

## **The impact of reservoir regulation on the processes of erosion and sedimentation of the delta in Lake Øyeren, Norway**

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**Abstract** The 9 km<sup>2</sup> delta in the Lake Øyeren reservoir has been affected by water level regulation since 1862. This paper reports the results of investigations carried out to identify the factors controlling the processes of delta erosion and sedimentation and to evaluate the impact of recent changes in the operational directives for power stations. Successive regulation phases have gradually reduced the amplitude of seasonal variations in water stage from the natural range of 8 m and resulted in an extended period of high and more constant water level. Local sediment redistribution within the delta has decreased over the years reducing the downstream extent of the sedimentation zone. As a result, a new phase in the delta development was initiated with marked proximal accumulation. The sub-aerial part of the delta increased rapidly in area as a greater proportion of the suspended load tended to be deposited on the delta plain. The impact of the delta changes on fish communities and fish habitats is discussed.

**Key words** erosion; sedimentation; sediment transport; delta; reservoir regulation; hydropower impacts; eco-geomorphology; habitat; rules of operation

### **INTRODUCTION**

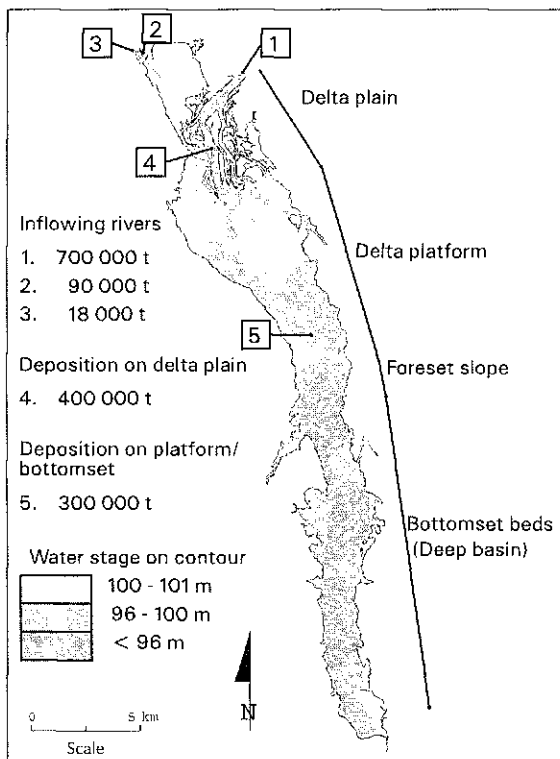
The present paper is based on the results from a project initiated to predict the impact of future changes in the operational directives for power stations affecting Lake Øyeren reservoir. It was decided to base such evaluations on a general study of the deltaic depositional processes and the documented impact of earlier regulations. The main focus of the paper is to discuss the physical consequences of these earlier regulations. The project was however, part of a multidisciplinary study which also included biology and habitat studies.

Fluvial forms and deltas are chiefly controlled by the variables of water discharge, water stage, sediment supply and sediment grain size. Regulation that affects one or several of these variables is likely to induce changes that involve aggradation or degradation which in turn may alter ecological parameters.

Reduction in sediment supply and water discharge are the most widespread impacts of river regulation on deltas. Reservoirs may act as major sediment traps within a drainage basin, disrupting the downstream transport of sediment load. Increases in channel-bed erosion below dams have often been reported in such cases (e.g. Rashid, 1979; Stanley, 1951; Petts, 1984; IEA, 2000). The reduction in sediment load may also affect the balance between erosion and sedimentation, and hence the stability, of deltas in downstream reaches. A shoreline erosion rate of 30 m year<sup>-1</sup> has

been reported for the delta of the Rioni River in the Black Sea (Makkaveyev, 1970) and more than  $100 \text{ m year}^{-1}$  for the Rosetta branch of the Nile Delta after construction of the Aswan Dam in 1964 (Khafagy & Fanos, 1993). In the backwaters of the reservoir, deposition upstream of the deltas has been a problem. The focus here is on the impact of changes in water level on the deltaic depositional processes. Severe erosion of lake deltas has often been the result of lake drawdown during power plant construction and operation (Tesaker & Dahl, 1992). Documentation of delta development in reservoirs where a rise of water level has taken place is however scarce, although laboratory experiments have indicated that a rise in the water level would cause a multiple delta development at a higher level (Jopling, 1963).

The delta complex in Lake Øyeren was affected by water level regulation as early as 1862. The need for flood control and a constant water level for navigation and lumber transport were the main incentives. During the twentieth century further regulations were initiated for hydropower development. The delta deposits cover about  $9 \text{ km}^2$  and are composed of several sedimentological units (Fig. 1). The delta plain, between the 103 and 101 m contours, is built up of overbank sediments and is traversed by both active and abandoned channels. Downstream from the outer rim of the delta plain there is a large platform occupying the area between the 101 and 96 m contours and extending about 9 km downstream to the foreset slope. The foreset slope grades into the bottomset beds of the deep basin around contour 36 m.



**Fig. 1** Sediment supply of inflowing rivers and sedimentation in various parts of the delta.

A number of old maps and aerial photographs were examined to document the development of the delta. The sediment deposition in the delta area was investigated by measurements of sedimentation rates and a sampling programme of channel bed sediments. These samples were analysed with respect to grain-size distribution. Bed load in the delta channels was measured with Helley–Smith samplers, so that transport rates could be calculated. Isco automatic samplers were deployed to measure sediment load in inflowing rivers. Sampling methods and laboratory analyses were carried out according to the procedures given by Bogen (1992).

## **SEDIMENT LOAD AND SEDIMENTATION**

The delta in Lake Øyeren is a complex system created by sediments delivered by three rivers, the Leira, Nita and Glomma. By far the largest volumes of sediment and water discharge are supplied by the Glomma, where a suspended load of 500 000 t year<sup>-1</sup> was measured as the mean for the years 1995–1999 and bed load was estimated to be of the order of 75 000–150 000 t year<sup>-1</sup>. In the smaller rivers, the Leira and Nita, the corresponding estimates of suspended sediment transport were 90 000 t year<sup>-1</sup> and 18 000 t year<sup>-1</sup>, respectively (Bogen *et al.*, 2002).

Longer-term sedimentation rates were investigated by Bogen *et al.* (1994). Sediment cores from the lake suggest a slight increase in sedimentation rates from the period 1934–1967 to the period 1967–1991. This increase was attributed to the combined effects of a change in agricultural practice and an increase in flood frequency.

Overbank sedimentation rates during the flood in 1995 were mapped. During this event the water discharge in the River Glomma reached 3400 m<sup>3</sup> s<sup>-1</sup>. The water level of Lake Øyeren culminated at contour 104.34 m and the whole delta plain was inundated.

After the retreat of the flood the sedimentation rates in the various parts was measured. The largest rates of 20–30 cm were found on the levees along the channels in the eastern part of the delta. In this area the main flow seemed to have remained inside the channels whereas the overbank water was almost stationary. The sudden decrease in sedimentation rate away from the levees was due to the large velocity gradient in this direction. Along the main channel at Årnestangen, only moderate rates of less than 5 cm were observed. This fact is believed to be related to the high current velocity of overbank flow in this area. Sedimentation rates were plotted on a map, from which the total amount of overbank sedimentation was calculated as 400 000 t. This was about 40% of the suspended load delivered by the inflowing rivers during the flood.

## **DELTA DEVELOPMENT**

The movement of bed load is controlled by flow velocity and bed shear in the inflowing rivers. Flow velocity is not only dependant on water discharges but also on the slope of the water surface in the delta area. The slopes during the large floods and high lake water levels in 1966 and 1967 are compared with the slope during low discharge of the inflowing river and low water stage of the lake in the spring of 1998

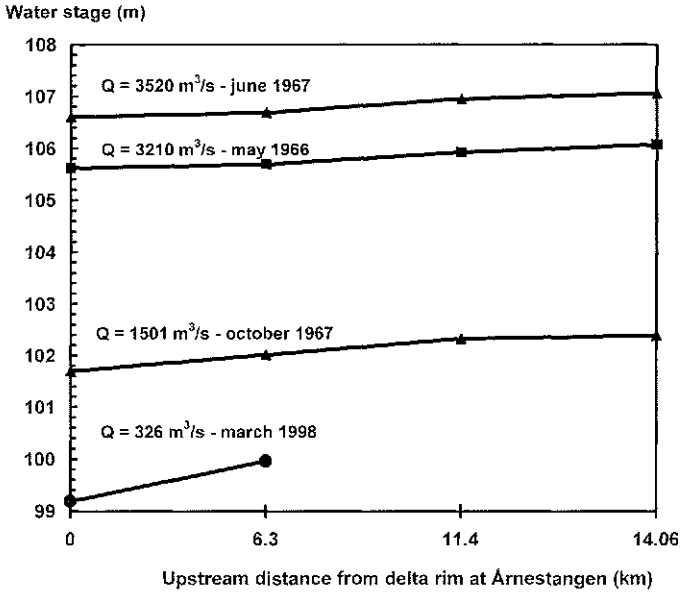


Fig. 2 River surface slopes during various discharges in the River Glomma and different water stages in Lake Øyeren.

(Fig. 2). Calculations and measurements of a number of situations (Bogen *et al.*, 2002) indicated that slopes were high during the rising stage of floods and decrease significantly as the water level is such that the delta plain is inundated. It was further concluded that slopes may also be high on low river discharges when lake water levels are very low.

A high water surface gradient allows for transport of bed load even at low water discharges of the inflowing rivers. Thus, sediment deposited at high water stage in the lake may be carried further into the delta area when the lake water level is reduced. Before the first regulation was initiated in 1862 the delta area was affected by large

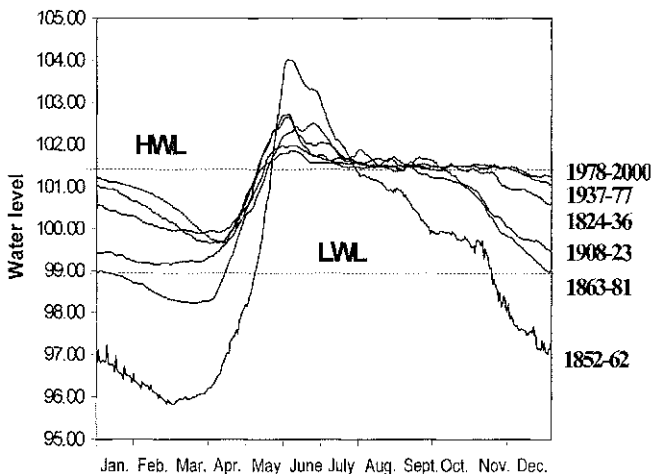


Fig. 3 Seasonal variations in mean water stage of Lake Øyeren during selected time periods.

seasonal water level variations (Fig. 3). The difference between mean spring flood water stage and mean winter low water stage was as much as 8 m. During such a situation the bed load supplied by the inflowing rivers was deposited over a large area in the channels. This area was found to reach from the 104 m contour in the proximal part of the delta to the 96 m contour at the rim of the foreset slope. As the water level was reduced during late summer and autumn, the sediments deposited during high spring stage were carried further into the distal parts of the delta. During the following 100 years a number of lake regulations increasingly constrained water stage fluctuation. Seasonal variation was reduced and water level tended to be constant during the summers. After 1945, the water level variations have been less than 2 m. For large parts of the summer and autumn the water level in the reservoir is fairly constant and rarely falls below the 101.34 m contour.

A rapid decrease in grain size also indicates the occurrence of extensive sedimentation. In the proximal part of the delta the mean grain-size range is between 0.3 and 0.5 mm. Downstream from the island, the range is reduced to 0.063–0.125 mm. A similar reduction is also recorded in the two other channels (Fig. 4). Thus, sedimentation also take place in these channels, but the rate is apparently too small and the current velocity too high to form bars and islands. In the delta platform area a further decrease in grain size is observed, with silt fractions dominant 1.5–2 km downstream from the delta rim at Årnestangen.

A map of the extent of the sedimentation zones has been constructed on the basis of available information on sedimentation rates and grain-size distributions (Fig. 5). During large floods, the level of the lake is high and sedimentation tends to be concentrated in the northernmost part of the channels. When the prevailing water level is close to 101.34 m, the main areas of sedimentation are displaced southwards. The limit for sedimentation of sand fractions is located 1–2 km downstream from the rim of the sub-aerial part of the delta. Before regulation, the limit was at the delta front, indicating that the regulation practices introduced in 1863 and 1908 moved the limit into intermediate positions.

Permanent sedimentation caused by changes in the longitudinal profile may reduce the channel cross profile area, causing the river to adjust by lateral erosion of its banks. Extensive erosion is observed in the river banks around the Flatsand island.

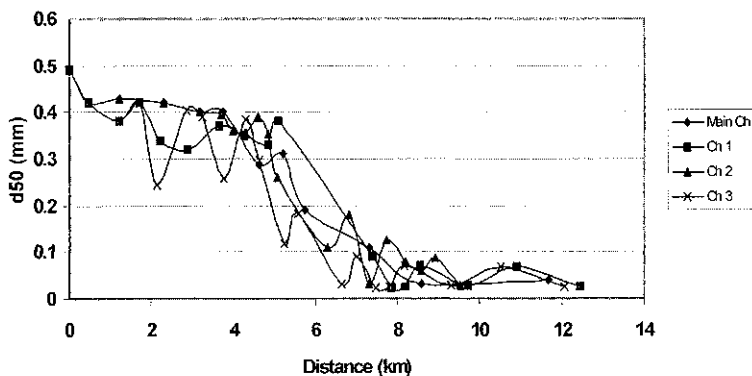
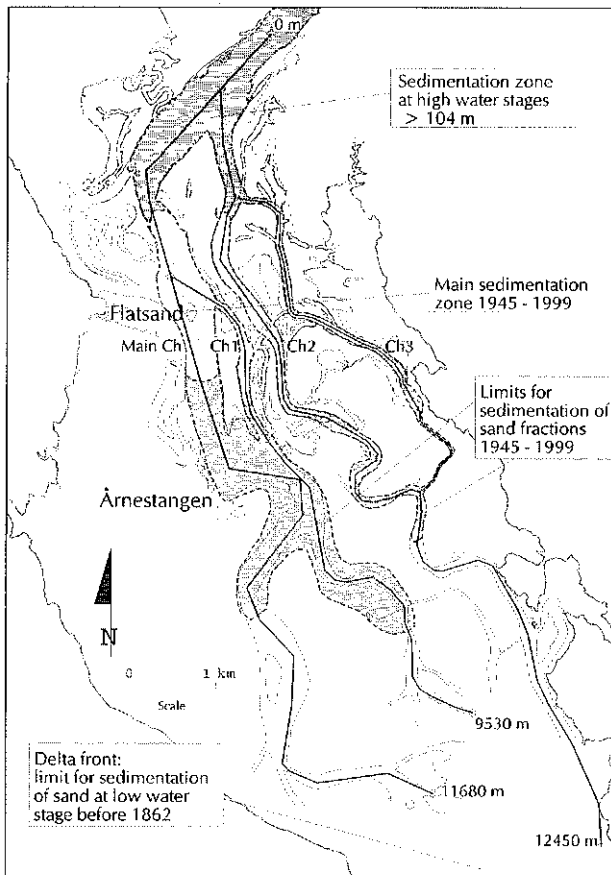


Fig. 4 Median grain size of samples from delta channels. Distance is measured along lines in the channels indicated in Fig. 5.

## EROSION

In 1977 a reservoir operational practice was introduced, that involved a longer duration of very low water stages during winter (Fig. 3). Maps and reports from local people indicate that this new practice moved the accumulation of sediments downstream. The island and the associated bank system thus appeared to move a short distance downstream after 1977. Lateral erosion also seemed to move with the main point of sediment deposition with the intensity of erosion reduced in the upper parts and increased in the downstream areas. Erosion of riverbanks also takes place in areas where the main flow is directed towards the banks and exposed to high current velocities. However, processes related to bank soil freezing and thawing are also important. Gatto (1995) found that in areas where seasonal frozen ground occurs, frost processes cause more bank recession annually than shear processes caused by running water only. Seasonal frost weakens the soil structure and soil particle interlocking by the formation of ice lenses. Upon thawing, previously frozen soils temporarily have an excess of soil water, which significantly reduces internal friction and cohesion and thus soil shear strength. The longer duration

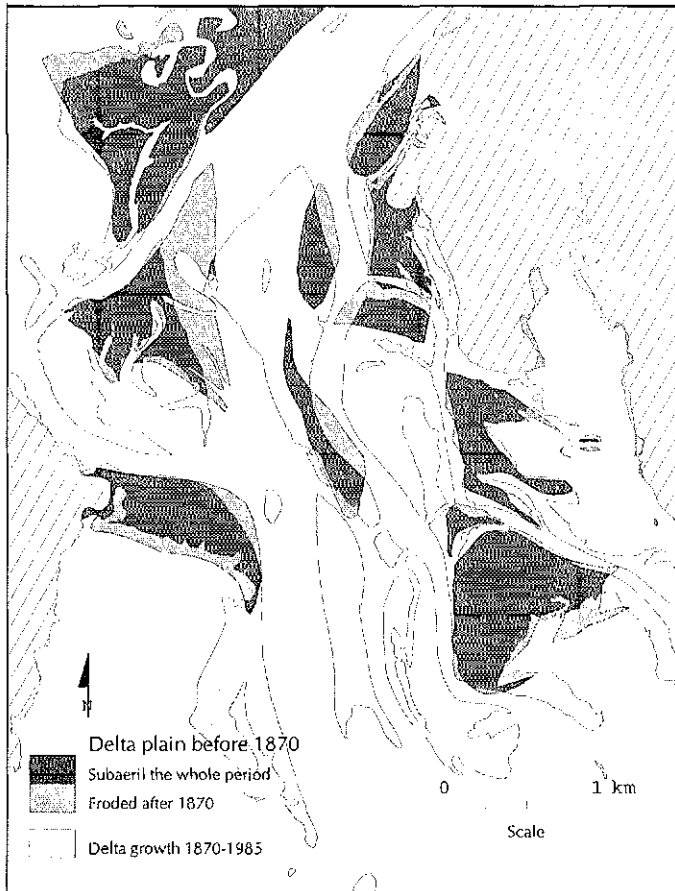


**Fig. 5** Sedimentation zones during different seasonal water level variations caused by different regulation practices. The wavy line in the centre of the channels indicates locations of grain-size samples shown in Fig. 4.

of low water stages introduced by the operational practice from 1977 therefore most probably increased bank erosion as river banks became more exposed to frost action.

## LONG-TERM DEVELOPMENT

A comparison of maps from 1870 and 1985 shows that the area of the delta plain has considerably increased in this period (Fig. 6). The main channel lay more to the east and there were fewer channel bifurcations. The channel migrated westwards as a result of intense erosion of the western bank. The eastern bank have been extended correspondingly. The rate of annual growth of the sub-aerial part of the delta has in general been more extensive during the last 100 years than during the preceding postglacial period. This fact is due to the change in main area of sedimentation caused by regulations. Changes did not only take place in the channels, but also in other parts of the delta. As all the bed load is dumped on the platform rather than the foreset slope, this area shallows up quite rapidly. A constant water level also seems to favour a faster

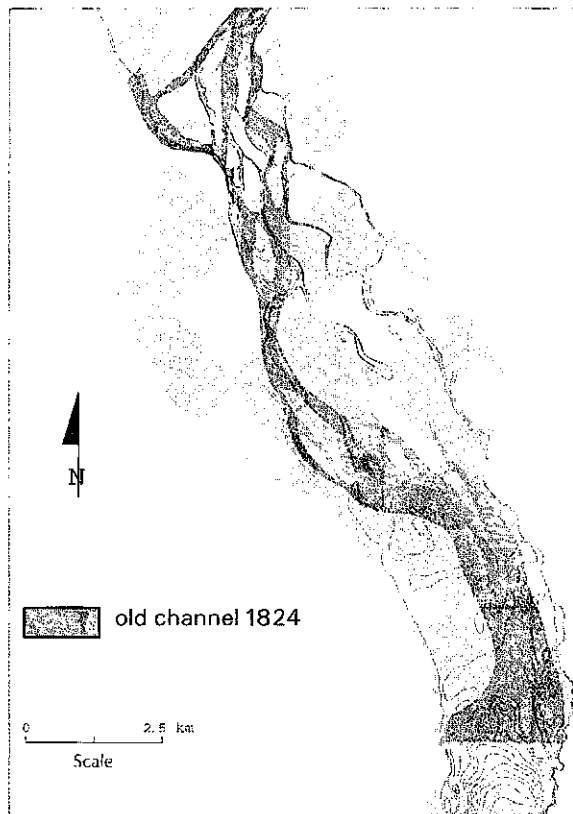


**Fig. 6** Delta development 1870–1985.

build-up of the delta plain by overbank sediments. As the water stage is bound to stay above contour 101.34 m for large parts of the year, even minor increases in water discharge inundate the platform area. Sediments that before the regulation were carried into the platform area, are now more likely to be deposited further upstream on the lower part of the delta plain. The number of lagoons has increased after the regulations. Lagoons are formed when the levees along active channels are developed faster than the intervening areas. A relatively constant water level seems to favour such a development.

## ECO-GEOMORPHOLOGY

This paper has focused on the impact of lake water level regulation on sedimentary processes in deltas. It is, however, believed that the results demonstrate the importance of lake water level as a variable in deltaic depositional systems in a more general context. The large amplitude of lake level variation was a characteristic feature of the long deltaic system that existed prior to the initial regulation of Lake Øyeren in 1862. A reconstruction of the old delta based on maps from 1870 and 1824 is shown in Fig. 7



**Fig. 7** Reconstruction of delta before regulations were initiated in 1862. Contours from 1985.

along with contours from the modern one. It is apparent that in the platform area most of the present channels follow the old ones from the early eighteenth century.

However, other parts of the modern delta appear very different from the old one and have developed features created by the relatively constant water level at 101.34 m. The modern delta appears very different. The introduction of a constant water level increased the extension of the delta plain and the number of lagoons, bays and backwater areas. According to Brabrand (2002) the fish community in the northern part of Lake Øyeren constitutes a shallow water community composed of pike, ruff, perch, pikeperch and several species of cyprinids. Before regulations were initiated, these species existed in marginal zones in the southern part of Lake Øyeren. The drying out caused by the rapid seasonal fall of the water level in July rendered the northern habitats unsuitable. The shallow water fish community was thus established when these species took advantage of the new habitats created by the new style of delta development. In some areas, high concentrations of suspended sediments reduced water transparency and affected fish habitats through several pathways. The turbidity affects light penetration and photosynthesis of plants and thus affects fish habitats by influencing the cover of aquatic plants. In shallow areas two types of fish habitat are recognized within the delta. In areas dominated by high sediment concentrations from the inflowing River Leira, or in the large open areas exposed to strong winds, turbidity is high. Aquatic vegetation is scarce or absent and river banks are often bordered by bare erosion rims. These areas are dominated by roach, bream, white bream, bleak and ruff. In the sheltered lagoons and bays the turbidity is low, thus providing more favourable conditions for littoral vegetation. These areas are dominated by species with a preference for clear-water habitats. This clear-water community is dominated by roach, with smaller populations of ide, perch, bream and pike.

The aquatic vegetation is important to fish habitats and is very rich in this delta. According to Rørslett (2002), more than 325 species of aquatic macrophytes, helophytes and marshland vegetation have been observed. The large seasonal changes in water level before regulation most probably restricted the number of species at that time. During the last 30 years, the combined effect of changes in land use in the catchment area of the delta and of climate changes is believed to have caused an increase in the turbidity of the inflowing rivers. As a result of increased turbidity, a change in the littoral vegetation and an expansion of the fish species utilizing the high turbidity habitats at the expense of the others has been observed.

**Acknowledgements** This paper is based on a project funded by the City of Oslo and Akershus County, Glommen and Laagen Water Management Association, Norwegian Water Resources and Energy Directorate and the Directorate for Nature Management.

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