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Agricultural activity as cause of aggradation of small Siberian rivers

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Abstract Several examples of the influence of agricultural activity on small rivers of Siberia are discussed. A reduction of river net length has been observed in the western part of the agricultural zone of Siberia a few decades after an increase in the area of cultivated land. Two main factors influence the intensity of river aggradation: the decrease of underground runoff, and the increase in the transfer of sediment to the river channels. Evidence of channel aggradation can be found on rivers with catchment areas up to 22 000 km^2, previously used for shipping. There is no simple relationship between the intensity of erosion on cultivated land and the rate of river net shortening, because of the difference in slope–channel connectivity and channel morphology. Climate fluctuations do not exert an important influence on the trend of river aggradation processes in the agricultural zone of Siberia. Small rivers draining intermontane depressions and the foothills of the eastern part of the agricultural zone of Siberia are less sensitive to increasing erosion rates within their basins. The higher gradients of their river channels contribute to the high transport capacity of these rivers and the wide river valley bottoms promote sediment redeposition in deluvial and proluvial cones. Evidence of aggradation of small rivers is not found in the eastern part of the Siberian agricultural zone, even in cases of extreme erosion within their basins, caused by a marked increase of precipitation in recent years.
Key words small rivers; gully; erosion; channel aggradation; Siberia

INTRODUCTION

Small rivers are frequently the part of the large river system that is most seriously affected by any changes within the basin. The length of small rivers can change considerably, depending on the amount of precipitation, the relationship between surface and underground flows, and the nature and intensity of the anthropogenic activity within the basin. Appreciable changes in stream head location have been documented on an annual scale for some small rivers in southern England (Calver, 1990) and these were shown to be directly related to the amount of precipitation. A similar situation was reported in Srednee Povolzie by Dedkov *et al*., 1995. Increases in the extent of the area of arable land can lead to changes in soil infiltration rates and increased surface runoff coefficients and erosion rates, as reported for many different part of the world (Trimble, 1983; Phillips, 1991; Golosov & Panin, 2005).

Siberia represents a vast area of Russian territory, mostly with a low density population because of the extreme climatic conditions. Only a relatively narrow strip of the forest-steppe and steppe zones in the southern part of Siberia is used as agricultural area. This can be divided into two parts. The western Siberian agricultural area mostly comprises lowland, plains and plateaux. The eastern Siberia agricultural zone is mostly located in intermontane depressions. Another key difference between these two agricultural areas is the proportion of land under cultivation. This ranges from 75 to 85% in the western part of Siberia and from 15 to 45% in the different areas of eastern Siberia (Bazhenova *et al*., 1997).

The rapid growth of the Siberian population began at the end of the 19th century, after the construction of the trans-Siberian railway from Moscow to Beijing. The major increase in the area of cultivated land coincided with climatic fluctuations during the 20th century, which are typical for areas with a continental climate. Both these factors have influenced the intensity of small river aggradation in different parts of the agricultural zone of Siberia. The main goal of this contribution is to evaluate the effect of anthropogenic activity and climate fluctuation on small river aggradation, using examples from three key areas located in different parts of the agricultural belt of Siberia.

STUDY SITES AND METHODS

Three areas of the agricultural belt of Siberia were chosen for detailed study of the influence of agricultural activity on small river aggradation. These are the Ural-Tobol plateau (western Siberia), the Prialtaiskoe Plain (the Ob River basin) and the Aksha River basin (the Amur River basin, Zabaikalie) (Fig. 1). Different methods and approaches were used for each study area. A method involving a comparison of medium-scale topographic maps for different dates, analysis of the trend of water and sediment discharge, and field observations of the present-day location of stream heads was used to study small river aggradation in the Ural-Tobol plateau. Topographic maps produced at different times (1855, 1950, 1970 and 1989) and having the same or very similar scales, were used to compare the total number of streams of different order (Horton system) at different dates. In the case of undisturbed areas, the number of streams of different orders typically did not change appreciably, confirming the validity of the approach. It is interesting that the comparison of the different maps permits both shrinking and expanding river networks to be identified. The latter were usually found in areas with high erosion rates directly connected with intensive gully incision and following activation of underground flow sources. In addition, a detailed survey of the present-day state of small rivers was undertaken.

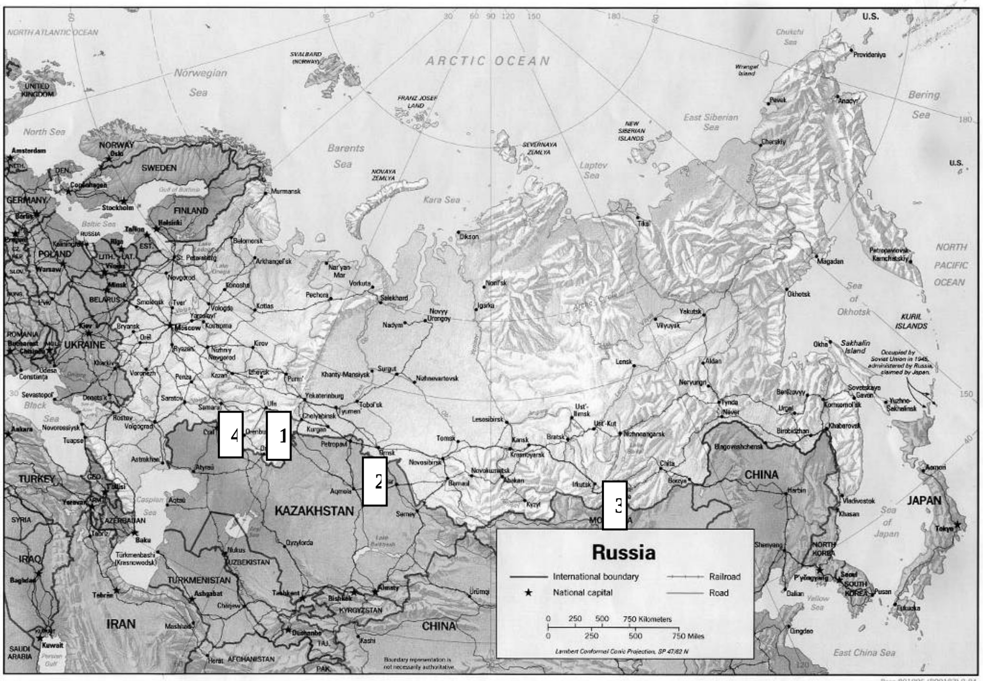

Fig. 1 Location of the study areas. 1, Ural-Tobol plateau; 2, Prialtaiskoe Plain; 3, The Aksha River basin, Zabail; 4, Preduralie.

The Ural-Tobol plateau is located in the south of western Siberia. The mean annual precipitation is around 300 mm. Until the beginning of the second half of the 20th century the area of cultivated land did not exceed 15% in the Ural-Tobol interfluve area. After 1954, a State programme of expanding the area of cultivated land in the dry steppe zone was promoted. As a result of this programme, the area of cultivated land increased up to 60–65% within only a few years. This was marked by a sharp increase in surface runoff during snow-melting and a decrease of river discharge during the summer. Simultaneously, the intensity of soil erosion increased.

A detailed field-based study of small rivers was undertaken in the Prialtaiskoe Plain study area (Fig. 1). A complex set of methods was used, including quantitative assessment of erosion rates based on erosion modelling, detailed mapping of river channels and flood plains, assessment of the water regime and its seasonal dynamics, and evaluation of anthropogenic influences on the river channels. The results provided a quantitative assessment of the behaviour of the small rivers of the Prialtaiskoe Plain.

The Prialtaiskoe Plain is located near the Altai mountains. It is a steppe area with chernozem soils and an annual precipitation in the range 250–350 mm, which has been intensively cultivated since the beginning of the 20th century. Both water and wind erosion observed on the Prialtaiskoe Plain.

A systematic analysis of climatic conditions and water discharge and a field study of land degradation were undertaken in the Aksha River basin (Eastern Siberia, Zabaikalie) (Fig. 1). A comparison of large scale topographic maps was used for evaluation of gully density and badland formation.

The Aksha River basin is located in the southern part of Zabaikalie at an altitude of 1000–1300 m a.s.l. It is an area of forest-steppe with a mean annual precipitation of about 400 mm. Cultivated lands occupy the concave slopes dissected by hollows and cultivation has promoted an increase in the intensity of linear erosion processes. Since 1984, the frequency of high intensity rainfall has increased in this area, because of the expanding influence of the monsoon in the north. Annual precipitation ranges up to 600 mm.

RESULTS AND DISCUSSION

A comparison of changes in stream density over time for two neighbouring regions of the steppe zone with similar climatic conditions can be used to demonstrate the effect of an increase in the area of arable land on small river (Fig. 2).

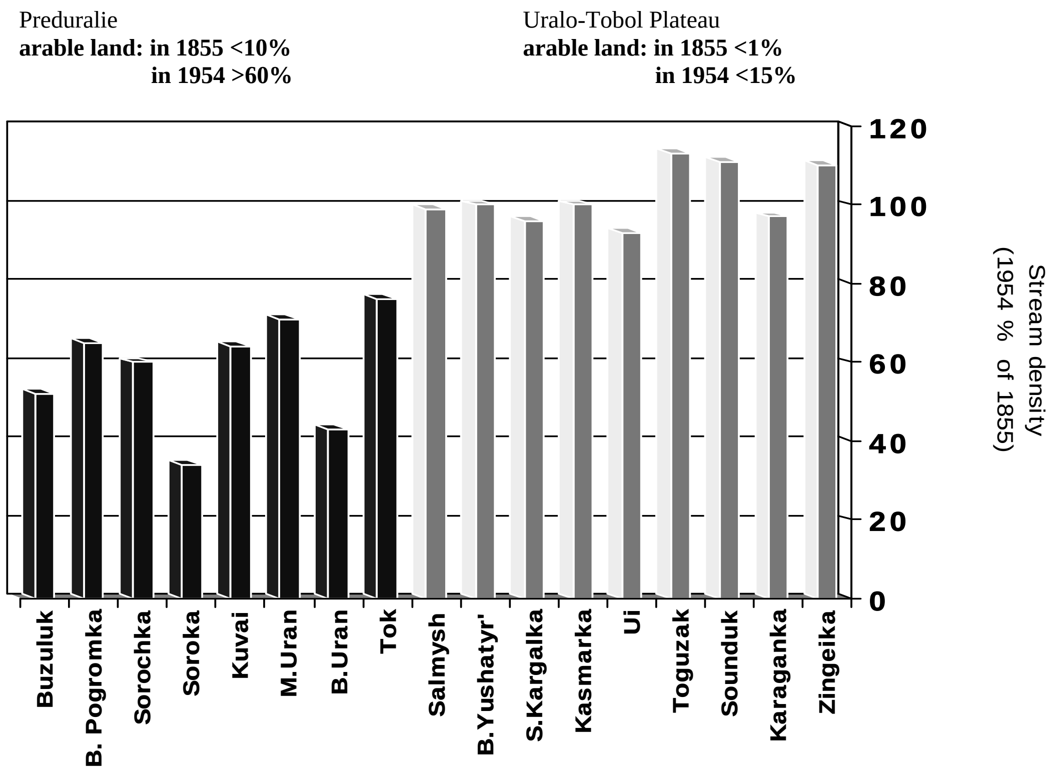

Fig. 2 The change of stream density in Preduralie and the Uralo-Tobol Plateau over a century (1954 as a percentage of 1855).

No clear change in stream density was found for the Uralo-Tobol Plateau between 1855 and 1954, because of the very small increase in the area of cultivated land. In contrast, the extent of the river network within the Preduralie area (Fig. 1) decreased to 22–63% of the original value over the 100 year period because of a 6-fold increase in the area of cultivated land. After 1954, the area of arable land in the Uralo-Tobol Plateau increased to 60–65% within 5–7 years. This immediately resulted in a decrease in the number of perennial streams for basins with an area of less than 100 km^2 (Fig. 3). It is interesting to note that streams with a catchment area <50 km^2 appear to be less susceptible to changes in the water and sediment regime than those with basin areas of 50–100 km^2. This can be explained by two factors: increased underground supply and high channel gradient that result in increased capacity to transport the sediment delivered from cultivated fields to the river channels in these particular basins. A decrease in the number of perennial streams occurred despite a tendency for water discharges to increase during the period 1950–1970 (Fig. 4). The tendency for the number of perennial streams to decrease continued during the next two decades until 1989. This was connected with two factors: firstly, the decrease of water discharges (Fig. 4) and, secondly, progressive transfer of eroded sediment along the river system. The rapid increase of the area of cultivated land in the Ural-Tobol plateau promoted a change in the relationship between surface and underground runoff. It led to an increase of sediment transfer to the river channels, combined with a decrease in water discharge during the mean water period.

It was found during the field study that the valley bottoms were often cultivated up to the river channels. As a result, all sediment eroded from the slopes was delivered directly to the river channel. In some cases, deluvial cones overlapped small river channels. The results of the study made it possible to conclude that small river aggradation on the Ural-Tobol plateau is directly connected with the anthropogenic influence. Unregulated ploughing of the banks of small rivers exerts a key influence on the intense small river aggradation.

The small rivers of the Prialtaiskoe Plain were widely used for transport at the beginning of the 20th century (Table 1). However, after the beginning of intensive cultivation the water regime of the small rivers changed considerably. This was connected with increasing surface runoff coefficients and erosion rates associated with ploughed land, when compared with virgin land. As

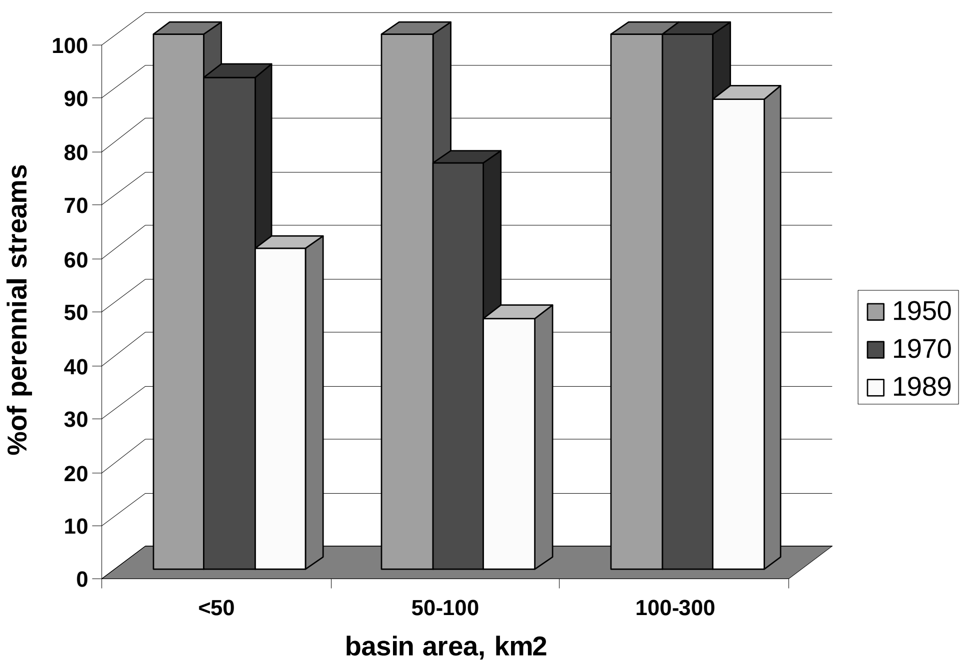

Fig. 3 The change in the number of perennial streams for basins of different size on the Uralo-Tobol Plateau, for different time intervals after 1954 (beginning of intensive cultivation).

a result, first order streams became intermittent watercourses (Bryukhanov, 1991), the amplitude of water level changes increased for the other small rivers and the low water discharges fell to minimum values (Table 1). A quantitative assessment soil erosion rates on cultivated land showed that these are relatively low for the left bank tributary basins of the Ob River (Table 2). Hence it is unlikely that an increase of sediment input from cultivated land is the only reason for small river aggradaton. The high variability of water discharges confirms that increasing surface runoff from cultivated lands during snow-melting also contributed to small river aggradation.

A trend of increasing precipitation erosion index (modified USLE equation) from west to east, with maximum values (>10 units) in Zabaikalie, is the main feature of the steppe and forest-steppe zones of Eastern Siberia (Bazhenova *et al*., 1997). Also Zabaikalie is the area with maximum values

Fig. 4 Curves depicting the relative change of annual water discharge (Ki) during the period 1934–1985 for the Ui River (basin area 3600 km^2) on the Uralo-Tobol plateau.

Table 1 Some characteristics of the Prialtaiskaya Plain rivers previously used for shipping.

River	River length (km)	Basin area (km^2)	Length used for shipping before period of intensive cultivation (km)	Water discharge (m^3 s^{-1})			Water level amplitude (mm)	
				Max.	Mean	Min.	Mean	Max.
Biya	301	37000	225	5770	1550	234	331	573
Anui	338	6850	132	462	130	5.4	387	601
Charysh	547	22000	180	2650	650	15.2	447	643
Aley	858	18200	137	1440	180	3.05	673	794
Chumysh	644	24100	418	2600	1250	17.0	397	552

Table 2 Mean annual erosion rates associated with the arable lands of the Altaisky krai within different morphological regions.

Morphological Region	Mean annual erosion rate. (t ha^{-1} year^{-1})	Calculated erosion rate (t ha^{-1} year^{-1})						
		<0.5	0.5–1	1–2	2–5	5–10	10–20	>20
		% of total area of arable land						
Kulundinskaya plain and Priobskoe plateau	0.7	71.5	19.3	4.4	2.6	1.6	0.6	0
Biysko-Chumyshskaya upland	4.7	14.1	14.4	17.4	23.2	16.4	11.5	3.0
Predaltaiskaya plain	1.4	36.6	29.3	14.1	14.0	5.4	0.6	0

of the relief factor (LS) (Litvin, 2002). As a result, the intensity of soil loss from cultivated lands in Zabaikalie is the highest in Siberia. Here sheet, rill and locally gully erosion are very intense.

The Aksha River basin, a tributary of the Onon River, is a typical small river basin of Eastern Siberia, located in southwestern Zabaikalie. Cultivated land occupies the concave slopes with lengths of 400–500 m dissected by hollows and a maximum gradient up to 10°. Detailed estimation of sheet erosion rates was undertaken for a few typical cultivated catchments, using a modified version of the USLE. It was found that sheet erosion rates change along the slope over the range 1–26 t ha^{-1} $year^{-1}$, with rates in excess of 15 t ha^{-1} $year^{-1}$ occurring on 44% of the area of the slopes. Direct observations of the consequences of several storm rainfall events was made within a small 1.3 ha slope catchment. The observations indicated that most of the sediment produced by sheet erosion was redeposited at the bottom of the slopes. According to direct measurements, the intensity of rill erosion exceeds that of sheet erosion by 2.5 times, with typical values of 25 and 10 t ha^{-1} $year^{-1}$, respectively. The input of gully erosion is relatively small (Table 3). Sediment eroded by linear erosion is transported directly to the river valley bottom.

Comparison of large scale topographic maps produced before and after increasing precipitation in the Aksha River basin showed an increase in the intensity of gully erosion on cultivated slopes and the formation of several badland areas. All developed after precipitation increased over a period of 5–6 years. The mean gully volume is 15 000 m^3, with values ranging

Table 3 A comparison of sheet, rill and gully erosion rates in a typical slope catchment in the Aksha River basin.

Type of erosion	Mean annual volume of erosion, (m^3 $year^{-1}$)	Percentage of total volume of soil loss
Sheet erosion	1035	26.5
Rill erosion	2870	71.1
Gully erosion	130	3.3
Total erosion	4035	100

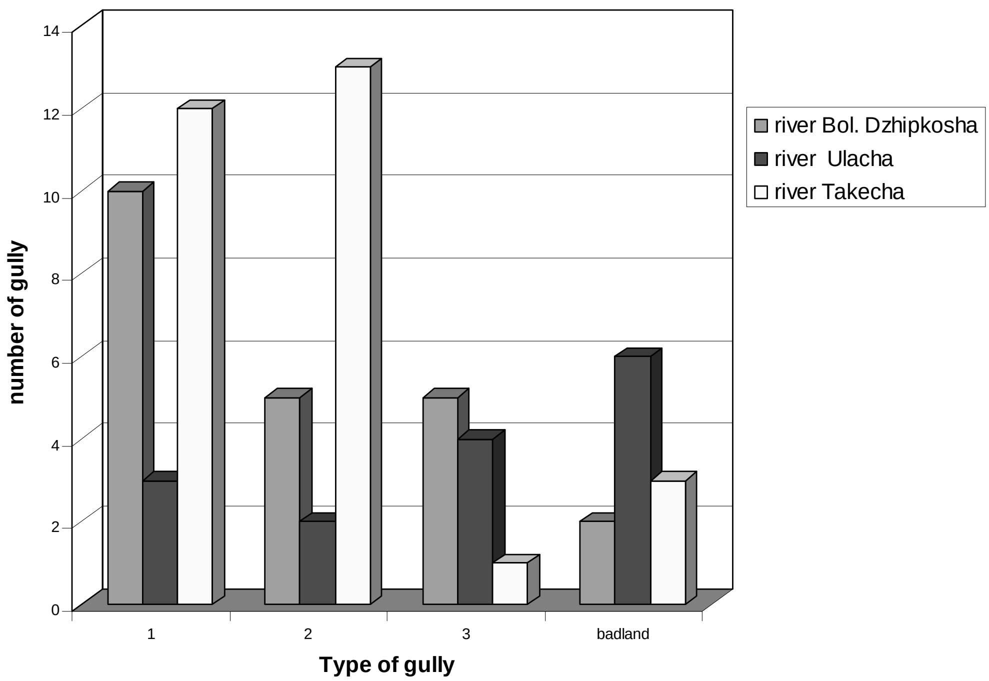

Fig. 5 Distribution of gullies of different types and badlands for different first order streams. Type of gully: 1, in the bottoms of hollows, developed because of retreat of the gully head; 2, deepening of rill along the entire slope; 3, bottom gully along the depression between individual hills.

between 10 000 and 55 000 m^3. It is possible to identify three types of gully (Fig. 5). Badlands represent a system with a few gullies with a mean volume of 120 000 m^3. All sediment produced during badland formation reached the valley bottoms. As a result, a huge volume of sediment was delivered to the river valleys during a relatively short time interval. However, the small rivers in the Aksha River basin did not aggrade. This situation can be explained in terms of three reasons: firstly, the wide bottoms of the small river valleys (termed "pads" in Russian terminology), secondly, the high gradients of the river channels and, thirdly, the relatively small area of cultivated land. As a result, the transport capacity of the flow in the river channels exceeds the volume of sediment supplied from the cultivated land and badlands.

CONCLUSION

Small river aggradation has been observed in the agricultural belt of western Siberia. A detailed study of river net transformation in the Uralo-Tobol Plateau area during the period 1850–1990 has demonstrated that the process of intensive river aggradation started immediately following the rapid increase of the area of cultivation after 1954. Aggradation of the small rivers was primarily caused by changes in the intra-annual water discharge distribution and second order streams were more affected, because headwater streams received more groundwater supply. During the second stage of river aggradation (the period 1970–1989) the increased sediment delivery from the slopes was a key driver of the intensified aggradation, because the water discharge distribution did not change compared with the previous period (1954–1970). After about a century of intensive cultivation, most of the first-second orders streams in the Prialtaiskaya Plain area were completely aggraded and became dry valleys. There were no further changes of river pattern during recent decades. The intra-annual water discharge distribution of middle size rivers changed markedly, producing very high water discharges during the spring flood and extremely low water discharges during the summer in most rivers. Climate variability does not exert an important influence on the river regimes in the western part of the agricultural belt of Siberia.

Aggradation processes have not affected the first order streams of Eastern Siberia, even in areas with very high erosion rates on the cultivated land, because of the relatively small area of arable land (<50%) in the individual river basins, the morphology of their valley bottoms and the relatively high gradients of the river channels, which result in the transport capacity of channel flow exceeding the sediment supply.

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