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The Influence of Man's Activities in Rivers on Sediment Transport

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An attempt to use old semicompiled data on turbidity, transport and deposition of suspended material is carried out. The influence of different activities is illustrated. The change of water chemistry during storage in new reservoirs, the influence of short periodic water release and the dam construction itself as a trap to the sediment transport are exemplified. The use of the Sundborg formula as an aid to predict the increased concentration of suspended material during dredgings is shown.

Introduction

Water regulations, dredgings or other artificial controls of rivers often change water quality in physical terms as well as chemical. A redistribution of contaminated sediments and a soaking out of nutrient salt are the dominant chemical consequences (Arnborg 1973, Axelsson 1974).

Three kinds of physical consequences are the subject of much interest; optical conditions of the water, duration of different suspended sediment concentrations, and the sedimentation.

Raw water plants at pulp mills, communities etc are interested in the duration of sediment concentrations higher than their optimal tolerance level, and also of course the total raised concentration at their raw water intake. Fisheries are also interested in the optical conditions of the water and the silting of spawning areas.

Basic data on turbidity, concentrations, transport and sedimentation of suspended sediment are needed in order to make a reasonable prediction of the influence of man's activities in the river during the building operations and then afterwards.

Turbidity

The most common data obtained in connection with artificial controls on Swedish rivers is turbidity. It is usually measured as the scattering of white light in ninety degrees and expressed as Z-units. During the fifties and early sixties, turbidity was measured as the scattered green light in fortyfive degrees and given in ZP-units (Karström 1970).

Turbidity is a function of the total exposed area of suspended materials although water colour may also have an influence. Consequently, a greater amount of coarse material is needed than the amount of fine material to obtain the same turbidity. Disregarding the influence of suspended organic material, the quotient Z/c, where c is concentration of suspended inorganic material, should increase with distance from the working area due to the settling of coarser material.

Consequently, turbidity is inadequate as a measure of the concentration of suspended sediment unless the sediment is very fine and well sorted.

Sediment Transport

The transport of suspended inorganic sediment by a river is largely dependent on three different factors in addition to grain size of the soils: interfluvial erosion, fluvial erosion and artificial controls.

Interfluvial erosion is dependent on climatologic factors and land use. It shows a periodic activity and is positively correlated to mainly precipitation and run off.

Fluvial erosion is dependent on water discharge, flow velocity and the grain sizes of the bed and banks. Before any working operations are started on a river it is clearly very important to know the normal annual sediment transport cycle.

Measurements of sediment transport have been used not only to document the transport per se, but also to highlight reaches of erosion or deposition by using the transport difference between two or more stations.

The best way to analyse sediment transport data is probably to construct sediment discharge curves. Commonly they are constructed by linear least-squares regression of the logarithm of the sediment discharge T on the logarithm of the water discharge Q.

The formula is:

$$\log T = a + b \log Q \tag{1}$$

Also the concentration c may be solved by using the same kind of equation. As

$$T = Q \cdot c \tag{2}$$

and substituting T in (1) we can write

$$\log C = a + (b-1) \log Q \tag{3}$$

Since water discharge is better documented than sediment concentration, Eq. (3) may be used in construction of a duration curve of concentration.

The regression coefficient is almost always positive. If $0<b<1$ the *concentration* will decrease when the water discharge increases, but the *transport* will always increase with a higher water discharge.

If $b \equiv 1$ the concentration is constant and equal to *a*, which means that all additional water has that concentration. If $b>1$, both *concentration* and transport will increase as water discharge increases (Nilsson 1971).

The value of *b* of the equations established for Swedish alluvial rivers is about two or more. The statistics often show very good relationships. Varying release of water from power plants or reservoirs will, however, tend to spoil such relationships and very bad statistics are often obtained in those cases. The regression coefficient *b* is often less than one and this could even be a negative correlation (Sundborg and Norrman 1963, Nilsson 1972). This implies that the sediment producing factors (interfluvial and fluvial erosion) are not in phase or that the erosional activity has changed in relation to water discharge.

When constructing a sediment discharge curve it is often nescessary to separate the data according to rising or falling stage of the water discharge. On rising stage the water velocity is higher than that on the corresponding water discharge at constant or falling stage. Short period regulations will increase the water discharge with several hundred per cent during a very short time every week and sometimes every morning. Due to the storage of water within the river channel the water discharge will increase faster than the stage, which means that velocity increases at least at the beginning of every water release (Wundt 1953). As a consequence the bed load may start at lower water discharge than before the regulations.

A regulation of water discharge will cut off flood peaks and cause a higher discharge during winters. The increased discharge during winters, when water temperature is low (higher viscosity) could be a factor of importance to the transport. It is however difficult to distinguish ice processes, pushing or damming, from the increased capacity of the river.

Sedimentation

Silting in reservoirs is a very severe problem in most areas of the world. In Sweden, however, it is a problem of only marginal importance.

In order to calculate how much and how far a river stretch will be influenced by dredging, it is necessary to estimate the transport and the sedimentation of the material suspended in an artificial way.

By the selective sedimentation of suspended inorganic particles of different size it is possible to compute the distance a given particle size will be transported before it settles. Sundborg (1956, 1958, 1964) has proposed the following formula for computing the rate of deposition as a function of flowing time, t. The formula is here given slightly modified.

$$\frac{c_L}{c_0} = e^{\frac{-v\cdot f(c)\cdot B\cdot L}{Q}}$$

c = concentration at distance 0 (100% at time 0) and after flowing the distance L (x% at time t) of a particle φ,
v ≡ settling velocity of particle φ,
$f(c)$ ≡ a function depending on the vertical distribution of particle φ. in the river,

B = the mean channel width,
L = river length at flowing time t,
Q = water discharge,
e ≡ base of the naperian logarithm.

Provided that each particle fraction suspended by the dredgings is known, it is possible by this formula to estimate the deposition on different sections of the river, disregarding the normal transport.

In using the formula many assumptions have to be made, but by carefully treating those assumptions, use of the formula has been proved to be valid and valuable.

The fall velocity of one given particle and the function (c) are dependent on water temperature. Calculations must therefore be carried out for different temperatures.

Water regulations influence the stage of saline water at the river mouth and thus change the entire depositional environment, also detrimental to navigation.

Case Studies

The above mentioned facts are more or less what you may expect when analysing old discontinuous data series. Great attention must also be paid to the fact that the data presented below were obtained by different authorities using different methods. The purposes of the investigations were also different. The case studies are therefore not directly comparable, but will perhaps give an idea of the different degrees of damage. Fig. 1 shows the locations of the different case studies.

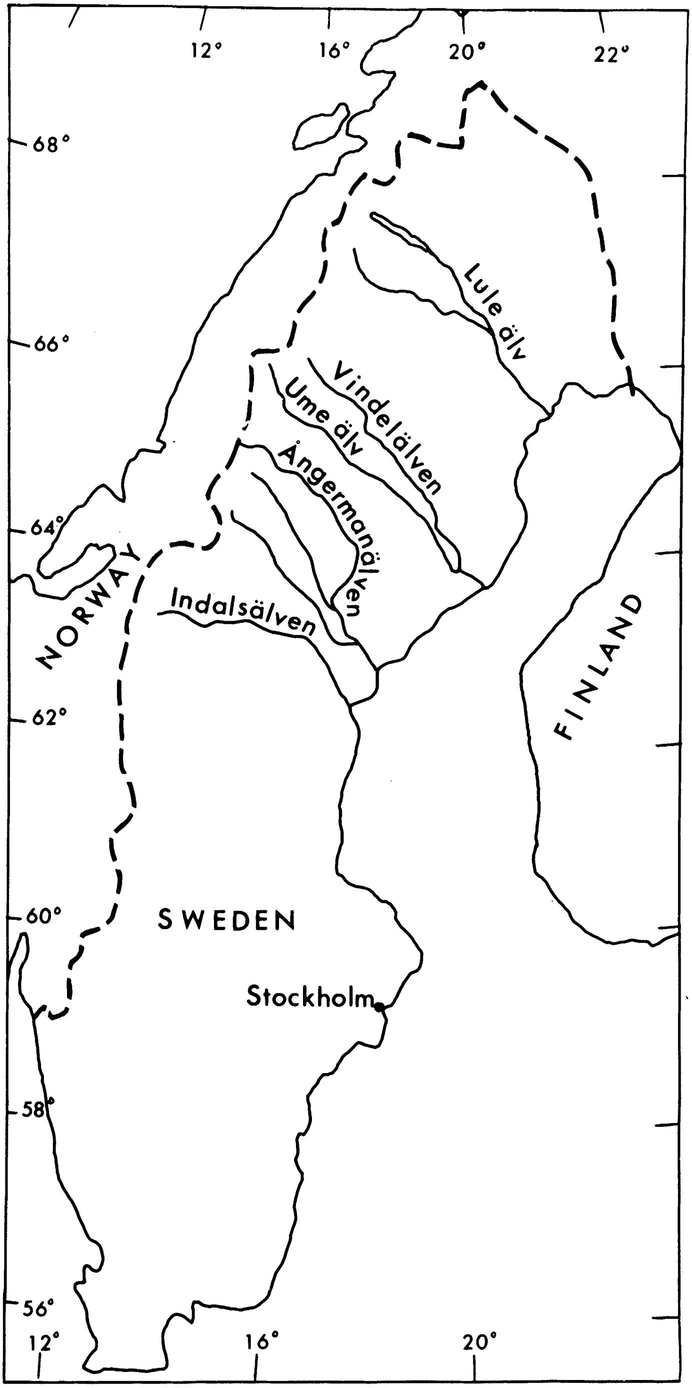

Fig. 1. Location of the different case study rivers.

The River Lule Älv

During the last twenty years there has been an intense period of building operations for regulations and power plants in the river Lule Älv. Investigations on the turbidity and on the sediment concentration were initiated in 1958. Nowadays the main point of the investigation has moved to the chemical aspects.

Four power plants, one of them located at a tributary and together using a head of about 285 m, were built during 1958-63 and huge volumes of mostly sandy to silty valley deposits were moved. The dredgings and building operations were concentrated to a river stretch 100-160 km from the river mouth. The river then falls to the Gulf of Bothnia after 100 km of smooth flowing except for 10 km long rapids about 30 km from the sea. Water samples have been collected at six sites within the controlled area and seven sites downstream from it.

Using the old data on turbidity and concentration the influence of man's activities were easily traced at the stations within the working area (Figs. 2, 3,), but hardly downstream from that area. The relation between mean turbidity (*Zp*) and mean concentration (*c*) however showed an increase with flowing time from the working area. At the mouth of the river one ppm of suspended material gave double the turbidity as one ppm 5 km downstream of the working area (Fig. 3).

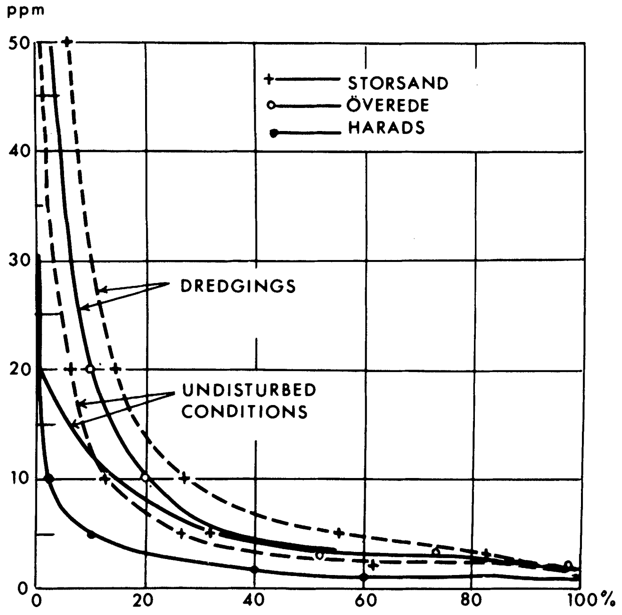

Fig. 2. Duration of suspended sediment concentration at different sites and periods. The location of the sites is given in Fig 3.

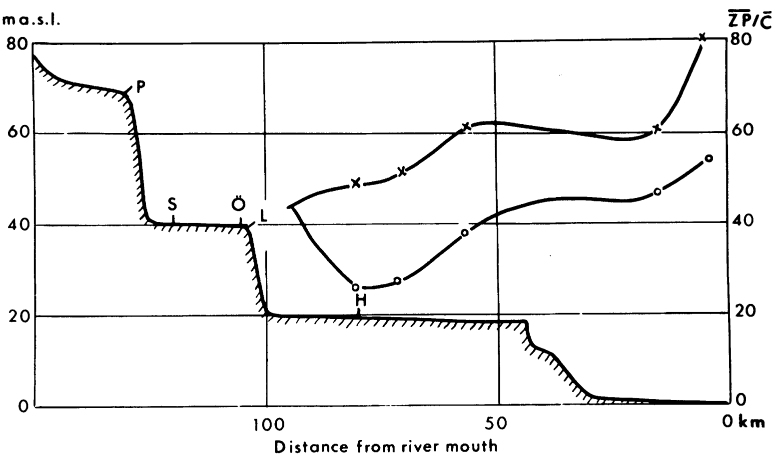

Fig. 3. Longitudinal profile of the lower part of the river Lule Älv and the ratio $\overline{Zp}/\overline{c}$ at different control stations downstream from the working area. Circles show the ratio during the working period, crosses during undisturbed conditions. Letters refer to: *S* Storbacken, *Ö* Överedet and *H* to Harads. *L* and *P* show the sites of power plant constructions.

The River Ume Älv

-The river Ume Älv consists of two big branches, the main branch Ume Älv and the undisturbed river Vindelälven. The main river Ume Älv is now completely controlled. The storage capacity is about 25% of the annual runoff. The soils in the upper part of the drainage area consist mostly of till but there are some glacifluvial deposits also. During working operations in this part of the river water samples were collected from fifteen stations. The concentration of suspended sediment was quite normal (2-8 ppm), but as there are no data from the period before the start of the operations it is hard to estimate the effect of the workings.

The turbidity was raised by more than 100 per cent at times. The downstream distance of water affected was rather short, however, and after a flowing through a lake, the water was relatively clear again (SMHI 1968, Rehn 1976).

The lower part of the river flows through old valley deposits containing sand and finer grain sizes. Due to the postglacial land uplift, glacial and postglacial silts and clays are also exposed to fluvial erosion.

Fifteen to thirty km from the river mouth the river falls about 70 m, a head which is now exploited in a power plant. About 900 000 m^3 of sediment were dredged during a period of two years when the power plant was built. Among other things a new channel 2 km long was cut. The influence of these constructions on the sediment concentration is shown in Fig. 4. The concentration was raised during fifty per cent of time when the dredgings were going on (Arnborg 1965). The transport amount was doubled and about 215 000 tons of suspended inorganic sediment were transported to the Baltic during 1959.

Inadequate data for the period before construction make it hard to estimate its influence on sediment transport. A rough estimate however gives a yield of 50.000-65.000 tons a year during 1958-60 as a consequence of the dredgings. The river apparently adjusted rather rapidly to the new conditions. In 1961 the transport had decreased by about 30.000 tons to 130.000 tons and during the hydrological year 1963-64 the transport was only about 12.000 tons, a decrease of about 90% since the dam construction (Arnborg 1965). Hörnberg (1974) estimated the transport decrease to about 50-60% during the period 1962-70.

The mean grain size, measured by celloscope, of the suspended sediment during 1963-64 ranged between 14-5 microns.

Arnborg (1972) estimated the bed load to the river mouth by using the Kalinske bed load formula (1947). Before the constructions the bed load amounted to 2,600 metric tons a year and after the dam had been built decreased to a ten year mean

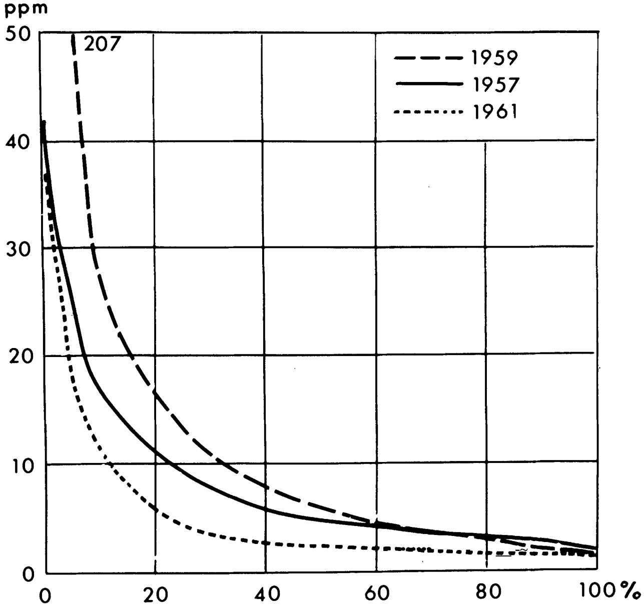

Fig. 4. Duration of suspended sediment concentration 10 km from the working area. The constructions started in 1958 and was finished in 1960. (From Arnborg, 1965).

value of 1,400 tons. Bearing in mind that the dam traps the material transported from the upper part of the river and that the flood peaks are now reduced, the decrease of the bed load seems to be too low.

On the other hand, due to the short period regulations, high flow velocities may be more frequent now and thus initiate the transport at lower water discharges. If this is true and the estimated transport of 1,400 tons a year is correct, and no bed load material passes through the dam, it means that about 1,400 tons of bed material per km of the river stretch below the dam has been eroded from 1961 and onwards. If it can be assumed that the vertical erosion keeps step with the land uplift, a quantity of about 55,000 metric tons will be eroded annually from the river bed between the outlet of the power plant and the sea. However, in the bed, generally sandy, cohesive fine silt and clay are exposed at some stretches and the process can thus be assumed to be rather unevenly distributed over the whole stretch (cf Sundborg and Norrman 1963).

The concentration of dissolved solids, ranging around 20-40 ppm, showed a slight increase of 1 ppm a year from 1958-1961. The proportion of disolved organic matters, however, increased rather abruptly in the beginning of 1959 at the same time as the second turbine was started, and continued to increase gradually from about 40 per cent in 1958 to 65 per cent in 1961 of the total dissolved amount. It is hard to explain the decrease of dissolved inorganic matters, as an increase could be expected due to the raised pollution of water and air borne salts as well. One feasible explanation is that during the silting in the reservoir the salts aid flocculation due to the electrical charges. The increase in total content of dissolved matters is partly a consequence of soaking out from the soils of the inundated forests and bogs, besides the normal pollution. Also a greater proportion of water from the uncontrolled river Vindelälven during a filling up of a new reservoir in the upper part of the main river could play a certain role occasionally, but not for as long as 2-3 years as in this case (cf Arnborg, Eriksson, Peippo 1971).

The River Ångermanälven

Into the river Ångermanälven two big tributaries fall at the lower part of the main river (Fig. 5). Power plants along the whole river and reservoirs especially the upper part have been built since the forties and the constructions are not yet finished. The storage capacity is 40% of the annual runoff.

During the building operations water samples have been collected in the lower part of the river since 1950. The IHD-initiated programme for sediment transport measurements, started in 1967, has a sampling station at the same place as the other investigation programme.

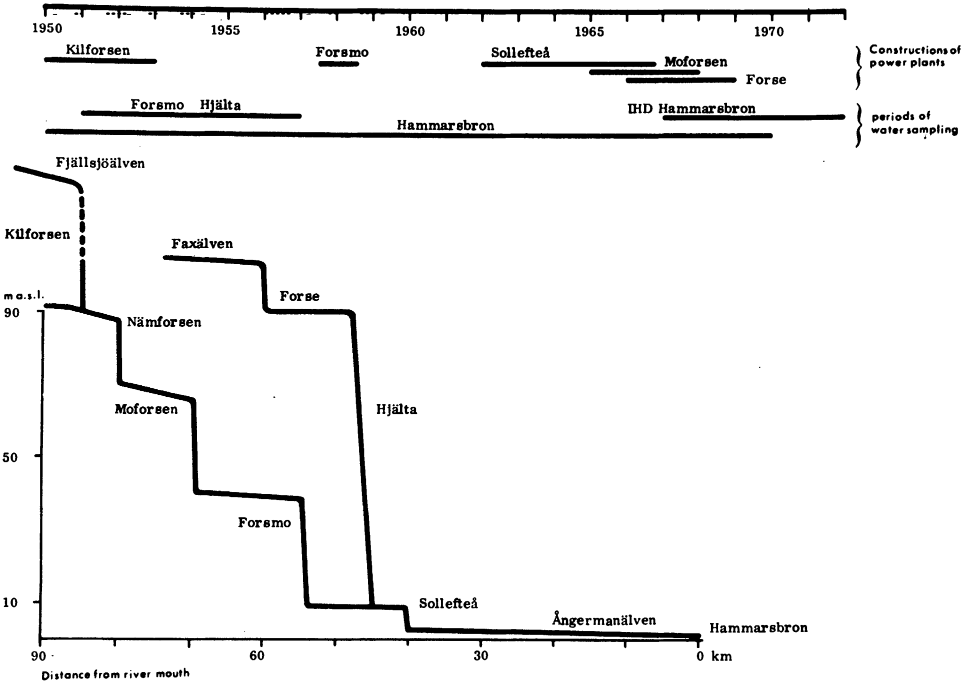

Fig. 5. Longitudinal profiles and work-table over the lower part of the river Ångermanälven and its tributaries. (After Nilsson 1974).

The two investigations are using different techniques of water sampling and during the fifties also the analyzing technique was different (Arnborg 1958, Nilsson 1971, 1974). The IHD data are obtained by depth integrated samples and show 25 per cent higher concentration than the other investigation during days when the samples were almost simultaneously collected. The old technique, one instantaneous sample 0.5 m below the surface, has been used in the river Lule Älv and the river Ume Älv as well.

By means of the twentyone year series of data the influence of the constructions at Sollefteå during 1962-66 on the sediment transport has been evaluated (Nilsson 1974).

Sediment discharge curves were established on a three year basis, and the sediment transport amount evaluated. The annual transport was then correlated to the annual mean water discharge, a technique which however may have shortcomings from a statistical point of view. As is shown in Fig. 6 the relationship is good during the period 1950-61, data to which the curve is fitted, and an equation established. Crosses indicate the annual transport during the period of construction and circles the transport afterwards.

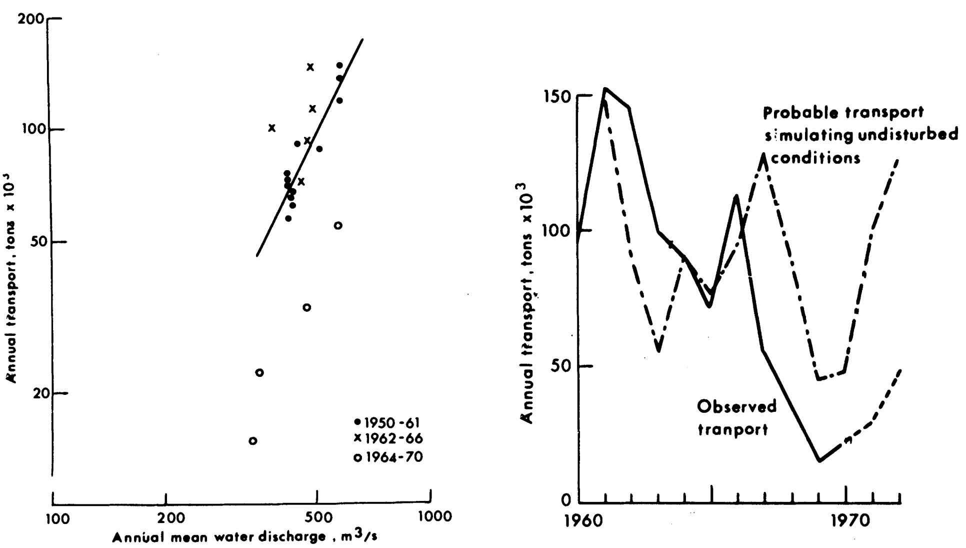

Fig. 6. Regression analysis on the annual mean water discharge and the annual transport (to the left). The curve is fitted to data from 1950-61. Power plant and dam constructions were going on during 1962-66.

Measured and probable transport during the 1960's (to the right). Dotted part of measured transport is compiled from IHD-data. The probable transport is calculated by means of the relation to the left. (After Nilsson 1974).

By using the relation obtained from data covering the period of relative undisturbance the probable transport was estimated during 1962-1972 (Fig. 6) simulating undisturbed conditions. The last two years could be estimated also by means of comparisons with the IHD data.

During the period of disturbance or more unstable conditions, 1962-66 there was a mean transport increase of 24,000 metric tons a year. Taking into account the contribution of sediment from Forsmo and Hjälta (Fig. 5) the suspended sediment yield had increased from six hundred to eight hundred tons per km for the river stretch from Sollefteå to the river mouth af Hammarsbron, if most of the material transported to the reservoir at Sollefteå was deposited there. As there were no available data on the grain size of the suspended sediment, the silting in the reservoir could only be briefly discussed.

By the use of Eq. (5) the calculated amount of sediment remaining in suspension at the spillway of the Sollefteå power was shown for different fall diameters (Fig. 7). The calculations were made for a given water temperature of ten degrees centigrade.

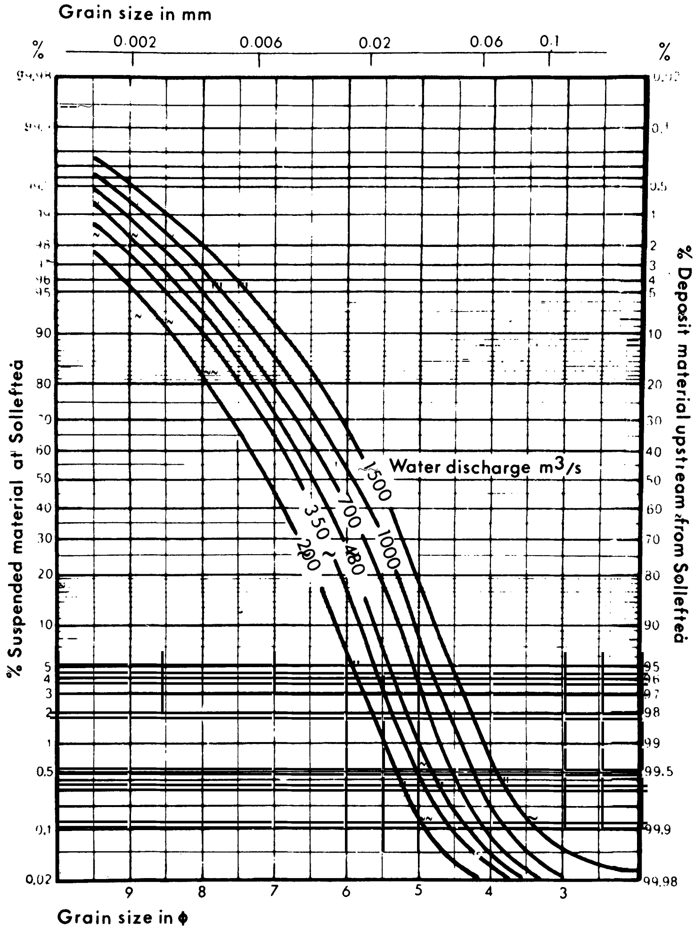

Fig. 7. Calculated amounts of sediment remaining in suspension at Sollefteå (to the left) and deposited in the reservoir respectively (to the right). The calculations were made for a given water temperature of 10 degrees Centigrade. (From Nilsson 1974).

From the nomogram it could be shown that at the annual mean water discharge of 480 m^3/s, ninety per cent of the material coarser than twenty microns should accumulate in the reservoir, while 99% of clay particles should remain in suspension.

Before the constructions of Sollefteå power plant started, Arnborg (1961, 1965) predicted the increase of sediment concentration at the raw water plant of the pulp mills, which were located at Hammarsbron (Fig. 5). Dredging started in August 1962 and was largely completed in April 1964. About 1,300,000 m^3 of material were removed. From geological projecting works the amount of particles < 60 microns

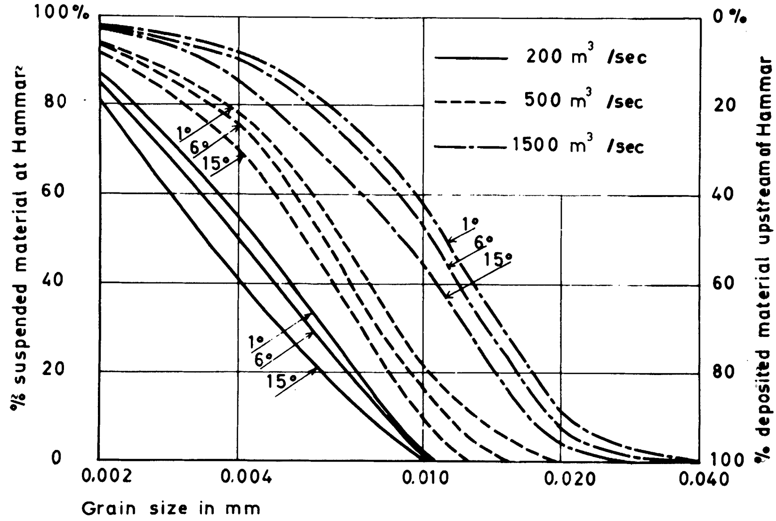

Fig. 8. Estimated suspended load in the river bulk at Hammar and deposited upstream Hammar at 35 km distance from the dredging area at Sollefteå respectively during different water stages and water temperatures. (From Arnborg, 1965).

was estimated to about 250,000 tons of which about 5% was < 6 microns. Coarser material was not considered to make any contribution to the concentration at Hammarsbron. The estimations were made for three different water discharges and water temperatures (Fig. 8) The dependence and consequence of low water temperature should be pointed out here, though not discussed any further.

Arnborg (1961) assumed the range of suspension of the dredged material to be between 6 and 50%. Later (1965) he concluded that »with more detailed information on the rate of dredging of different soils the prognostic limits of 6 and 50% of suspended material could be narrowed to 15 and 30%«.

However, Arnborg's calculations were made without considering the possibility of resuspension of already deposited material (cf Sundborg 1963). In this case 20-40% seems to be a reasonable estimate of the temporarily deposited material which could be resuspended at higher velocities.

If the 50% level of suspension is chosen the increase of the water discharge weighted concentration should be 1.6 ppm, assuming a constant dredging intensity. This increased concentration corresponds to a transport increase during the dredging period of 67,00 tons. Using the other technique and data as previously described (Nilsson 1974) the calculated transport increase could be estimated as 81,000 ton during the same period (Aug. 1962-April 1964).

Summary

It is shown that man's activities on various rivers can produce varying results in terms of water quality, and erosion on the banks and bed. During the construction of dams and power plant, dredging is common and will of course give rise to a locally increased turbidity and concentration of suspended sediment, which may affect areas some distance downstream, if the dredged material is sufficiently fine. The influence of the dredging could be estimated by careful use of the Sundborg formula (Sundborg 1956).

Storage of water in reservoirs smoothes out the annual cycle of chemical characteristics of the water. From inundated podsolic soils and from bogs, a sudden increase of nutrient salts and humus dissolved in water, is normal. The level of dissolved solids will probably adjust gradually to a more normal level after some years.

Short periodic water release tends to increase the duration of high flow velocities, often higher than the critical erosion velocity of the bed material. Besides increased bank erosion in connection with shifting water stages (Sundborg and Norrman 1963) this implies a higher erosion rate.

Dam construction traps the sediment load. Bed material load (Einstein 1950) is completely stopped. Disregarding the material which is eroded from the banks near the dam especially during windy situations, only wash load can be transported past the construction. Measured bed material load must therefore come from the river stretch between the dam and the sampling point.

Conditions leading to bed load are more frequent after the regultations, but the amount is difficult to estimate (Arnborg 1967, 1972). It must be emphasized, however, that the flow velocity is 30% higher when the bed load motion begins than when it ceases (cf Sundborg 1956). Thus, in spite of the absence of flood peaks and higher velocities, the amount of bed load may well increase after the river control.

During the whole construction period sediment transport increased. Table 1 in rough terms gives the amount of suspended load before, during and after the periods of disturbances. In order to facilitate comparisons, data from the river Indalsälven, compiled by Arnborg (Arnborg 1967) also are included.

Table 1 - Suspended load before, during and after the power plant constructions

	Transport in tons x 10^3			
River	before	during	after	decrease
Ume Älv	100	150-165	40-50	50-60
Ångermanälven	92	116	34	58
Indalsälven	76	95	26	50

However, according to suspended load measurements, a probable increase of erosion of about 30% was estimated for the river Ångermanälven from the dam to the delta (Nilsson 1974). Data from the other rivers are not available. A redistribution of material is probable and also net erosion immediately downstream of the dam.

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