Temporal variations in the transport of mine tailings through the Knabeåna-Kvina river system, and into the Fedafjord, Norway

MARIANNE LANGEDAL

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Mine tailings from the Knaben Molybdenum Mines were discharged into two lakes in the headwater area of the Knabeåna-Kvina drainage basin in the period 1918-1973. A dam was built downstream of the two lakes in 1976 to prevent spreading of the waste. However, large amounts of tailings were previously washed out of the lakes, and approximately 420,000 tons are now deposited along the river. Chemical analysis of 8 samples of suspended sediment, collected in 1993-1994, was performed to examine whether the tailings could be recognised in the suspended sediment load. The median acid-soluble contents of Cu and Mo were 120 and 48 ppm, respectively. The concentrations are similar to those in the spoil heap and one order of magnitude higher than in the local natural sediment. The suspended sediment transport rate in the period March-December 1993 was monitored by frequent sampling of suspended sediment (1-4 times a day) and continuous measurements of water discharge. In the monitored period, the total suspended sediment yield was 600 tons. Of these, 90% were transported during 7% of the time. The sediment transport occurred in pulses corresponding to periods with high water discharge. Rapid variations require monitoring by frequent sampling in order to assess the amounts of tailings that are transported towards the fjord. The relationship between sediment transport and water discharge seems to be governed by major floods that open up sediment sources which remain vulnerable for erosion in the coming years. After large floods the transport rate of tailings may therefore increase significantly in the supply-limited Knabeåna-Kvina river. This implicates that future international negotiations and abatement strategies concerning fluvial input of heavy metals to marine areas should assess the risk of input of particle-bound historical pollution, both in normal flow situations and in extreme flood events.

Marianne Langedal, Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology, N-7034 Trondheim, Norway.

Introduction

The objective of this paper is to demonstrate the temporal variations in the particulate heavy metal load carried by rivers, and to point out implications for the input of heavy metals to marine areas.

The North Sea Declaration of 1987 aims at 50-70 % reductions in the riverine input of certain heavy metals by 1995, with 1985 as a reference year. In Norway, monitoring of the fluvial input is based on monthly water sampling of the main rivers entering the North Sea (Holtan et al. 1991). Little attention has been paid to particle-bound heavy metals, although several studies have shown that the major part of the heavy metals transported by rivers exists as particles or is adhering to particulate matter (Förstner & Kerstens 1988, Leenaers 1989). The transport rate of particle-bound heavy metals is probably more dependent on sediment transport rate than on the heavy metal concentration in the particulate matter since the former exhibits larger temporal variations (Walling et al. 1992a, Langedal et al. 1996).

Heavy metals in the particulate stream load can originate from both natural and anthropogenic sources. Regional geochemical mapping has shown that the natural contents of metals in soils and sediment normally vary regionally by a factor of 10 or more (Bølviken et al. 1986, Ottesen & Bølviken 1987). Superimposed on this distribution pattern are metals from anthropogenic discharges in present and earlier times. An example is the 17 billion tons of heavy metal containing waste left by historical mining in Europe (RIVM 1991). The spoil heaps are commonly situated near rivers, where the waste is subjected to natural erosion, transport and deposition cycles. Chemical analyses of overbank sediment on floodplains have shown that mine waste has been scattered downstream from spoil heaps in approximately 30% of all drainage basins in Europe (Demetriades et al. 1990, Bølviken et al. 1993). In this way, large amounts of heavy metals are temporarily stored in drainage sediment that may be entrained in the river load and brought into the marine environment.

This paper discusses the temporal variations of fluvial transport of historical mine waste from the Knaben Molybdenum Mines through the Knabeåna-Kvina river system and into the Fedafjord, Norway (Fig. 1). The discussions are based on chemical analysis of suspended sediment load and monitoring of suspended sediment transport. The probable influence of future major floods on the input rate of historical pollution into the Fedafjord is discussed, based on sediment erosion and transport data from rivers that have recently been subjected to major floods. Practical implications for monitoring programmes, risk analysis, and new treaties concerning input of heavy metals to coastal areas are also pointed out.

Study area

The Knabeåna-Kvina drainage basin belongs to a geochemical Mo-province underlain by Precambrian granites and gneisses (Sigmond et al. 1984, Ottesen et al. 1989). About 50% of the drainage basin consists of outcropping, barren rock while the remaining drainage area has rather thin glacial and glaciofluvial deposits with a strong vegetation cover. Fluvial deposits are restricted to the immediate vicinity of the river. The larger portion of the river bed is armoured by gravel and pebbles, indicating that the sediment transport capacity exceeds the sediment supply Bathurst 1987). Such rivers were called 'supply limited' by Pitlick & Thorne (1987), and in the following this term will be used about the Knabeåna-Kvina river.

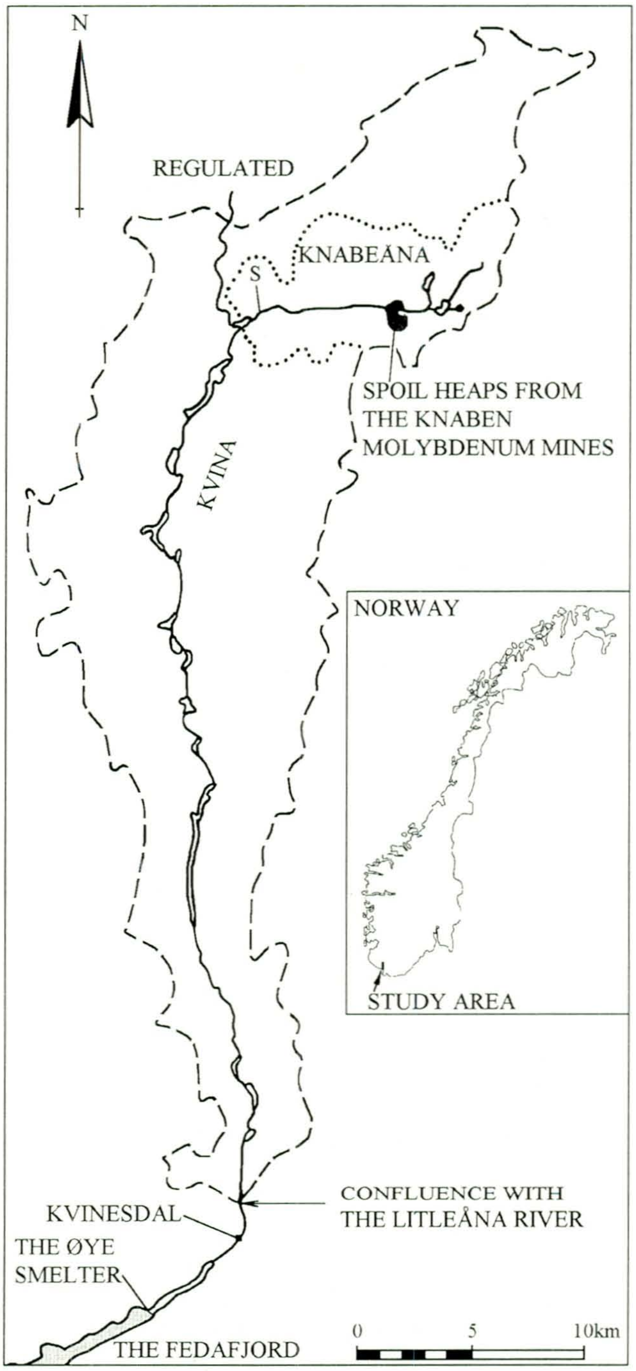

Fig. 1. Map over the unregulated part of the Knabeåna-Kvina drainage basin, with sampling location of suspended sediment marked by S.

The Knaben Molybdenumines are situated some 50 km upstream from the outlet of the Kvina river into the Fedafjord. Mining and milling took place from 1918 to 1973. In this period at least 8 million tons of waste material were produced and deposited in two nearby lakes. These tailings contain approximately 200 ppm acid-soluble Cu and 40 ppm acid-soluble Mo (median values, Langedal 1995). To reduce the spreading of tailings by fluvial processes, a dam was built downstream of the lakes in 1976. However, considerable amounts of tailings had previously been washed downstream by the Knabeåna-Kvina river. Today, an estimated 420,000 tons of this material are visible as large sandbars within the river channel and as overbank deposits on the floodplains (Langedal 1995). The median concentrations of Cu and Mo in these deposits are one order of magnitude higher than in the pre-mining sediment from the bottom part of overbank sediment profiles (Fig 2, Langedal 1995, Langedal & Ottesen 1995). The construction of the tailings dam helped out to cut off the sediment supply from the major waste heap. Today the most erodible material in the drainage basin is the tailings deposited within the channel (Langedal & Ottesen 1995). Minor sediment sources are tailings on floodplains and natural till, glaciofluvial and fluvial deposits. Open natural sediment sources, however, are few, due to the limited amount of Quaternary deposits and the strong vegetation cover.

Methods

Water discharge measurement, sampling and sample treatment

Water discharge was measured continuously in the period March-December 1993, using a Stevens Limnigraf. Samples of water with suspended sediment were pumped up from a turbulent section of the Knabeåna river (Fig. 1) by an ISCO automatic pumping sampler, according to a procedure described by Bogen (1988, 1992). A 50-litre sample was collected every 10 days for chemical and grain-size analysis, while 1-litre samples were collected 1-4 times a day for sediment transport monitoring. The samples were filtered on 0.45 µm millipore filters to separate suspended particles from water. Since few 50-litre samples contained enough particulates for the selected chemical analysis (> 1 g particulate material), 7 samples from 1993 were combined to 4 samples. In addition, 4 were collected in 1994.

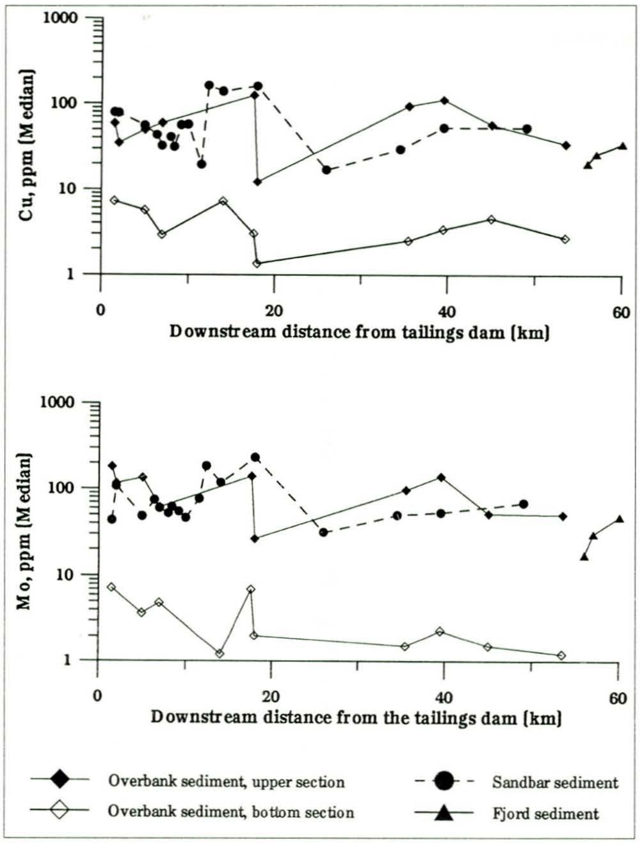

Fig. 2. Median acid-soluble Cu and Mo concentrations in drainage sediment versus the distance from the spoil heaps (Langedal & Ottesen 1995).

Chemical analysis

Samples of suspended sediment were analysed for Cu, Mo and 30 other aqua regia soluble elements by ICP-AES at the Geological Survey of Finland (Edén & Björklund 1994). The same procedure was previously used for chemical analysis of material from the spoil heaps and sediment within this drainage basin (Langedal 1995).

Calculation of suspended sediment transport

Suspended sediment concentration (mg/l) was determined by weighing the filter residue and the remaining water sample. The suspended sediment concentrations between the times of sampling were estimated by linear interpolation. The suspended sediment transport rate could then be obtained by multiplying sediment concentrations by the continuously measured water discharge.

Table 1: Acid-soluble Mo and Cu concentrations in suspended sediment samples from the Knabeåna river

Date(s)	Cu (ppm)	Mo (ppm)
26 March 1993	–	54.4
3+10 May 1993	–	37.4
17 May 1993	–	179
24 + 31 May + 7 June 1993	–	19.5
25 April 1994	142	50.7
2 May 1994	255	33.5
8 May 1994	65	44.3
11 May 1994	97.5	82.9

To test whether suspended sediment sampling once a month would give a similar result as the frequent sampling described above, the first samples collected on the 3rd of every month were selected. A regression analysis of logtransformed data for suspended sediment concentration versus water discharge was performed. For every day in the period March to December, the suspended sediment concentrations were calculated by use of the regression equation and the observed mean daily water discharge. Since the sediment rating curves were obtained from logtransformed data, transformation bias was corrected for by multiplying the calculated suspended sediment concentrations by the factor $e^{(2,651 \cdot S^2)}$, where S^2 is the standard error of the estimated rating - curve in log 10 units (Ferguson 1987). Estimated daily sediment transport rates could then be obtained by multiplying the sediment concentration with the observed mean daily water discharge. The same procedure was repeated for samples collected on the 13th, the 18th and the 24rd of every month.

Results and discussion

Chemical analyses of the suspended sediment show that tailings constitute the larger part of the suspended load (Table 1). The acid-soluble contents of Cu and Mo are similar to those in the spoil heap and one order of magnitude higher than in the natural sediment. Since only samples collected at high discharges were large enough for chemical analysis, the sediment load in low flow situations may have a different composition. However, the major part of the monitored sediment transport occurred in periods with high water discharge (Fig. 3) and the obtained concentrations are therefore thought to be representative for the suspended load.

From March to December, 1993, the suspended sediment yield of the Knabeåna river was approximately 600 tons. Of these, more than 150 tons were transported on the 19th of December, another 200 tons in a three-day period in April, and another 70 tons in a five-day period in March. In fact, 90% of the sediment transport occurred in

Table 2: Estimated sediment yield March-December 1993 using data from the same date every month.

Date	Sediment yield (tons)	% of measured yield
3rd	270	44
13th	130	21
18th	500	82
24rd	215	35

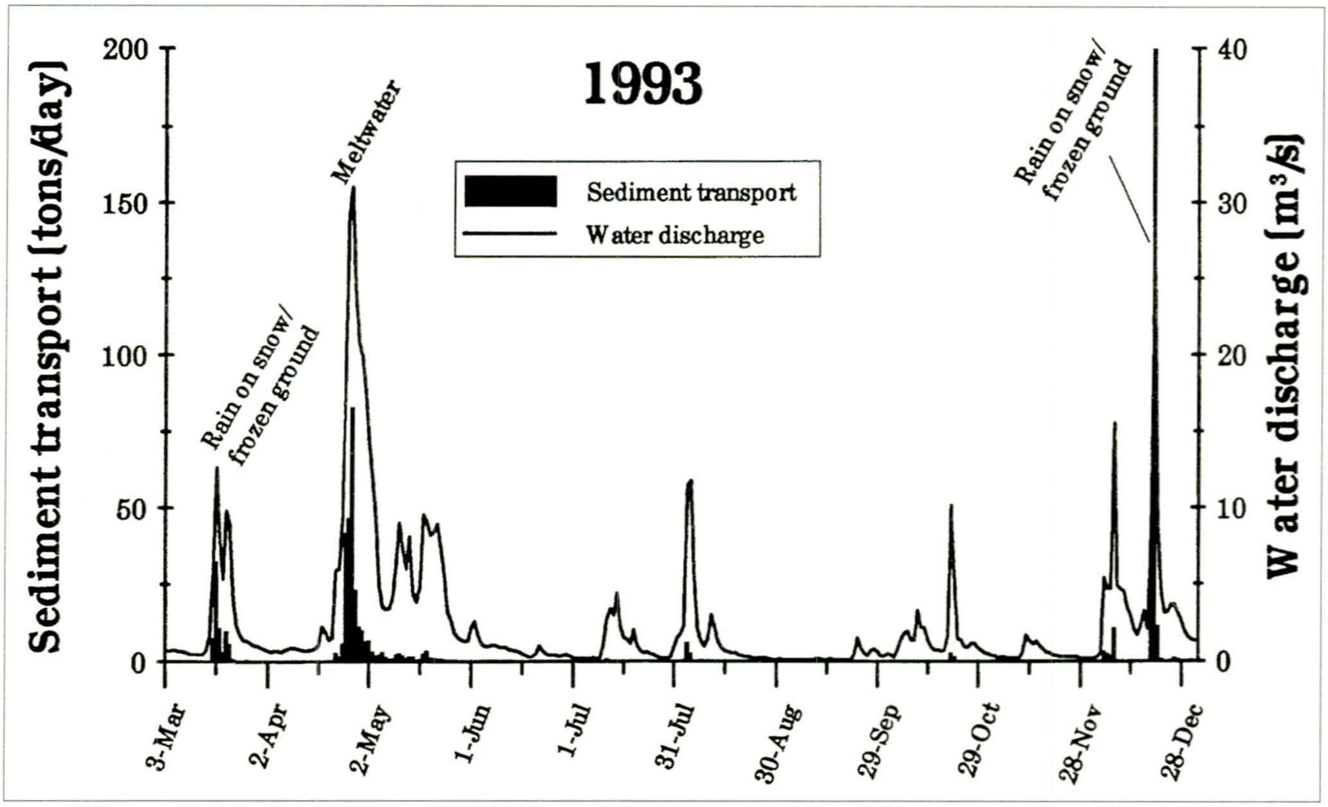

Fig. 3. Sediment transport (Gs) and water discharge (Q) in the Knabeåna river in 1993, based on 1-4 samples of suspended sediment a day. 90 % of the transport occurs in 7 % of the time (Langedal & Ottesen 1995).

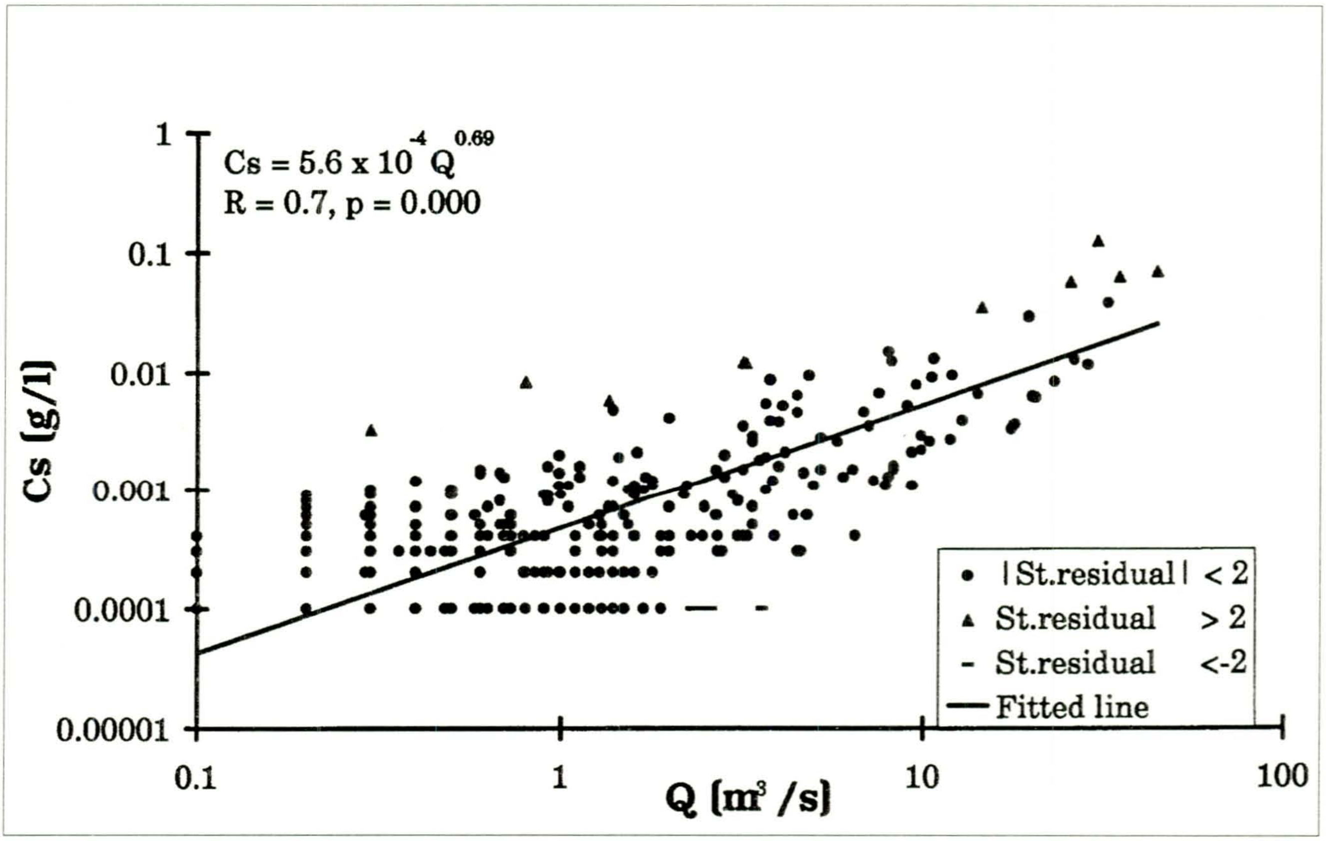

Fig. 4. Regression analysis of sediment concentration (Cs) versus water discharge (Q) in the Knabeåna river in 1993. St.residual = standardised residual, the vertical distance between an observation and the fitted line, divided by the standard deviation of the residuals (Norušis 1990).

Fig. 5. Erosion scar by the 200-year flood in the Østerdalen valley, Norway. The protectional structures along the river have caused turbulence on the floodplain and a large trench was carved out by the flood (Photo by J. Bogen, 1995).

7% of the time, closely corresponding to periods with high water discharge. Several other studies also show that the transport rate of suspended sediment and associated heavy metals are largest in flood situations (Bradley 1988, Leenaers 1989, Walling et al. 1992a, Langedal et al. 1996).

Suspended sediment yields estimated from monthly sampling of suspended load in the Knabeåna river range from 21 to 82% of the measured yield (1-4 samples a day, Table 2). The large deviations between the estimates show that more frequent sampling of suspended sediment is necessary to detect the rapid fluctuations in the sediment transport rate (Fig. 3), and thus to determine the amount of particle-bound heavy metals that are brought to the sea. Similar results were obtained for the river Ex, UK, where the suspended sediment yield was clearly underestimated when calculated from rating curves based on weekly sampling (Walling et al. 1992a). Application of parametric and non-parametric correction factors suggested by Ferguson (1986) and Koch & Smillie (1986) reduced the underestimation. However, the precision obtained by 50 replicate data sets was not satisfactory, indicating that even weekly sampling is too infrequent to estimate the sediment yield.

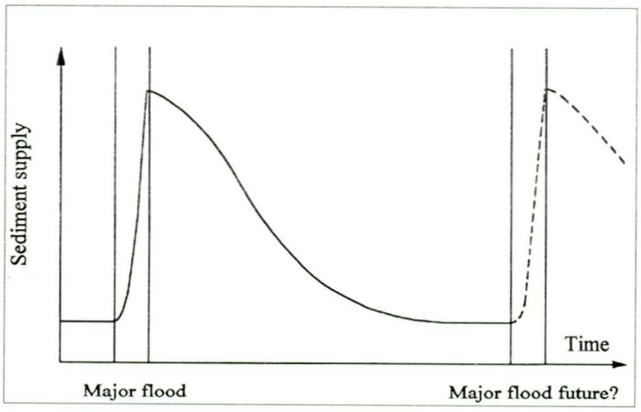

Fig. 6. Model for variations in sediment supply according to the occurrence of large-magnitude floods in supply limited rivers. Large-magnitude floods will open sediment sources which supply sediment for river transport, until they are depleted or closed by re-vegetation or human interference.

In the Knabeåna river, there is a loglinear correlation between suspended sediment concentration and water discharge (Fig. 4). If observations that fall more than two standard deviations from the fitted line are treated as outliers, there are twelve outliers above the regression line. Of these, eight are connected to situations with heavy rain on snow and frozen ground, giving rapidly increased water discharge. It is, however, uncertain whether the rapid discharge-increase itself is responsible for the high sediment transport rate, or if the within-channel deposits are more vulnerable for erosion during the prevailing thawing conditions. Of nine outliers below the regression line eight are connected to falling water discharges. In other supply limited rivers, a reduced transport-discharge relationship on waning stages has been recorded on several occasions (e.g. Walling & Webb 1987, Batalla & Sala 1994, Bogen et al. 1994). This feature is generally attributed to the previous outwash of the available sediment at the rising or peak stage.

Both the daily and the annual sediment transport rates depend on natural factors, such as runoff, frequency of water level fluctuation, temperature, previous exhaustion of sediment supply, form of precipitation, and ground wetness (Bogen et al. 1994). A combination of these factors may cause large variations between the annual yields of tailings in the Knabeåna-Kvina drainage basin. For instance, did the annual sediment yield in the Leira river, Norway, double from 1989 to 1990 due to the occurrence of winter floods at the time when the topsoil was vulnerable for erosion (Bogen et al. 1994). The flood did not have an extraordinary magnitude, but the timing of the event was unusual.

Building of protectional structures along the river banks may prevent entrainment of historical pollution in the suspended sediment load at normal discharges. However, the situation during a large-magnitude flood would be entirely different. During the 200-year flood in the Østerdalen valley, Norway, in June 1995, the protectional structures along riverbanks created strong turbulence on the adjacent floodplains, and the flood carved out large trenches behind the protectional walls (Fig. 5, J. Bogen pers. comm.). Unprotected floodplains were, in fact, less influenced by this large-magnitude flood. The erosional impact on unprotected floodplains seems to be strongly dependent on the hydraulic relationship between the river and the floodplain (Brakenridge 1988, Hickin & Sichingabula 1988, Nanson & Croke 1992). Extreme floods may even strip down complete floodplains in headwater areas (Nanson & Croke 1992, Bourke 1994). In drainage basins with historical pollution, large amounts of contaminated sediment will then be brought to the downstream area and finally into the sea.

Major floods may also play an important role for the long-term sediment supply in rivers as shown by the following examples:

1) In the river Leira, Norway, a 100-year flood in 1987 lowered the erosion base in several tributary gullies (Bogen et al. 1994). Channel-scour undercut adjacent slopes and subsequently several slides were triggered. This greatly increased the sediment supply in the following years. Bogen et al. (1994) predicted that the rate of landslides will persist until the adjacent slopes regain stability. Increased sediment erosion and transport rates were also detected as increased deposition rates on floodplains in the period 1986-1990 compared with 1954-1985 (Walling et al. 1992b).

2) In the Howgill Fells area, UK, large sediment sources were opened by a 100-year flood in 1982 (Harvey 1987). During the flood the meandering Langdale and Bowderdale channels crossed a threshold into the braided regime. Three years after the large flood the sediment supply was still rich enough to maintain an essentially braided pattern, indicating that the sediment supply to the rivers was still governed by the major flood (Harvey 1987).

3) In the Fall river, Colorado, USA, a damburst in 1982 caused a flood with a magnitude 2-30 times the estimated 500-years flood (Pitlick & Thorne 1987). The sediment transport in the two following years was strongly dependent on sediment supply from sediment sources created during the extreme event.

These examples indicate that extreme flood events create sediment sources by channel avulsions, gullying, channel lowering and undercutting of adjacent slopes. Until such sources are depleted or closed by re-vegetation or the construction of protectional structures, they are vulnerable for erosion during future normal floods. Sediment supply (and thus sediment transport in supply limited systems) may therefore be governed by the occurrence of large magnitude floods. The model in Figure 6 is thought to be valid for temperate regions where re-vegetation of erosion scars is rather slow. According to the model, a major flood in the Knabeåna-Kvina drainage basin would not only cause a single episode of high input of tailings to the Fedafjord; it would also cause higher inputs during subsequent normal floods due to the increased availability of tailings for erosion. Thus, the occurrence of major floods may control the speed at which the estimated 420,000 tons of tailings, deposited downstream of the tailings dam, will be brought to the sea.

Practical implications

Results from chemical analyses of the suspended sediment load and sediment transport monitoring in the Knabeåna river show that historical mine tailings are remobilised and brought downstream by natural river processes. Since particle-bound heavy metals constitute a large part of the total metal load in rivers (Förstner & Kerstens 1988, Leenaers 1989), monitoring of the riverine input of heavy metals to coastal areas should include monitoring of sediment yield and composition. Fluvial transport of particulate heavy metals occurs in pulses, and frequent sampling is therefore necessary to estimate the amounts of particle-bound heavy metals brought to the sea each year.

As the industrial effluents and discharge of municipal waste water are being reduced by governmental regulations (Longva et al. 1994), the relative importance of historical heavy metal pollution will increase. The occurrence of large-magnitude floods may govern the availability of historical pollution for fluvial transport. In this way the total riverine input of heavy metals to coastal areas may, in fact, increase as the discharges from present-day human activities decrease. In future international negotiations concerning riverine input of heavy metals to marine areas, risk analysis and abatement strategies directed towards historical pollution should therefore be included.

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References

Batalla, R. J. & Sala, M. 1994: Temporal variability of suspended sediment transport in a Mediterranean sandy gravel-bed river. *In* L.J. Olive, R.J. Loughran & J.A. Kesby (eds.): *Variability in stream erosion and sediment transport.* IAHS Publ. no. 224, 307-315.

Bathurst, J.C. 1897: Differences between gravel and sand bed rivers. Discussion. *In* C.R. Thorne, J.C. Bathurst & R.D. Hay (eds.): Sediment Transport in Gravelbed Rivers. John Wiley & Sons, Chichester, 12-13.

Bogen, J. 1988: A monitoring programme of sediment transport in Norwegian rivers. *In*: *Sediment Budgets (Proceedings of the Porto Alegre Symposium, December 1988).* IAHS Publ. no. 174, 149-159.

Bogen, J. 1992: Monitoring grain size of suspended sediments in rivers. *In* J. Bogen, D.E. Walling & T. Day (eds.): *Erosion and sediment transport monitoring programmes in river basins.* IAHS Publ. no. 210, 183-190.

Bogen, J. Berg, H. & Sandersen, F. 1994: The contribution of gully erosion to the sediment budget of the River Leira. *In*: L.J. Olive, R.J. Loughran & J.A. Kesby (eds.): *Variability in stream erosion and sediment transport.* IAHS Publ. no. 224, 307-315.

Bourke, M.C. 1994: Cyclical construction and destruction of flood dominated flood plains in semiarid Australia. *In* L.J. Olive, R.J. Loughran & J.A. Kesby (eds.): *Variability in stream erosion and sediment transport.* IAHS Publ. no. 224, 113-123.

Bradley, S.B. 1988: Sediment - water interactions: The physical transport of heavy metals in the fluvial systems. *In: Metals and metalloids in the hydrosphere; impact through mining and industry and prevention technology.* Proceedings of an IHP-workshop, Bochum, Germany, UNESCO, Paris, 111 - 134.

Brakenridge, G.R. 1988: River flood regime and floodplain stratigraphy. *In* V.R. Baker, R.C. Kochel & P.C Patton (eds.): *Flood geomorphology.* John Wiley & Sons Chichester, 139-156.

Bølviken, B., Bergstrøm, J., Björklund, A., Konti, M., Lehmuspelto, P., Lindholm, T., Magnusson, J., Ottesen, R.T., Steenfelt, A. & Volden, T. 1986: Geochemical Atlas of Northern Fennoscandia scale

1:4,000,000. Geological Surveys of Finland, Norway and Sweden, 20 pp, 150 maps.

Bølviken, B., Bogen, J., De Vos, W., Ebbing, J., Hindel, R., Ottesen, R.T., Salminen, R., Schermann, O. & Swennen, R. 1993: Final report of the Working Group on Regional Geochemical Mapping 1986-1993. Forum of European Geological surveys (FORGES). *Nor. geol. unders. Report 93.092,* 18 pp, 6 appendices.

Demetriades, A., Locutura, J. & Ottesen, R.T. 1990: Geochemical Mapping of Western Europe towards the year 2000, Pilot project Report. *Nor. geol. unders. Report 90.105,* 9 pp, 10 appendices.

Edén P. & Björklund, A. 1994: Ultra-low density sampling of overbank sediment in Fennoscandia. *J. Geochem. Explor. 51,* 265-289.

Ferguson, R.I. 1986: River loads underestimated by rating curves. *Wat. Resour. Res. 22,* 74-76.

Ferguson, R.I. 1987: Accuracy and precision of methods for estimating river loads. Earth. Surf. Process, 12, 95-104.

Förstner, U. & Kerstens, M. 1988: Sediment-water interactions; chemical mobilization. *In: Metals and metalloids in the hydrosphere; impact through mining and industry and prevention technology.* Proceedings of an IHP-workshop, Bochum, Germany, UNESCO, Paris, 111 - 134.

Harvey A.M. 1987: Sediment supply to upland streams: Influence on channel adjustment. *In:* C.R. Thorne, J.C. Bathurst & R.D. Hey, (eds.): *Sediment Transport in Gravel-bed Rivers.* John Wiley & Sons, Chichester, 121-146.

Hickin, E.J. & Sichingabula, H.M. 1988: The geomorphic impact of the catastrophic October 1984 flood on the planform of Squamish river, southwestern British Colombia. *Can. J. Earth Sci. 24,* 1078-1087.

Holtan, G., Berge, D., Holtan, H. & Hopen, T. 1991: Paris Convention. Annual report on direct and riverine inputs to Norwegian costal waters during the year 1990. Principles, results and discussions. *NIVA-report* 452A/91.

Koch, R.W. & Smillie, G.M. 1986: Comment on 'River loads underestimated by rating curves' by R.I. Ferguson. *Wat. Resour. Res. 22,* 2121-2122.

Langedal, M. 1995: *Spredning av tungmetaller fra Knaben Gruber: Forurens- ningsstatus.* Rep. 30, Inst. for geologi og bergteknikk, Trondheim, 1995, 69pp.

Langedal, M. & Ottesen, R.T. 1995: Particle bound Mo and Cu in the Kvina river basin. *In* R.D. Wilken, U. Förstner & A. Knöchel (eds.): *Heavy metals in the Environment,* International Conference Hamburg, September 1995. Vol 1, 332-335.

Langedal, M., Ottesen, R.T. & Bogen, J. 1996: Time variation in the chemical composition of sediments from tree Norwegian rivers -Natural and anthropogenic causes. *Arch. Hydrobiol. 47,* 29-39.

Leenaers, H. 1989: The transport of heavy metals during flood events in the polluted river Geul (The Netherlands). *Hydrological processes 3,* 325 - 338.

Longva, S., Schei, P.J. & Rensvik, H., 1994: *Naturmiljøet i tall 1994.* Universitetsforlaget, Oslo, 431 pp.

Nanson, C.G. & Croke, J.C. 1992: A genetic classification of floodplains. *Geomorphology 4,* 459-486.

Norušis, M.J. 1990: SPSS/PC+ 4.0 Base Manual for the IBM PC/XT/AT and PS/2. SPSS Inc. Chicago, 511 pp.

Ottesen R.T. & Bølviken, B. 1987: Use of geochemical maps in regional planning. *In:* Wolff, F.C. (ed): Geology for Environmental Planning. *Nor. geol. unders. Special Publication 2,* 46-51.

Ottesen, R.T., Bogen, J., Bølviken, B. & Volden, T. 1989: Overbank sediment: A representative sample medium for regional geochemical mapping. *J. Geochem. Explor. 32,* 257-277.

Pitlick, J.C. & Thorne, C.R. 1987: Sediment supply, movement and storage in an unstable gravel-bed River. *In:* C.R. Thorne, J.C. Bathurst & R.D. Hey (eds.): *Sediment Transport in Gravel-bed Rivers.* John Wiley & Sons, Chichester, 151-178.

RIVM (National Institute of Public Health and Environmental Protection) 1991: Sustainable use of ground water. Problems and threats in the European Communities. *RIVM-report no. 600025001,* November 1991.

Sigmond, E.M.O., Gustavson, M. & Roberts D. 1984: Bedrock map of Norway 1:1million *Nor. geol. unders.*

Walling, D.E. & Webb, B.W. 1987: Suspended load in gravel-bed rivers: UK experience. *In:* C.R. Thorne, J.C. Bathurst & R.D. Hey (eds.): *Sediment Transport in Gravel-bed Rivers,* John Wiley & Sons, Chichester, 691-732.

Walling, D.E., Webb, B.W. & Woodward, J.C. 1992a: Some sampling considerations in the design of effective strategies for monitoring sediment associated transport. *In:* J. Bogen, D.E. Walling & T. Day (eds.): *Erosion and sediment transport monitoring programmes in river basins.* IAHS Publ. no. 210, 279-288.

Walling, D.E., Quine, T.A. & He, Q. 1992b: Investigating contemporary rates of floodplain sediments. *In:* P.A. Carling & G.E. Petts (eds.): *Lowland Floodplain Rivers Geomorphological Perspectives.* John Wiley & Sons, Chichester, 165-184.

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