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The impact of hydropower development on the sediment budget of the River Beiarelva, Norway

JIM BOGEN & TRULS E. BØNSNES

Norwegian Water Resources and Energy Directorate, PO Box 5091, Maj., N-0301 Oslo, Norway

jbo@nve.no

Abstract Since 1994, as a result of hydropower development, the River Beiarelva has been affected by a water diversion. From 1989 to 1993, before the diversion, annual suspended sediment loads varied from 7900 to 23 500 t year^{-1}, and suspended sediment concentrations (SSC) remained below 200 mg l^{-1}. Once the diversion was implemented, initial loads declined (<4000 t year^{-1}); however, in the following years they increased (i.e. 40 000 and 67 000 t year^{-1} in 2002 and 2003, respectively). Maximum SSC also increased and exceeded 4000 mg l^{-1}. These changes appear due to alterations in both sediment delivery and storage. Glacial sediment yields vary both between glaciers, and from year to year (i.e. between 16 and 2100 t km^{-2}). Unglacierized areas supply less sediment; however, higher rates may occur during floods. After the hydropower plant became operational, the Beiarelva's discharge and sediment transport capacity declined and sediment storage increased. About 50% of glacially-derived sediment is diverted, but overflow at the intakes during floods can cause extensive erosion in the regulated tributary reaches. Since the onset of regulation, sediment storage occurs during low-flow years, whereas channel flushing occurs during floods. Further, SSC changed from being supply- to discharge-limited.

Key words diversion; hydropower; reduced transport capacity; sediment budget; sediment flushing; temporal sediment storage

INTRODUCTION

In regulated rivers, diversions may reduce water and sediment discharges in affected reaches. Alluvial river reaches, affected by hydropower development, tend to re-equilibrate during the following years. Sediment deposition due to reduced transport capacity often occurs in regulated rivers, and may affect fish habitats (e.g. Rosenau (2000) for a British Columbia River and Rees (2003) for the Colorado River). O`Brien (1987) studied the deposition of sand in a gravel bed river, and discussed the design of a hydrograph to remove it, to preserve fish habitats.

In Norwegian glacial valleys, main channel river gradients tend to be low, whereas that of the tributaries draining the sidewalls tend to be steep. Fergus (1993, 1997) studied the River Fortunselv that was first regulated in 1953, and later subjected to more extensive regulation. River cross-sections measured in 1973 and 1989 indicated a net accumulation of 12 000 m^3. At the same time, river slope increased in response to reduced water discharge. It is anticipated that several other regulated rivers will change in a similar manner, dependant on sediment delivery rates and the volume of diverted water (Bogen, 1993). In the River Suldalslågen, Bogen & Bønsnes (2004) found that although morphological changes were slow, the sedimentological changes had affected fish habitats.

This paper focuses on sediment production, transport, and storage in the eastern part of the River Beiarelva catchment, located in Norway just north of the Arctic Circle (Fig. 1). Part of this catchment was diverted under the Svartisen hydroelectric project (Bogen & Bønsnes, 2001). The catchment covers an area of 351 km^2, of which 53 km^2

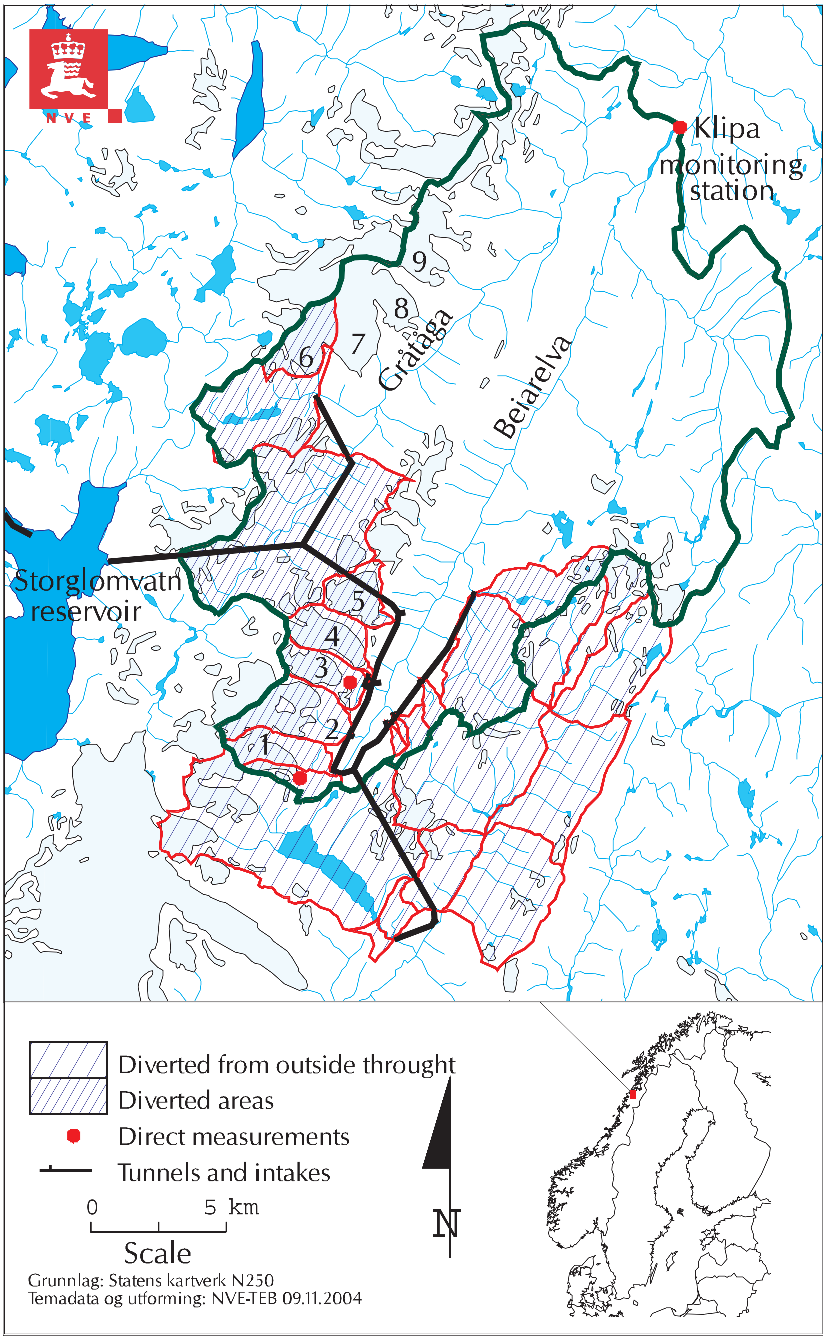

Fig. 1 Map of the catchment area of the River Beiarelva, and nearby diverted catchments. The numbers on the glaciers refer to Table 1.

is glaciated. The main course of the river follows a glacial trough, whereas the tributaries drain glacial and non-glacial areas down steep mountainsides. The monitoring station is situated at ~105 m a.s.l., whereas the highest mountains within the catchment can reach 1637 m a.s.l. The treeline is located ~600 m a.s.l; however, only 92 km^2 (26%) of the catchment is situated below the treeline. Sampling strategy and laboratory methods followed procedures established by the Norwegian Water Resources and Energy Directorate (NVE), as described by Bogen (1992) for the stations at Klipa and Øvre Beiarbre. The other stations followed a more simplified programme described by Kjeldsen *et al*. (1989).

SEDIMENT SOURCES

The most important sediment source in the catchment are glaciers. Measurements show that sediment yields from two of them (Øvre Beiarbre and Trollbergdalsbre) are the highest that have been measured in mainland Norway (Bogen & Bønsnes, 2003). However, specific glacial sediment yields display large year-to-year variations ranging from 362 to 2100 t km^{-2} year^{-1} and 173 to 1500 t km^{-2} year^{-1} for Øvre Beiarbre and Trollbergdalsbreen, respectively (Table 1).

Sediment yields from unglacierized areas are not of the same order of magnitude as from glaciated areas. Measured sediment yields for mountain rivers in mainland Norway range from 12 to 26 t km^{-2} year^{-1} (Bogen 1996). However, erosion rates may be considerably higher during major floods. In the mountain River Atna, sediment transport during the large 1996 flood was more than 40 times higher than the mean for the 1987–1994 period (Bogen, 2004).

As only 2 km^2 (0.6%) of the Beiarelva catchment is cultivated, agriculture is a minor sediment source. However, grazing may remove vegetation and thus, increase soil erosion. In some areas, unsuccessful reforestation programmes, introducing new

Table 1 Sediment budget of the River Beiarelva. See Fig. 1 for location of glaciers.

Glacier/ catchment	No.	Contrib. area (km^2)	Susp. sed. transport, 1987 (t year^{-1})	Susp. sed transport	Bed load (t year^{-1})	Susp. sediment yield (t km^{-2})
Beiarelv, not regulated 20 glacial units		19		2204		116
Øvre Beiarbre*	1	2.4	1500	1160	773	488
Lappflyttar elv*	2	5.3	80	125	83	24
Trollbergdalsbre*	3	2.02	950	2345	1560	1173
Skjelåtindbre*	4	1.28		576	384	450
Hanspolsabre*	5	2.67	800	1200	850	449
Leirbre (Vegdal)*	6	3.2	1150	1700		531
Hengfonna	7	2.75		1460		531
Skjelåfonna	8	4.85		2575		531
Jervåfonna	9	2.0		1062		531
Unglacierized part		100		1600–64000		16–640

* diverted glacier streams.

species, have led to limited increases in debris slides and gullying. Winter ice runs arise from increased water discharge when the river is frozen. Bank erosion, triggered by ice runs, is a significant source of sediment in the lower part of the catchment.

The Beiarelva is a gravel-bed river. As in similar rivers, low-gradient alluvial reaches alternate with steeper ones confined by canyon walls. The alluvial cross-sections are broad and shallow. Bedload sediment is derived from modern glaciers, as well as old moraines and glaciofluvial deposits dating from the last Ice Age. In the lower part of the river, the bed is composed of gravel and cobbles. In the upper reaches, grain size is more heterogeneous. Large immobile boulders often are present and create an irregular-shaped channel.

SUSPENDED SEDIMENT CONCENTRATIONS AND LOADS

Before the initiation of hydropower development (1989–1993), natural SSCs were low (10–20 mg l^{-1}) most of the time. High SSCs (100–150 mg l^{-1}) were associated with short duration pulses during floods. Discharge and SSC for 1990 are typical of pre-development conditions (Fig. 2(a)). The SSC was low during the snowmelt in early

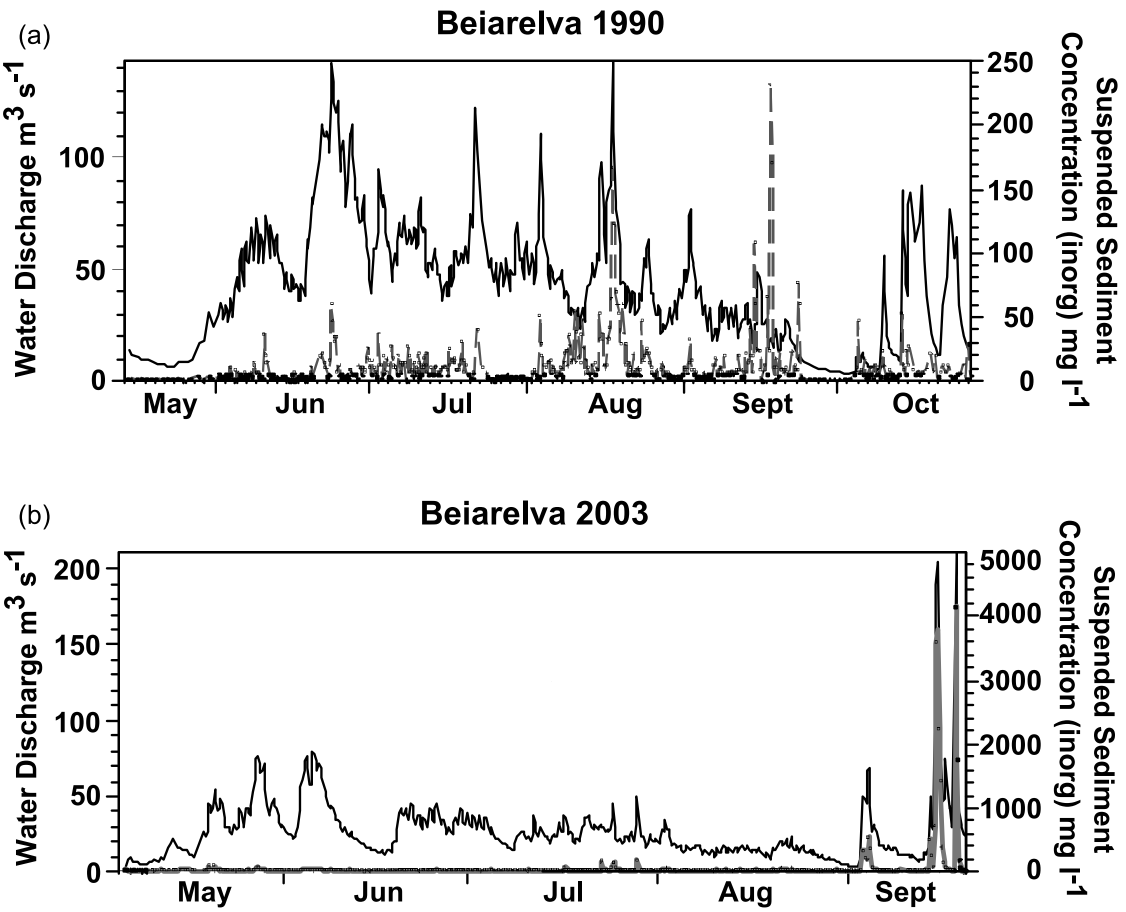

Fig. 2 Suspended sediment concentration (dotted line) and water discharge (solid line) at the Klipa monitoring station, River Beiarelva: (a) in 1990, before regulation and (b) in 2003, after regulation.

June, typically <10 mg l^{-1}. On 10 June, SSC reached 36 mg l^{-1} at a water discharge of 65.7 m^3 s^{-1}. Earlier in the season, similar discharges carried lower SSCs. In late June and July, SSC rose, sometimes exceeding 50 mg l^{-1}. On 17 August, SSC reached 167 mg l^{-1} at a discharge of 143 m^3 s^{-1}. The highest annual recorded SSC (231 mg l^{-1}) occurred on 17 September, at a much lower discharge (19 m^3 s^{-1}). This irregular pattern would appear to indicate that sediment is supply- rather than discharge-limited. Note that the very high SSC of 919 mg l^{-1} measured in August 1991 was not natural, but caused by the disposal of fine material discharged during construction work.

After the 1994 diversion, maximum annual SSCs increased considerably. During the first 5-year period (1994–1998) maximum annual SSC ranged from 94 to 392 mg l^{-1}. During the following period (1999–2003), maximum SSCs far exceeded these levels. Discharge and SSC for 2003 are typical of post-development conditions (Fig. 2(b)). During most of the year, discharge and the corresponding SSCs were relatively low. However, in September, two large floods occurred. They culminated at 320 m^3 s^{-1}, which corresponds to a 5–10 year recurrence interval. SSCs were very high during these floods, reaching a maximum of 4139 mg l^{-1} on 18 September.

Year-to-year variations in annual suspended sediment transport during the 1989–2003 period are shown in Fig. 3. Before the diversion took place (1989–1993), the suspended sediment load varied between 7900 and 24 000 t $year^{-1}$; however, the highest measured SSC remained below 200 mg l^{-1}. Once the diversions had been implemented, the suspended load decreased to 2000 t $year^{-1}$ because of reservoir infilling and reduced transport capacity. Sediment transport remained low for a time; the mean for the 1994–1998 period was 3700 t $year^{-1}$. Then, sediment transport gradually increased, ultimately exceeding the rates measured before the river was regulated. In 2002 and 2003, sediment transport was 40 000 and 67 000 t $year^{-1}$, respectively. These are very high, relative to pre-development levels. The diversion caused an immediate reduction in water discharge; however, maximum discharge increased later due to intake overflows.

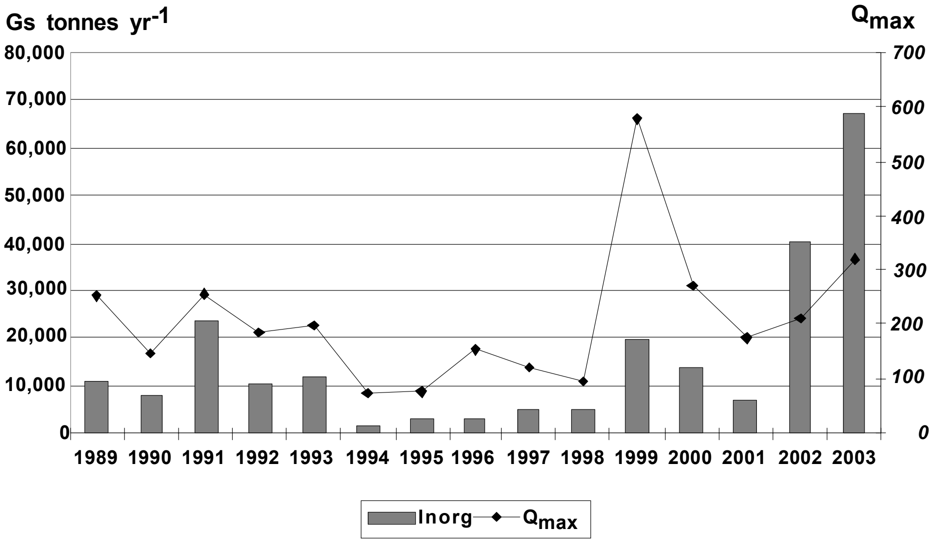

Fig. 3 Annual maximum water discharge and annual sediment transport at the Klipa monitoring station on the River Beiarelva during the years 1989–2003.

CHANGES IN SEDIMENT DELIVERY AND STORAGE

After the onset of regulation, tributary-derived sediment remained in the catchment. An evaluation of the sediment budget for the period-or-record revealed that average annual transport in the main channel of the Beiarelva amounted to 13 000 t year^{-1} before 1989–1993, and 3700 t year^{-1} during the first five years (1994–1998) after regulation began. The most striking change was the diversion of 50% of the sediment-laden glacial meltwater. Based on sediment budget estimates, this diversion should have reduced sediment delivery to the main channel by about 20 000 t year^{-1}; instead, there was a significant increase.

The increase may have been caused by overflow events occurring after 1998. The overflows are associated with completion of the Storglomvatn Reservoir, which took several years. The first overflow occurred when the reservoir approached its highest regulated water level (HRW). A filling curve for the Storglomvatn Reservoir is given in Bogen & Bønsnes (2000). At, or close to HRW, the diversion tunnel is submerged. The water backs up and the flow in the tunnel is reversed. During severe floods, the water flow at the intakes are also reversed. In such situations, the sediment-laden water bypasses the affected intakes and water and sediment are delivered both from the original sources, and through the diversion tunnels, from intakes located outside the Beiarelva catchment. The water discharge may then become excessive, and heavy erosion takes place along the affected reaches. Thus, in the tributaries, sediment yields from channel erosion and through debris slides triggered by fluvial undercutting have increased considerably. Hence, channel transport capacity has declined because water has been diverted and there is an increase in sediment supply from the overflows.

A comparison of runoff duration curves before and after the onset of regulation shows the changes in water discharge (Fig. 4). The overflows have caused an increase in the number of very large floods (160–200 m^3 s^{-1}), but the duration of water discharges of intermediate size, (e.g. 25–125 m^3 s^{-1}) has declined.

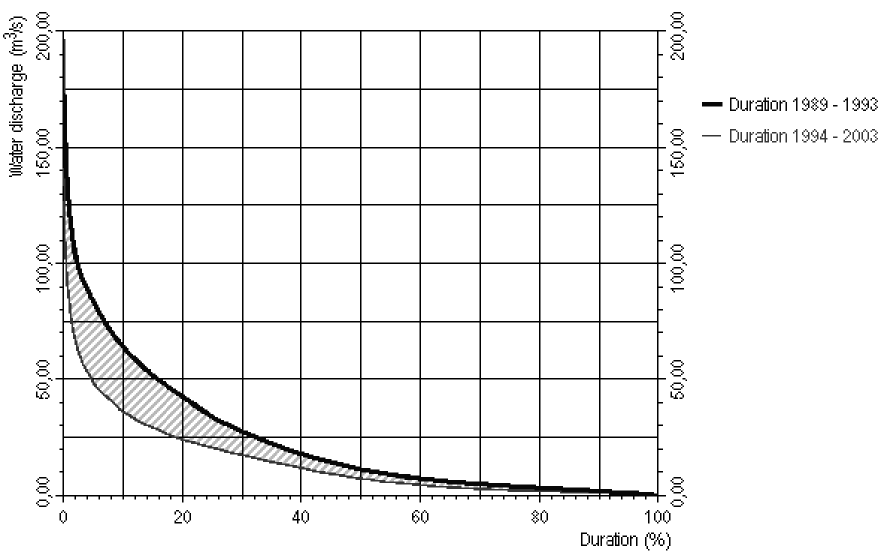

Fig. 4 A comparison of runoff duration curves for water discharge at the Klipa monitoring station on the River Beiarelva before (1989–1993), and after (1994–2003), the initiation of regulation.

Recent observations of the main channel at low discharge in May 2004 showed extensive sediment deposition zones. These sediments are resting on the armoured riverbed. In the lower reaches of the river, patches of sand and silt cover a gravel and cobble pavement. In some areas they form a thin layer overlying coarser material, whereas in others the interstices are completely filled. In the upper part of the river, silt and sand banks have been formed.

A plot of *SSC vs* water discharge (Q) for the 1989–2003 period shows no correlation (Fig. 5(a)). The irregular pattern of the *SCC–Q* plot probably is the result of sediment delivery from a number of scattered but different sources. The contribution from each one varies with time, and most probably is affected by periods of exhaustion.

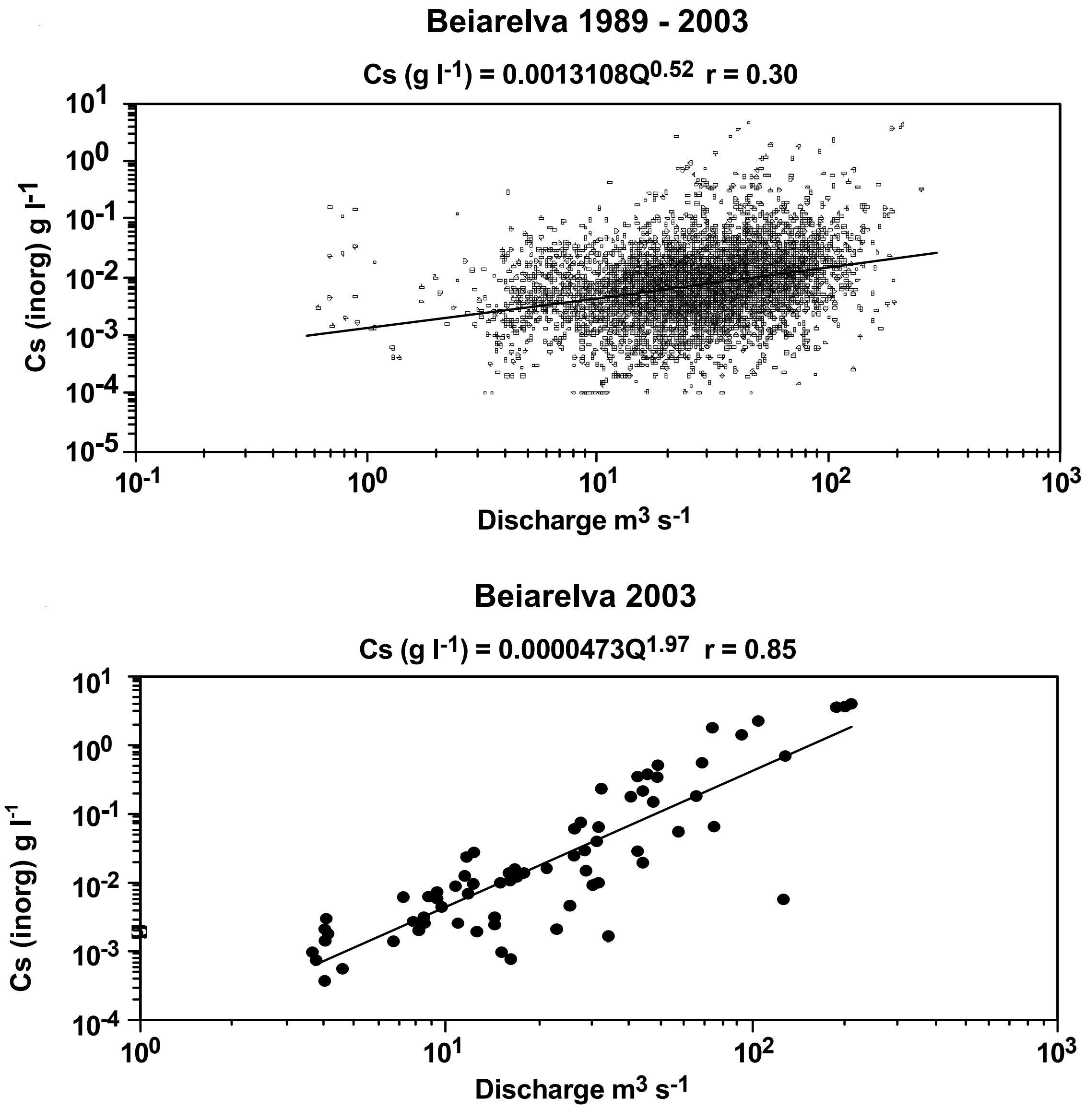

Fig. 5 (a) A plot of suspended sediment concentration *vs* water discharge at Klipa; data from the years 1989–2003. The black line indicates 0.200 g l^{-1}. Almost all the concentrations above this level were recorded after the initiation of regulations; and (b) a significant correlation between suspended sediment concentration and water discharge was found for the flood event in September 2003.

The general pattern of *SSC vs Q* (Fig. 5(a)) did not change with the initiation of regulation, except for the occurrence of very high concentrations, as indicated by the line in Fig. 5(a). However, behaviour during single flood events has changed. Prior to regulation, during single flood events there were occasional correlations between *SSC* and *Q*. However, after the onset of regulation, the number of such events increased, and often occurred when water discharge exceeded 40–50 $m^3 s^{-1}$. For example, during the large flood in September 2003, the correlation coefficient for *SSC* ($g l^{-1}$) and *Q* ($m^3 s^{-1}$) was 0.85 (Fig. 5(b)). Hence, it appears as if sediment transport changed from being supply-limited to discharge-limited in the catchment, probably as a result of increased access to material previously held in storage in the main channel of the River Beiarelva. Further, the elevated SSCs measured during floods may have the same source.

Prior to regulation, some sediment deposition and storage may have occurred in the main channel during low flows. However, this material would have been washed away during subsequent floods, thus giving rise to the strong positive *SSC–Q* correlations only noted during individual events.

The onset of river regulation caused substantial changes in the sediment budget of the catchment. Measurements at the glacier outlet indicate a net loss of sediment from diversions (denoted by *, Table 1) on the order of 7000 t $year^{-1}$. However, at least some of these losses have been counterbalanced by accelerated erosion in the tributaries as total sediment delivery from both glacierized and unglacierized sources at the Klipa monitoring site remain at pre-regulatory levels. Estimated sediment delivery during floods caused by intake overflows amounts to some 73 000 t $year^{-1}$. This is similar to the sediment transport measured during 2002 and 2003.

CONCLUSIONS

The most important sediment source within the River Beiarelva catchment is glacial erosion. The specific sediment yields of some of the glaciers are among the highest recorded in Norway. Sediment yields from the unglacierized area is much smaller, 16 t $km^{-2} year^{-1}$. However, measurements of a comparable mountain river, during a major 200-year recurrence interval flood generated yields 40 times the mean.

Runoff duration curves show that water discharge and sediment transport capacity in the low gradient main channel of the Beiarelva have been reduced as a consequence of diversions. The duration of water discharges of intermediate size (i.e. 25–125 $m^3 s^{-1}$) has declined, whereas overflows at the diversion tunnel intakes have caused an increase in the number of very large floods (i.e. 160–200 $m^3 s^{-1}$).

Overflows during high flood events have caused extensive erosion in the regulated reaches of the Beiarelva catchment tributaries; this material appears to be accumulating in the main channel under the present regulated regime.

Prior to the onset of regulation (1989–1993), annual suspended sediment loads at Klipa varied between 7900 and 24 000 t $year^{-1}$. The highest observed SSC remained below 200 mg l^{-1}. After the onset of regulation, suspended loads initially (1994–1998) declined to a mean of 3700 t $year^{-1}$. However, during the following years, transport increased considerably and 40 000 and 67 000 t $year^{-1}$ were measured in 2002 and

2003, respectively. The SSC also increased, and reached a maximum of 4139 mg l^{-1} during the August 2003 flood.

Extensive deposition and storage of fine sediments in the main channel of River Beiarelva has taken place in recent years. At the monitoring station at Klipa, the relationship between water discharge and SSC indicates that sediment transport in the catchment changed from being supply-limited prior to the onset of regulation, to being discharge-limited after the onset of regulation.

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