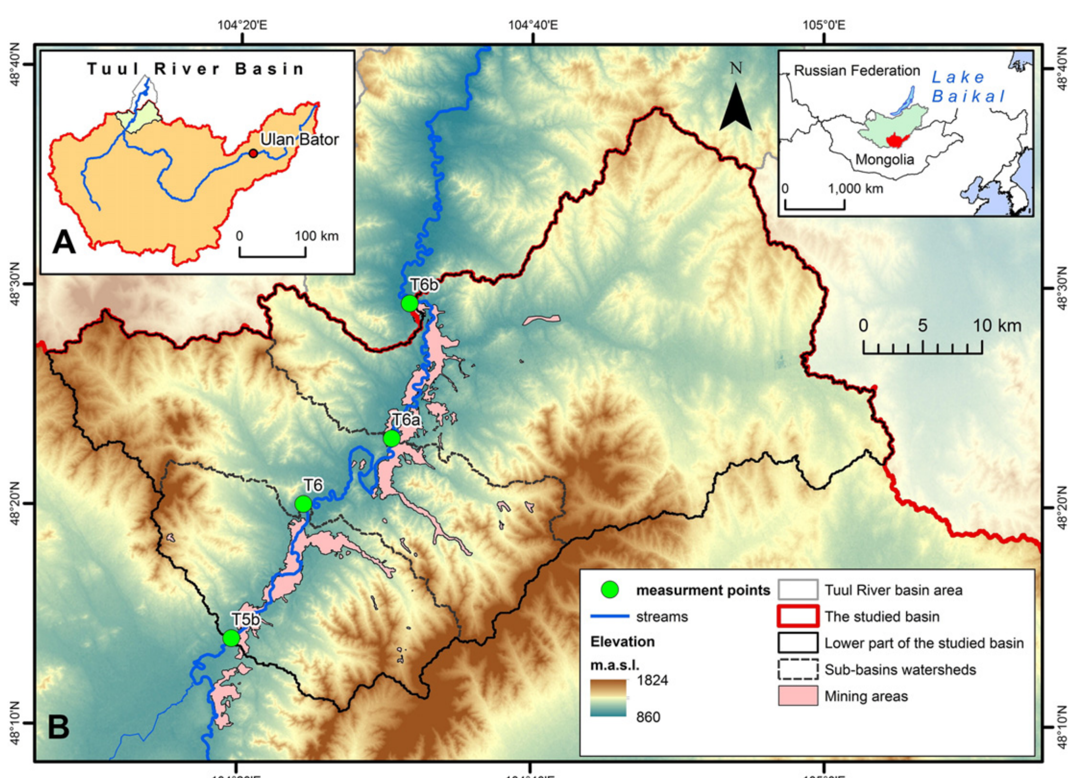


**Fig. 1.** A – The studied basin (red border) with its lower (green) and upper (orange) parts; B – The map of the lower part of the studied basin (black border); mini-map in the right upper corner – location of the Tuul River basin (red) within the Selenga River basin.