Erosion and Sediment Transport Monitoring Programmes in River Basins (Proceedings of the Oslo Symposium, August 1992). IAHS Publ. no. 210, 1992.

Monitoring of suspended sediment concentration in discharge from regulated lakes in glacial deposits

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ABSTRACT Following extensive regulation for hydropower, serious erosion along the shores of some lakes was observed. Obvious reasons were bank erosion from waves, ground water flow, and degradation of tributaries. A monitoring programme was established at three typical lakes: Suspended sediments; Time development of bank profiles; Aerial photos of tributary deltas; Regular photo recording of selected spots. The programme was most intensive from 1973 to 1980,but is still being followed up at intervals. Among the findings are: a) Sediment concentrations vary seasonally and with hydrological conditions e.g.waterlevels, wave activity, ice cover, tributary discharges, and surface runoff, but also regularly decrease with time. b) Bank erosion depends on depth, wind/wave direction, natural armouring,and gully formation from groundwater flow. c) Degradation of tributaries is related to drainage area and soil composition. Only a) will be reported.

INTRODUCTION

Several natural lakes in Norway are used as reservoirs for the purpose of hydro power production. Water levels have sometimes been raised by damming, but the most characteristic feature is the utilisation of volume below the natural water level. Some of the reservoirs are located in glacial deposits. The annual regulation has activated reservoir erosion attributed to four mechanisms:

- Slides resulting from loss of slope stability during drawdown.
- Stream degradation at outlets to the reservoir.
- Surface waves acting on new parts of shore profiles.
- Ground water seepage.

Figure 1 shows creek degradation, where an unsuccessful attempt has been made to stop it by pipe installation. Figures 2-3 show wave and groundwater erosion, from the same site in 1974 and 1986.

The shore erosion processes are characterized by very different lapse of time. Particularly the undercutting process caused by continual wave attack at low water levels will delay the development of a new stable situation in these lakes, Fig. 2.

FIG. 1 Creek degradation and unsuccessful. repair attempt, Gjevilvannet.

FIG. 2 Wave and groundwater erosion, Devdisjavri 1974.

FIG. 3 Devdisjavri 1986. Same site as Fig. 2.

A particular impact of regulation is the observed addition to the lake water of a suspended sediment load from the shore erosion processes, varying with the seasons and the hydrology, and gradually decreasing with time.

The suspended load is in itself an unwanted impact to usually very pure water systems. The suspended load represents on the other hand a convenient indicator about the scale of erosion activity from time to time along the lake shore and its tributaries.

A project for investigation of the erosion process caused by regulation was organized from 1973, financed by Konsesjonsavgiftsfondet (The fund of licence fees). In addition to monitoring of actual shoreline erosion at selected spots, the monitoring of suspended sediment load formed an important part of the project.

The main part of the project took place between 1973 and 1980, but irregular control observations are still being carried out as follow-up action.

The project has mainly been reported in Norwegian. Some details have also been referred in international fora as well (Carstens and Solvik, 1975), (Nielsen, 1980).

SITE SELECTION AND CHOISE OF MONITORING PROGRAMME

Important criteria for choise of reservoirs were:
- New regulation, such that as much as possible of the initiation process could be covered.
- Glacial deposits along a major part of the lake shore.
- Seasonal drawdown, well below the natural lake level.
- Accessability, particularly during the snowmelt period.
- Locally available operators for regular sediment sampling.

Figures 4-5 show the three lakes that were chosen, all recently regulated. Some data are given in Table 1.

TABLE 1 Typical data for the lakes.

Lake	Gjevilvannet	Devdisjavri	Målvatna
Map, Fig no	4	5	6
Natural WL	660.0	410.5	424.0
Regulated WL	660.8-645.8	413.5-380.5	430.0-397.0
Length, km	17	3	5
Width, km	1-2	2	1-2
Grainsize mm	0.25-0.40	0.06-0.8	0.04
Damages	Slides 1974, first year of drawdown Creek degradation Beach erosion Slightly red. visibility	Erosion of creek deltas Beach erosion Reduced visibility	Heavy creek degradation Erosion of connecting channel Beach erosion Strongly red. visibility
Measurements	Beach profiles Photos Sediment concentration near outlet Visibility (Secci)	Air photos Photos Sediment concentration in power stat Profiling of creek deltas	Photos Sediment concentration in power stat
Observed	1975-1977	1974-77 + 86	1974-1980
Results, Fig	8	9	10

THE SITES AND THE FIELD OBSERVATIONS

Gjevilvannet

The lake is long and narrow, with numerous tributaries as shown in Fig. 4. Large bank sections consist of fine sand, extremely vulnerable to erosion, while the contents of fine, easily suspendable sediments are moderate.

A narrow strip of the bed along the natural shoreline was covered by a stable armour layer of sorted out gravel. The regulation, 0.8 m up and 14.2 m down, exposed large areas of unprotected bottom below the armour layer to wave action and groundwater erosion, similar to the situation shown in Fig. 2.

Rapid degradation of the tributaries started right after the first drawdown. Some of the major tributaries were then permanently protected against further erosion, while some more amateurish attempts to stop erosion in minor creeks were wasted, Fig. 1. A gradual flattening of the exposed shoreline has occurred, and the minor creeks have now developed a rather stable profile, too.

Regular slides occurred during the first drawdown season at some places marked in Fig. 4.

The field programme comprised bed samplings, profiling of beach cross sections, and visual inspections at irregular intervals. Regular samplings of suspended material, visibility measurements by Secci disk, and temperature recordings were made from boat or from the ice near the outlet by local personnel. Water level recordings were supplied by the power company.

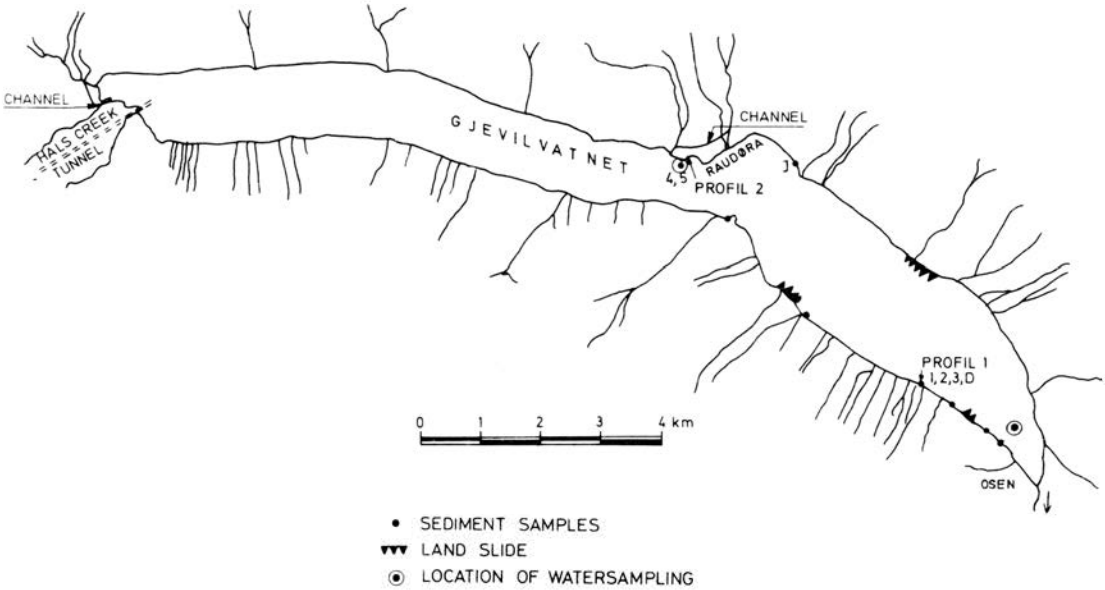

FIG. 4 Lake Gjevilvannet, with interesting spots.

Devdisjavri

The lake has a pear shaped outline, with one major and seven minor creek tributaries, Fig. 5. It is located in a bed of glacial deposits of varying composition. The range 0.06-0.8 mm refer to nine samples along the eastern side of the lake where the deposits are particularly heavy. Also this lake had a naturally stabilized shoreline. Regulation 3 m up and 30 m down resulted in very intensive erosion in all the tributaries. No measures have been applied to stop the erosion.

The field programme comprised bed samplings and irregular visits for observation and photographing, but no shore profile was taken. The most intensive erosion occurred in the creek deltas. This development was studied by use of air photos from 1973 and 1976.

Regular samplings of suspended material were made from the power plant discharge, i.e. the samplings represent the conditions just below the LRWL, 30 m below the natural surface level of the lake.

The results will be discussed in the next chapter.

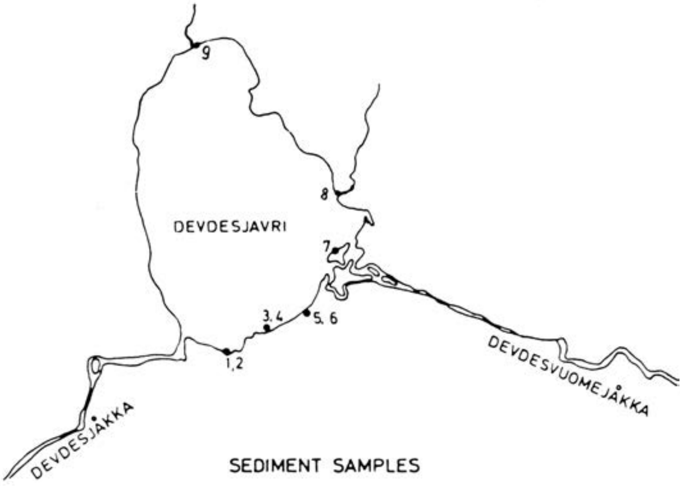

FIG. 5 Lake Devdisjavri, with tributaries.

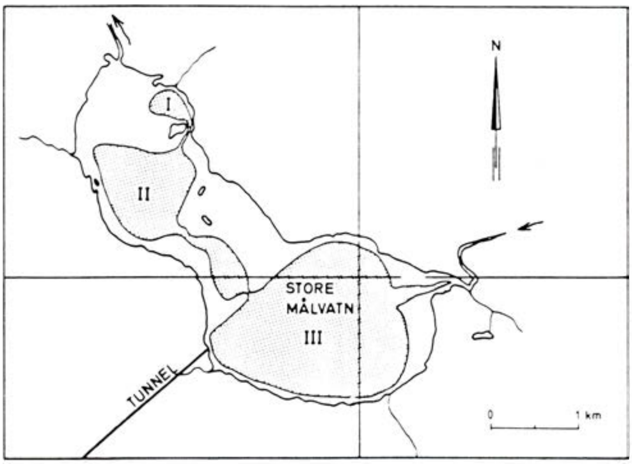

FIG. 6 The lakes Målvatna, with HRWL and LRWL.

<u>Målvatna</u>

The reservoir is formed by damming together three lakes, marked I, II and III on Fig. 6. The surrounding terrain above normal water level is mainly exposed rock, while the lake bed sediments probably are of postglacial origin, consisting mainly of fine silts, mean grain size about 0.04 mm. During drawdown, the original linking creeks between the lakes function as draining channels for the two smaller lakes into lake III. This has caused drastic degradation of the passage between the lakes, Fig. 7. Together with the degradation of tributaries and shoreline erosion from waves and seepage, this has resulted in suspended sediment loads otherwise rarely found in Norwegian watercourses.

No measures have been applied to control the erosion. The field programme comprised bed samplings and irregular visits for inspection and photos. A shoreline profile was surveyed in 1975, but the bench marks were later destroyed by severe erosion.

Regular samplings of suspended sediments were made from the power station discharge. Also some samples from the lake surface have been taken during inspection visits in 1974 and 1975. See Table 2.

FIG. 7 Erosion of the passage between basins I and II of Målvatna.

SUSPENDED SEDIMENT CONCENTRATION

About the data

Results of the sediment samples are displayed in Fig. 8-10, together with the water levels. For Gjevilvannet, temperatures and visibility recordings have been presented as well, Fig. 8. When possible, weekly samples have been made.

The samples in Gjevilvannet were taken from the surface, at four depths, 0, 5, 10, and 20 m below the surface. In fig. 8 the mean concentrations at 0, 5, and 10 m depths and the 20 m depth values are shown.

In most cases the 20 m values are higher than those nearer to the surface, up to double values. Periods where concentrations decrease with depth have also been found, both in 1975 and 1977. This may be the result of nearby wave erosion. Inflow of cold turbid meltwater may also lead to the same result, as this may spread over the surface early in the snowmelt season. In most cases, however, turbid water would rather sink due to its heavy load of particles.

The data from Devdisjavri and Målvatna are the result of samplings in the power station outlets. Since the tunnel intakes are located just below the LRWL, the 20 m depth values in Gjevilvannet should be compared with the other lakes when those are full, while surface values might be used comparing low water values from the two other lakes.

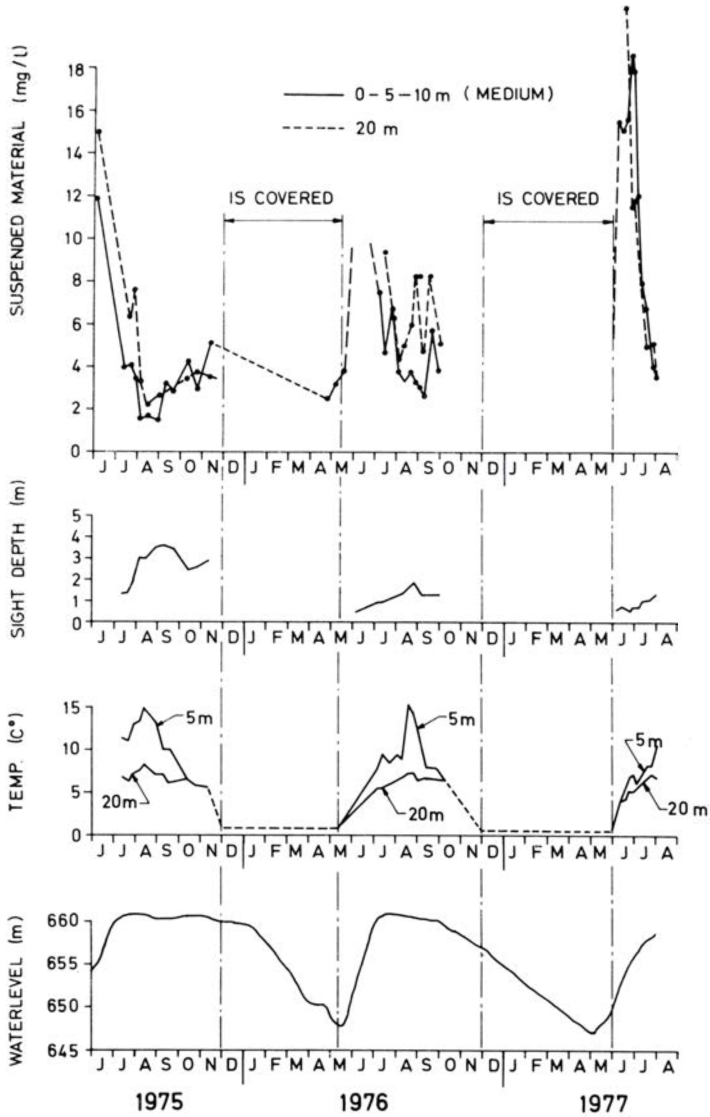

FIG.8 Observations from Gjevilvannet 1975-1977.

<u>Seasonal variations</u>

All data series show a marked increase in concentration around the snowmelt period, and the disappearance of the ice cover in May-June. Both events represent added contribution of sediments: The snowmelt by increased tributary erosion and groundwater seepage. The loss of ice cover by increased wave activity. Both most efficient at low water levels.

As soon as the lake has been nearly filled by meltwater, the supply of sediments decrease, and this is reflected in the sampling data. Occasional concentration peaks occur in the autumn, due to seasonal heavy precipitation, e.g. Devdisjavri 1977 (Fig. 9).

During the ice covered period the concentrations are generally low.

The visibility observed in Gjevilvannet has a regularly opposite trend to the concentration.

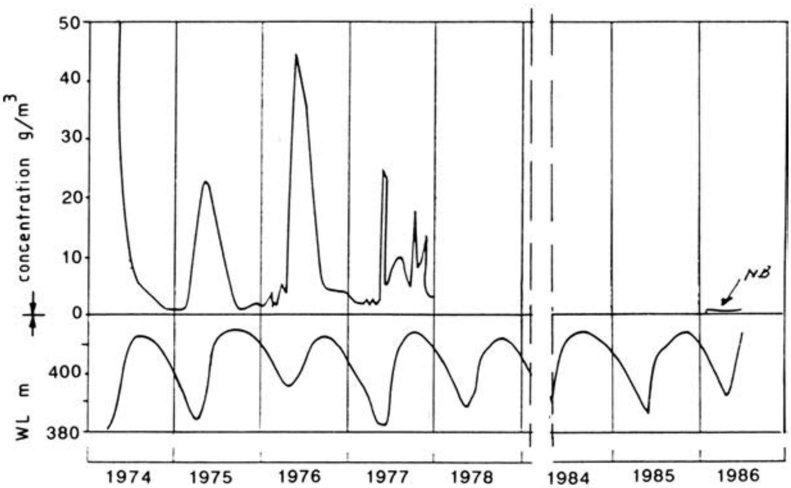

FIG. 9 Recorded sediment concentrations and waterlevels in discharge from Devdisjavri.

Long term trends

The observations in Gjevilvannet lasted only two years due to expenSive and difficult sampling conditions. In the two other lakes four and six years of nearly continous observations exist, enough to show a marked decline of the concentrations with time. In Devdisjavri a short series of samplings in 1987 confirmed that the heavy load caused by regulation is a temporary situation. How long depends on the local conditions. Important factors are:

a) Natural armouring of creeks and shorelines. This requires mixed soils, e.g. moraine. Possible erosion down to base rock will have the same effect.
b) Flattening of the new shoreline, reducing the effect of wave erosion.
c) Man made measures to stop erosion, e.g. as used in Gjevilvannet.

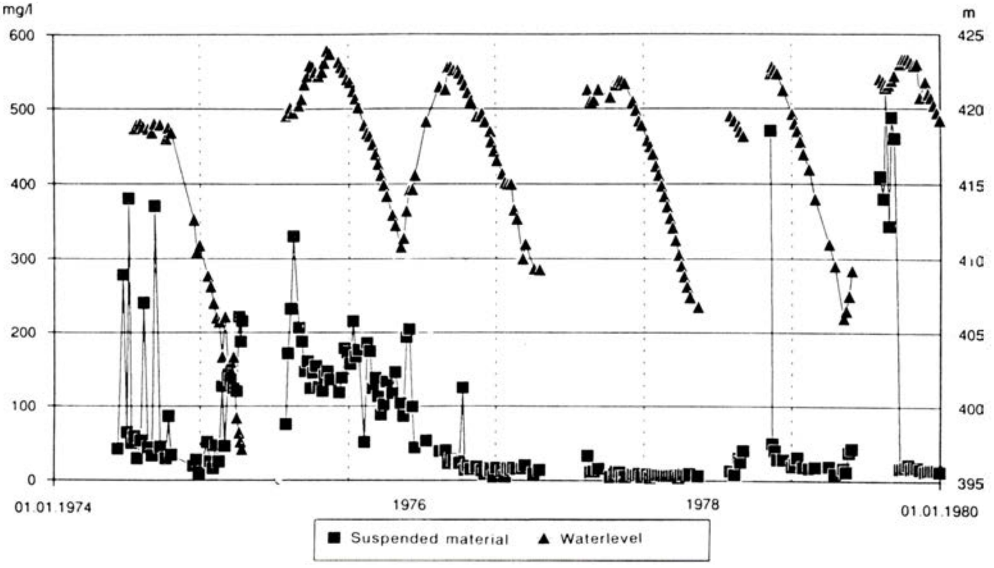

FIG. 10 Recorded sediment concentrations and waterlevels in discharge from Målvatna.

Differences between the lakes

The typical variation of the concentration is 1-15 mg/l in Gjevilvannet, 1-40 mg/l in Devdisjavri, and 5-500 mg/l in Målvatna. This differences are partly reflecting the grain sizes in the shorelines, finer grain sizes give higher concentration. In Målvatna there is in addition the effect of internal degradation of the connecting channel between the lakes, which is probably the main reason for the high values. As this process gradually has been completed, the concentrations in Målvatna become comparable to the other two lakes.

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