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SEDIMENT CONCENTRATION IN LAKES WHERE THE NATURAL SEDIMENT BALANCE HAVE BEEN CHANGED

by

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Abstract

The paper gives time-history data on suspended sediment concentrations in four lakes where the natural hydrology have been changed by regulation or by artificial sediment discharge.

The importance of creek erosion for sediment supply, and the dominating effect of wind on sediment concentration have been discussed by reference to field observations.

1. *Introduction*

Regulation of a natural lake may be a strong interference with nature in many repects. Shore erosion and slides are common consequences, which may damage property and interfere with the natural use of the lake shores.

One side effect of erosion is that additional sediments are being brought into suspension.This may in turn influence on fish production, water quality for consumption and recreation value.

Practical problems may also arise, as added sediment wear of pumps and turbines, or shoaling and contamination of fishing grounds.

Similar sedimentation problems may result from other man-made activities as well, causing added inflow of sediments to a lake. Examples are construction works in the tributaries, direct discharge of particulate waste from mines, and increase of tributary discharge by transfer of water from other water courses.

The River and Harbour Laboratory in Trondheim, a division of the Norwegian Hydrodynamic Laboratories, has collected data on sediments in three regulated lakes since 1972, and also investigated the consequences of mine waste discharge in a fourth lake. This programme is still in progress.

2. *The scope of the investigations*

When dealing with Norwegian watercourses, most sediment concentrations fall within the range 0—100 mg/l. Values higher than 1000 mg/l may be found in glacier rivers and in some rivers traversing marine deposits, but are exceptional in lakes, regulated or not.

We may classify the major concerns according to concentrations in watercourses as follows:

Table 1. Sediment concentration in lakes

Sediment concentration (mg/l)		Major concern	
	10^5 10^3	mainly physical	loss of land, abrasion of hydraulic machinery deposits
	10	biological	reduced fisheries reduced number of species
	10^{-1}	esthetical	reduced visibility reduced recreation value
	10^{-3}	negligible	

The high range cases are mostly of local character, but involve some of the larger rivers in the world. Such cases will always have to be delt with in separate programmes.

The bulk of experience from literature and theory falls within the range 10—10000 mg/l. The possibility of predicting and minimizing losses in this range is therefore rather good.

Very few cases in the range 0.1—10 mg/l could be found in the literature when we started this investigation. It may be said that this is a local problem of mountain watercourses with very little practical importance. However, the visual pollution is a major issue in countries used to watercourses and lakes with clear water. We have observed a drastic visual impact when the concentration of mine waste increases from 0.5 mg/l to 1 mg/l. The visibility has been reduced from 8—10 m to 1—2 m. It is not surprising that such easily observable changes cause concern and reactions among the public.

Only in one of the lakes we have investigated, concentrations above 100 mg/l have been observed. The other three cases lie in the range

0—100 mg/l. The investigation is therefore a contribution, though yet incomplete, to the scarce information available on lakes with low concentration of sediments.

3. *Effect of water level fluctuations*

3.1. *Gjevilvannet*

Gjevilvannet is a 16×2 km large lake in the central part of Norway. The shores are mainly composed of thick glaci-fluvial sediments in the silt-sand range. A protective cover of accumulated rocks formed a stable shoreline in the natural lake. This cover is now deteriorating due to yearly drawdowns for power production since 1974. Extensive shore recessions have resulted from the combined effect of slides, degradation of creeks and streams, wave erosion, and groundwater seepage [4].

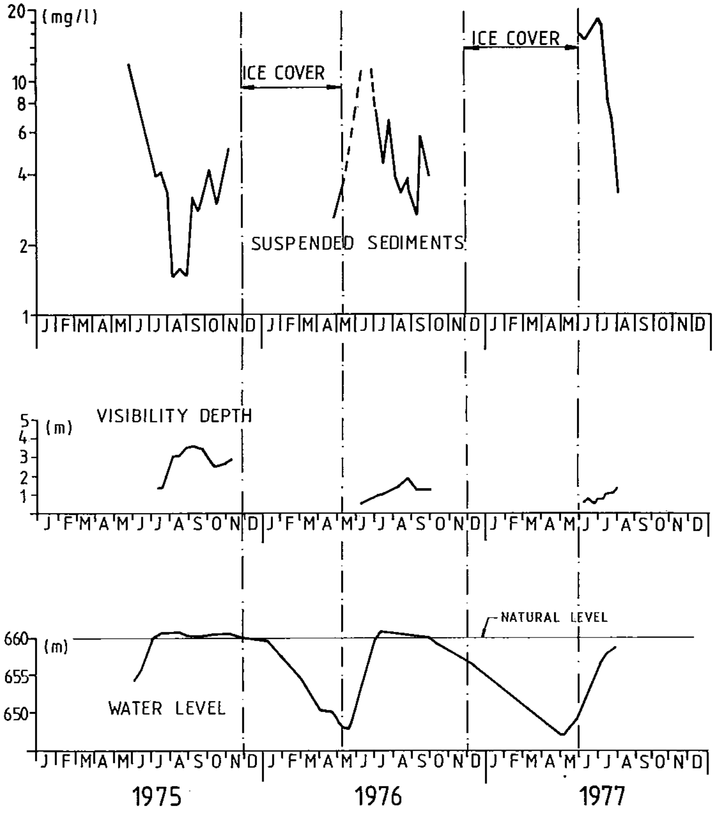

Fig. 1. Sediment concentrations and visibility in Gjevilvann 1975—77.

Before the power plant development, the lake water was very clear, with visibility depth (Secci disc) 10 m or more. The visibility is now varying in the range 0—4 m due to varying amounts of suspended matter.

Figure 1 shows the time-history of visibility and sediment concentration during 1975—77 compared with the water level variations.

When the lake is covered by ice, the shore erosion is slow and the supply of suspended matter correspondingly small. The turbulence in the water is also at a minimum, since no wind energy is being transferred to the water. The sedimentation rate is therefore faster than without ice cover. Figure 1 shows how the suspended load drops to about 2 mg/l under the ice.

The ice cover breaks up in May when the water level is still well below the old shoreline with natural protection. Consequently the erosion by waves and streams increases to a maximum, and the visibility depth decreases to less than 0.5 m.

The suspended load decreases very fast when the lake surface has returned to its natural level. The fast clearing of the lake water indicates that the share of fine silt and clay particles in the suspended load is very small. Grain size analysis of water samples have indeed shown that particles less than 0.006 mm are almost non existent.

3.2. *Devdesjavri*

Devdesjavri is an egg-shaped lake, 3×2 km in dimensions. It has one major and many small tributaries. Since 1972 it has been used as reservoir for power production. Maximum permitted regulation is 3 m up and 33 m down from the natural water level. First drawdown was in 1973 [6]. The shores consist largely of glaci-fluvial deposits, mainly of fine sand on the eastern side, and silt/sand mixtures on the western side. The drawdowns have initiated slides and erosion of similar character as described for Gjevilvann.

Figure 2 shows the time history of the suspended load and waterlevel 1974—1977. The range of sediment concentrations and the pattern of seasonal variations are similar to the Gjevilvann case.

For this lake we made a special investigation of the amount of erosion in the stream deltas related to the catchment areas and the annual flows in the streams [1].

The calculations were mainly based on air photos from 1973 and 1976 and the original maps from before the regulation.

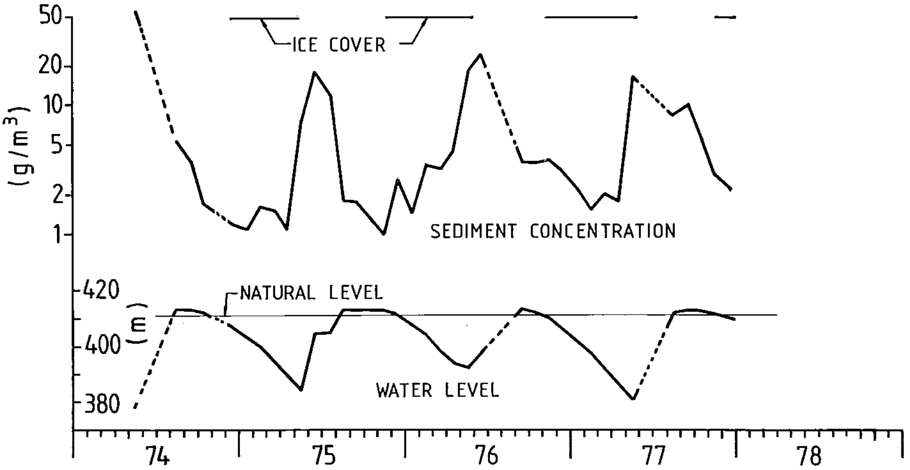

Fig. 2. Sediment concentrations in Devdisjavri 1974—77.

Table 2. Relation between erosion and catchment area.

Stream	Catch-ment area	7 July 1973		11 July 1979	
		Accumulated erosion	E/Ap	Accumulated erosion	E/Ap
	Ap (m²)	*E* (m³)	(m)	*E* (m³)	(m)
3	2.4·10⁶	30.000	1:80	5.000	1:48
4	210·10⁶	2400.000	1:88	3.600.000	1:58
5	20 ·10⁶	250.000	1:80	360.000	1:56
6	6.1·10⁶	70.000	1:87	120.000	1:51

Table 2 shows an apparent close relation between the eroded volume and the catchment area. However, what table 2 actually shows is a proportionality between the run-off and the eroded volume, since we can expect fairly even distribution of the precipitation over the total catchment of the lake.

In 1973 the accumulated run-off between 20 May and 7 July was $148 \cdot 10^6$ m³. Combining this with the total catchment area for the lake, $250 \cdot 10^6$ m², and dividing it evenly on the local catchments, we obtain ratios close to 1:50 between eroded volume and local run-off during the first season. In other words, the average sediment concentration during the first filling of the reservoir has been 2 per cent by volume *i.e.* 53 g/l for all the creeks in table 2.

The concentration decreased fast during the following years, but remained nearly the same in all creeks.

According to YANG [7] the sediment concentration (c) is given as a function of the unit stream power (VI) by

$$C = A\,(VI)^B \tag{1}$$

where

V = mean velocity, I = energy slope,

A and B = coefficients decreasing with increasing water depth (A also with increasing particle size).

It is seen that if depth and sediment conditions are nearly the same, as may be assumed here, constant concentrations will result if the unit stream power is constant.

By introducing approximate data, VI has indeed been found to lie within the range 0.0008 to 0.001 for average discharges during the first filling period.

Also Blench' regime formula implies that the unit stream pover shall be equal for creeks with equal particle size, independent on discharge.

$$VI = \frac{Q}{B \cdot D} \cdot I \sim \frac{Q \cdot Q^{-1/6}}{Q^{1/2} \cdot Q^{1/3}} = 1 \tag{2}$$

The findings are therefore in agreement with Yang's theory as well as Blench' formulas.

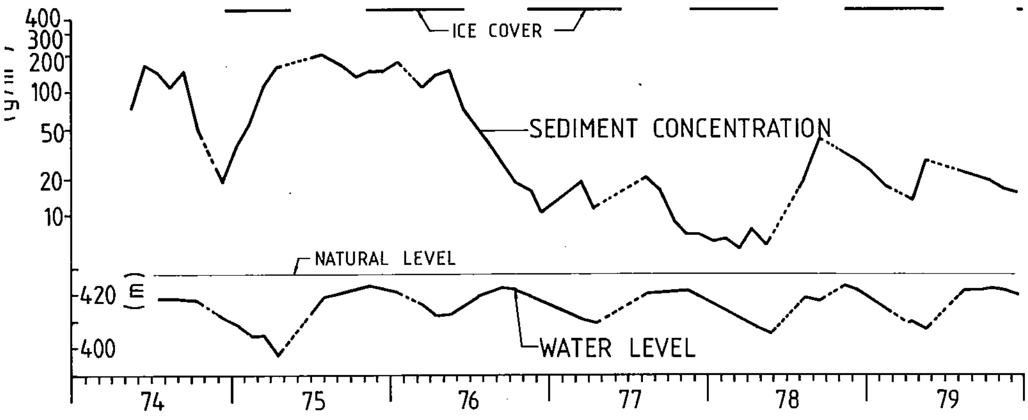

Fig 3. Sediment concentrations in Målvatn 1974—79.

3.3. *Målvatn*

Målvatn is 5 km long and 2 km wide when full. The permitted regulation is 6 m up and 33 m down from elevation 424. Near lowest level the lake becomes divided into four small basins joined by creeks or narrow channels, where erosion is still very active. Otherwise the bank conditions are rather similar to the other lakes described above. First drawdown was in spring 1972 [5].

Figure 3 shows the time history of sediment concentrations and corresponding waterlevels.

The curve differs from Figure 2 at least in three respects:

1) The curve is less regular. The correspondence between ice cover periods and low concentrations is poor.
2) The peak concentrations are higher.
3) The peak concentrations are decreasing with time.

All three effects can be explained by extra erosion at low waterlevels in the connecting channels between the four basins:

a) The erosion is not prevented by ice cover formation.
b) It adds directly to the peak sediment concentration otherwise produced by wind action.
c) It must be expected to decrease as the connecting channels widen and stabilize.

The lake is therefore an example that shows how local factors may overthrow otherwise general experience.

4. *Consequences of mine waste discharge*

4.1. *Site conditions at Huddingvann*

Huddingvann is actually two lakes separated by three shallow sounds (1—2 m deep), Figure 4. The natural flow is from east to west. The eastern lake is about 2.8 km^2 in area.

Slurry from a dressing plant for sulphurous pyrite has been discharged into the eastern part of the lake since 1972. The present discharge rate amounts to about 60 tons of dry particles per hour (roughly 30000 tons per year). 90 per cent of the particles are finer than 0.044 mm and 50 per cent finer than 0.018 mm.

The lake and its adjoining river system are known for valuable trout fishing. The permit to discharge slurry has therefore been given under the condition that the fish life should be disturbed as little as possible. In

Fig. 4. Huddingvann.

particular, passage of slurry to the western part of the lake should be avoided.

The eastern lake is only 21 m deep. The deposition is planned to fill up the lake to 10 m below the surface. To obtain this, the discharge pipe has to be moved at intervals.

The pipe arrangement shall fulfill two partly contradictory aims:

a) The concentration of suspended matter in the upper layer shall be kept as low as possible.
b) The horizontal spread of slurry along the bottom shall be as wide as possible to minimize the moving frequency.

Initially, a submerged 177 mm diameter pipe with horizontal outlet was used. A deairing tower was located on the shoreline. This system is still intact for use as reserve.

The present arrangement has a combined vertical drop shaft and deairing tower mounted on a float. A floating hose carries the slurry to the drop shaft. This system is easier to move. The vertical shaft results in less suspended matter in the top layer.

4.2. *Suspended sediment observations*

The slurry deposits mainly as a cone under the pipe outlet, but a thin layer of diluted slurry also spreads along the lake bottom [6]. Table 3 shows how this layer rapidly deteriorates with distance from the outlet.

Table 3. Suspended solids near the bed.

Sampling point	Distance from bed m	Suspended solids mg/l Total	Ignited
5 m from outlet	1.0	45—105	40—90
30 m from outlet	0.50	14	10
Deepest point	1.0	6	2

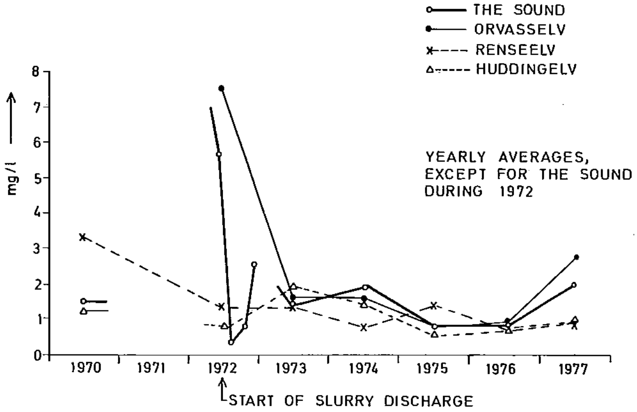

Fig. 5. Sediment concentrations in Huddingvann 1970—77.

Figure 5 compares the average vertical concentration of suspended particles in the sound between the two parts of Huddingvann with data from adjoining rivers. Renselelv and Orvasselv are tributaries to the lake, and are not contaminated by the plant during normal operation. Huddingelv flows out of western Huddingvann. See Figure 4, where the sampling points are marked.

The concentrations in the sound and in Huddingelv differ little from the natural concentrations in the tributaries during 1973—75. Some irregulatities occurred in 1972 both before and after the slurry discharge was started. Construction works may have contaminated Orvasselv early in 1972.

The rise in consentration in the sound to about 3 mg/l late in 1972 is probably the result of an accidental spill, when slurry was poured directly into the lake from some time.

The drop in concentration at the sound from 1974 to 1975 is probably the result of switching from the horizontal pipe system to the floating drop shaft. The 1976 data seem to confirm this trend. The rise again in concentration at the sound in 1977 may be related to some extraordinary contamination of Orvasselv, but we have not been able to check this in detail.

5. *Energy and suspension with Huddingvann as example*

Supply of energy in necessary to bring particles in suspension as well as to maintain a stable suspension against gravity.

The main energy sources are wind drag, heat exchanges and inflow/outflow of water to the lake.

The alternating supply and drainage of heat energy through the water surface will most of the year tend to stabilize the stratification and actually reduce the suspension activity. During spring and fall, however, when the surface temperature passes 4°C, exchange of bottom and surface water occurs, with the result that some heat energy is spent on suspension work. It is very difficult to analyse the effect of this process both in theory and from field data, because other significant changes also occur in the lake in these periods.

The importance of wind has been qualitatively demonstrated in Figures 2—3 by the regular drops in sediment concentration during periods with ice cover on the lakes. Only a small fraction of the wind energy transferred to the lake is available for suspension work, however. The rest is spent to overcome friction, to produce waves breaking along the shores etc. Also energy input from currents is mostly dissipated by internal friction.

In a stable suspension the necessary power supply is given by:

$$P_s = A \cdot H \cdot c \cdot g \cdot \frac{s-1}{s} \cdot w \qquad (3)$$

where

w = fall velocity of particles

c = concentration (mass)

H = mean water depth

A = area of water body

s = specific gravity of particles in relation to water

Taking Huddingvann as example ($A = 3.1 \cdot 10^6$ m², $H = 10$ m) the following table is obtained for illustration.

c (mg/l)	d (mm)	P_s (Nm/s)
1	0.01	30
	0.03	270
	0.05	740
10	0.01	300
	0.03	2700

Table 4.
Suspension power in Huddingvann for various concentrations and particle sizes (d)

It is interresting to compare these data with the theoretical input from currents and wind to the lake, by means of a simplified calculation:
a) *Kinetic energy from inflow* is expressed by

$$P = v^2 \cdot \gamma \cdot Q/2g \qquad (4)$$

where
v = velocity
γ = volume weight
Q = discharge
g = acceleration of gravity

For the horizontal pipe outlet, known values are $v = 2.5$ m/s, $\gamma_j = 1200 \cdot 9.81$ N/m^3, $Q = 0.055$ m^3/s, giving $P_0 = 190$ Nm/s

For the main river, Renselelv, if max flood values are inserted ($v_r = 0.2$ m/s, $\gamma_r = 9810$ N/m^3, $Q_r = 30$ m^3/s) we obtain $P_r = 600$ Nm/s

b) *Potential energy contribution* from settling of the slurry discharge is given by

$$P_p = (\gamma_j - \gamma_w)\, h\, Q \qquad (5)$$

where h = vertical distance from outlet to bed. For instance $h = 5$ m gives

$P_p = 200 \cdot 9.81 \cdot 5 \cdot 0.055 = 540$ Nm/s

c) *Energy from wind*

The wind power may be expressed by

$P_w = \tau A \, v_0$

τ = shear stress due to wind at the water surface
A = surface area exposed by the wind
v_0 = water velocity at the surface
V = wind velocity (10 m height values)

We use the approximations
$v_0 = 0.03 \, V$ (persistent wind) and $\tau = \tau_r \, (V/V_r)^2$
giving
$P_w = 0.03 \, A \tau_r V^3 / V_r^2$

We insert the reference values $\tau_r = 0.04 \text{ N/m}^2$ for $V_r = 4$ m/s, obtaining for Huddingvann ($A = 3.1 \cdot 10^6 \text{ m}^2$):

V (m/s)	1	2	4	10
P_w (Nm/s)	230	1840	14900	230000

Table 5.
Wind power input to Huddingvann.

The overwhelming importance of strong winds of the suspension is demonstrated by these figures. It is also seen that the slurry effluent represents about the same power input to Huddingvann as Renselelv gives during floods.

Table 6 gives theoretical sediment concentrations for the hypothetical case that all available power is spent in suspension work.

It is seen that the effluent alone has power enough for many times the observed concentrations in case of very fine particles. The wind conditions are not known in detail, but winds exceeding 4 m/s are frequent. The calculated concentrations for winds around 4 m/s are one or more orders of magnitude higher than observed. The conclusion is that much less than ten per cent of the power input is being used for suspension work in Huddingvann. Literature sources [2] and own laboratory investigations have given various results in the same low range. With such a marginal amount of the total energy input used for suspending fine sediments, local variations in geometry, stratification and hydrology may indeed be expected to cause large variations in the sediment concentration from lake to lake. It seems therefore a long way to go before the motion of fine sediments in a lake can be fully understood and predicted.

Table 6. Theoretical concentrations in Huddingvann assuming 100 per cent efficiency on power input from effluent jet or wind.

Case		Power Nm/s	Stable concentrations mg/l		
			d = 0.05 mm	0.03 mm	0.01mm
Jet	h = 0 m	190		0.5	6
only	h = 5 m	730	1	2.5	22
	1 m/s	230		1	8
Wind	2 m/s	1840	3	7	60
only	4 m/s	14900	20	60	500
	10 m/s	230000	300	850	7500

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