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Effect of water level regulation on gradients and levee deposits in the Lake Øyeren delta, Norway

Peggy Zinke and Jim Bogen

ABSTRACT

Water level changes resulting from a hydropower regulation have influenced water flow, gradients and sediment processes in the Lake Øyeren delta for about 150 years. They are reflected in the morphology of the islands on the delta plain. Under current regulation practices, water levels during the mean annual flood are maintained at about 1 m lower than during the previous regime prior to 1978. As the channels continue to mature, the recently deposited tongues and levees in the southern part will therefore probably maintain a distinctly lower elevation than that of the older islands. The influence of flood regulation on levee deposits during the extreme 1995 flood was estimated by comparing simulated overbank deposits resulting from different flood regulation schemes. The simulations showed that reduced water levels during floods in the presence of older islands extend the period of in-channel flow and promote the development of levee-like deposits in the lower part of the delta plain. This explains some of the characteristics observed in the morphological development, most notably the increased number of lagoons resulting from a higher number of levees.

Key words | delta, gradient, Lake Øyeren, levee, water level regulation

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INTRODUCTION

Water level regulation leads to modifications in the magnitude, frequency, timing, duration and rate of change of water flow, thereby fundamentally transforming rivers and altering wetland, floodplain and delta ecosystems (Gergel *et al.* 2002; Renöfält *et al.* 2010). Floodplain species are often distributed along gradients of flood frequency, duration and physical force (Sparks & Spink 1998; Nilsson & Svedmark 2002; Lytle & Poff 2004). The effects of regulation are of special interest if they affect the development of nature conservation areas such as the Lake Øyeren delta in southern Norway. It is therefore important to understand the impact of changes in water level regulation practices on morphological processes taking place on the delta plain.

The development of the channel network and islands on the delta plain is closely related to the formation of levees and river mouth bars on the topsets. River deltas forming on gently sloping shelves and fed by a sufficiently high incoming discharge are expected to exhibit a topset-dominated first-order stratigraphy (Postma 1990; Edmonds *et al.* 2011). When sediment-laden channelized flows debouche into a shallow, sloping basin, they initially form subaqueous levees followed by river mouth bars. The growth of the mouth bars deflects and splits the flow causing the channel to bifurcate and resulting in the formation of new islands with inter-levee basins (Axelsson 1967; Wright 1977). The relative position of the river mouth bars is influenced largely by the initial channel depth, and the bar ceases prograding when a particular water depth above the bar is reached (Edmonds & Slingerland 2007).

The aggradation of levees will also occur during overbank flows along the channel banks, due to reduced flow velocity and sediment transport capacity on the floodplain. The maximum water levels, discharges and sediment concentrations during a flood dictate the extent of the zones of deposition and influence overbank sedimentation processes, thus controlling the morphology and slope of the

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natural levees (Cazanacli & Smith 1998; Filgueira-Rivera *et al.* 2007; Smith & Pérez-Arlucea 2008). During floods, temporally and spatially variable deposition and erosion occur on levees due to backwater effects associated with nearby channel bars and irregular rises of the channel bed forced by channel extension (Smith *et al.* 2009). Levee deposits alone, however, may not be representative of the floodplain deposits as a whole. Overbank sedimentation proceeds by the settling out of fine-grained sediment during pondage (Simm 1995).

River deltas are progradational in character. The range of channel characteristics observed relative to distance from the shoreline reflects channel maturation. Juvenile channels at distal reaches are wide and shallow, whereas more proximal mature channels are usually more deeply incised (Hoyal & Sheets 2009; Edmonds *et al.* 2011). Given near steady-state conditions over moderate time scales, the characteristics of mature delta channels can be described in terms of 'hydraulic geometry' relations depending on bankfull discharge and the suspended sediment load (Andrén 1994). Bankfull discharge is the discharge at which flow overtops the river banks and spills from the channel onto the floodplain. It represents the dominant channel-forming discharge mechanism, since over long periods it transports the majority of the sediment volume (Wolman & Miller 1960; Wormleaton *et al.* 2005). In rivers under quasi-equilibrium conditions, the mean annual flood (MAF) equals or slightly exceeds in frequency the bankfull discharge which usually has a recurrence interval of 1.5–2 years (Leopold *et al.* 1963). These relations were also found to be true for the upper and middle parts of the delta plain in other unregulated Scandinavian freshwater lakes (Axelsson 1967; Dahlskog & Johansson 1977), although the fluvial system of a delta plain of this type can never be expected to attain the theoretical longitudinal equilibrium profile (Swenson *et al.* 2005). If the hydrological regime is altered permanently, the system starts to adapt to the new conditions. The time required for the re-establishment of quasi-equilibrium conditions following major disturbances ranges from decades to centuries for the river reach scale (Kern 1994).

The main objective of this study is to demonstrate that 150 years of water level regulation have affected the morphological development of the Lake Øyeren delta and that some recently observed tendencies can be explained by changes in flood regulation practice introduced about 30 years ago. To achieve this, we have analysed the elevations, water levels and gradients on the delta plain based on morphological and hydrological data, combined with flow simulations using a computational fluid dynamics (CFD) model. The configuration, testing and performance of the CFD model used to simulate the flow distribution in the delta and the process of levee deposition during a large flood in 1995 have been described earlier (Zinke *et al.* 2010, 2011). In this study, we apply this model to carry out a scenario investigation addressing the influence of different flood regulation practices on levee deposition during the 1995 flood event.

BACKGROUND

Lake Øyeren

Lake Øyeren extends over 87.4 km^2 and is situated about 25 km east of Oslo, Norway. It is a freshwater lake with a maximum depth of about 70 m. The area exhibits a marginal continental climate with relatively warm summers, cold winters and a mean annual temperature of 4.1 °C. Annual rainfall averages 820 mm (MET 2009).

In the northern part, the sediments of the three incoming rivers (the Glomma, Leira and Nitelva) have formed a river delta extending over approximately 56 km^2, including its subaqueous parts. Bogen & Bønsnes (2002) distinguished between the delta plain, delta platform, forest slope and deep basin as the morphological units of the delta (Figure 1). The delta front is situated approximately 15 km downstream from the Glomma river mouth, approximately in the centre of the lake. Parts of the delta were formed under marine conditions prior to the last post-glacial rebound, when the northern part of Lake Øyeren was a coastal inlet. Today, the Lake Øyeren delta is the largest freshwater delta in northern Europe and an important nature conservation area, hosting a broad diversity of bird, fish and plant species (UNESCO 1994; Berge 2002).

The Glomma River accounts for the largest inflow into the delta since its basin represents 97% of the delta's total 40,055 km^2 catchment area. Marine and glaciofluvial deposits consisting of clay, silt, sand and gravel derived from the

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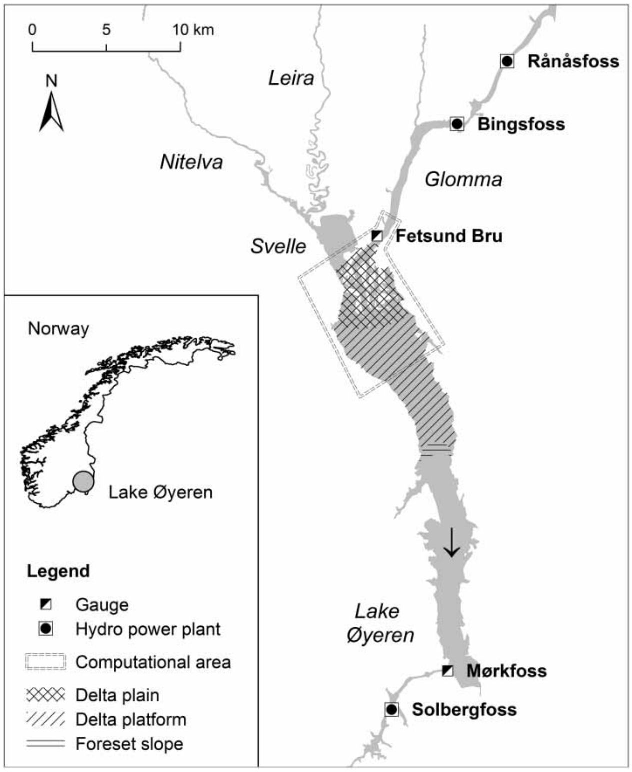

Figure 1 | Lake Øyeren, location map showing measurement stations and morphological units according to Bogen & Bønsnes (2002).

lower part of the catchment area represent the main source for the incoming sediments. Sediment transport is dominated by suspension. The channel beds within the main distributaries of the delta plain consist of well-sorted sands with a mean grain size (D_{50}) ranging between 0.3 and 0.4 mm, which exhibit a pronounced downstream fining as they enter the delta platform. The channel banks along the delta islands consist primarily of silt.

The majority of the banks are cohesive and stabilized by vegetation, as indicated by the steep or vertical bank walls. The vegetation of the delta exhibits a typical zoning from horsetail and sedge swamps to birch- or grey-alder-dominated woodlands, depending on the elevation and moisture gradients (Zinke *et al.* 2011).

Regulation and flooding practices at Lake Øyeren

Lake Øyeren has been influenced by water level regulation since 1862, initially to facilitate flood control, navigation and lumber transport and later as part of hydropower development (Bogen & Bønsnes 2002). Since 1924, lake water levels have been regulated hydraulically by operations at the Solbergfoss hydropower plant (Figure 1). Successive phases of regulation have gradually reduced the amplitude of seasonal variations in water stage from its natural range of 8 m to an average of less than 4 m. This has resulted in an extended period of elevated and more stable water levels, as illustrated in Figure 2 (Ortveit *et al.* 2000; Bogen *et al.* 2002). Here the line between black and grey represents the median water level. For the period 1986–2005, the median lake water level was 101.37 m above sea level (m a.s.l.) and the average discharge through the delta 700 m^3 s^{-1}.

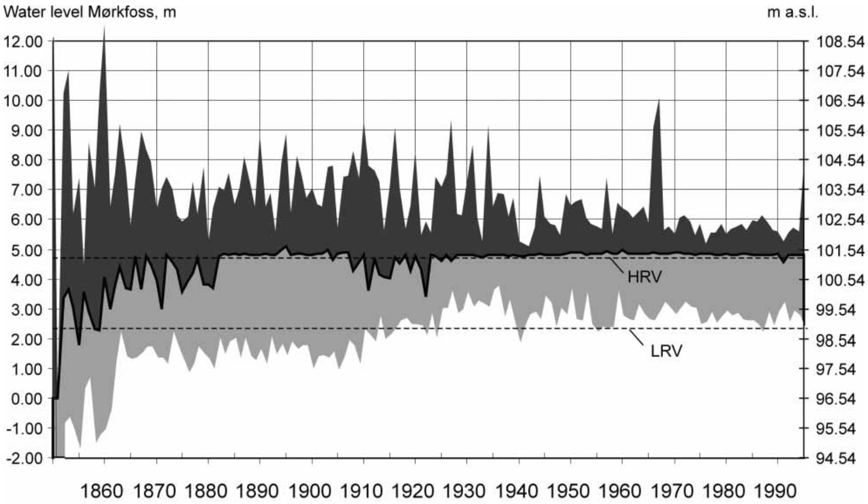

Figure 2 | Annual minimum, maximum and median water levels at Mørkfoss together with regulation limits (dashed lines). Modified from Ortveit *et al.* (2000).

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The current rules governing the regulation of water levels at Lake Øyeren came into force in 1934 and were amended on 15 May 1981 after the opening of the Bingsfoss hydropower plant in 1978. They define an upper regulation limit (HRV) of 101.34 m a.s.l. and a lower limit (LRV) of 98.94 m a.s.l. measured at the gauge station at Mørkfoss. These limits are shown in Figure 2. During the summer and autumn season, the water level is maintained close to the HRV. During the subsequent winter months the water level is lowered, reaching a minimum prior to the spring flood in March/April as shown in Figure 3. Operational practices since 1978 have involved an extended period of very low water levels during the winter, compared to the previous regime. Some details of the operating regime are currently being assessed.

The flooding regime was altered largely following rock blasting in the narrow outflow river reach between Mørkfoss and Solbergfoss carried out between 1860–1869 and 1918–1924. This facilitated higher discharge levels boosting water levels above 102.54 m a.s.l. and was taken into account during flood operations licensed from 1934. Two extreme floods in 1966 and 1967, resulting in maximum water levels of 105.62 and 106.61 m a.s.l. respectively, led to major inundations across the neighbouring municipalities and promoted the introduction of additional flood-control measures. Subsequently, flood capacities at the lake outlet were increased and regulated flooding practices were modified after 1978. The current licence stipulates that the spillways at the Solbergfoss hydropower plant must be opened step by step for water levels greater than 102.04 m a.s.l. at Mørkfoss, and completely open when the water levels exceed 102.54 m a.s.l. Lake levels were regulated according to these rules during an extreme flood in 1995, enabling the peak water level to be maintained at approximately 2 m lower than during the extreme flood in 1967 (as illustrated in Figure 4). Both floods had a frequency of 50–100 years in terms of the maximum culmination or momentary discharge of the Glomma River at the inflow into Lake Øyeren (Pettersson 2002).

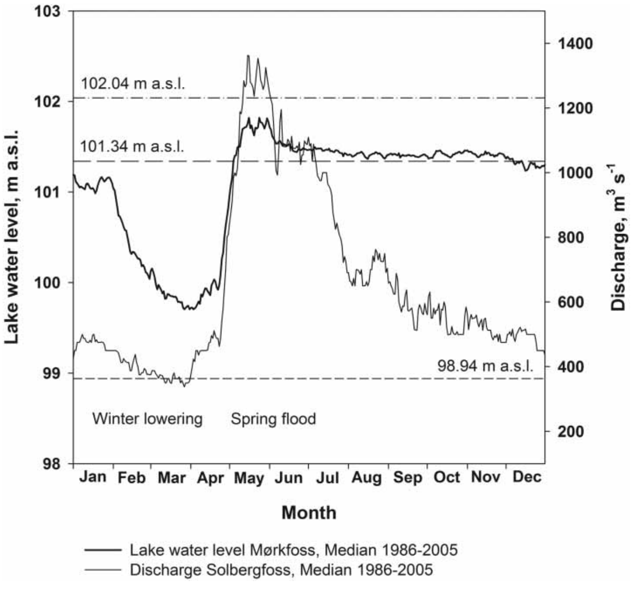

Figure 3 | Median water level and discharge values for the period 1986–2005, based on mean daily values recorded at Mørkfoss (water level) and Solbergfoss (discharge).

Table 1 lists culmination discharges and water levels for different flood recurrence intervals according to Pettersson (2002). This analysis was based on discharge data from the period 1846–2001. The probability analysis accounted for the effects of regulation measures in the Glomma basin upstream of Lake Øyeren. The culmination water levels at Mørkfoss were calculated using flood routing simulations that incorporated current flood regulation rules.

The mean hydraulic gradient along the 25 km between the delta plain outlet and Mørkfoss is generally low, between 0 and 0.1 m (based on observed transient flow processes up to 0.2 m; Pettersson 2002).

Morphological development and sediment transport

Historical maps of the delta have been available since 1775 and have permitted us to investigate the land area increment (Pedersen 1981; Bogen & Bønsnes 2002; DN 2007). Figure 5 illustrates the development of the delta islands over time. Since 1874, the delta plain has expanded considerably and is now characterized by a greater number of lagoons, bays and backwater areas, enlarged depositional features at the lower parts of the delta plain and the occurrence of new islands. Bogen & Bønsnes (2002) ascribed this development to a decrease in local sediment redistribution (i.e. a decrease in the area over which periodic channel flow with higher sediment transport capacity occurs) within the delta over the years, leading to a reduction in the downstream extent of the zone of sedimentation.

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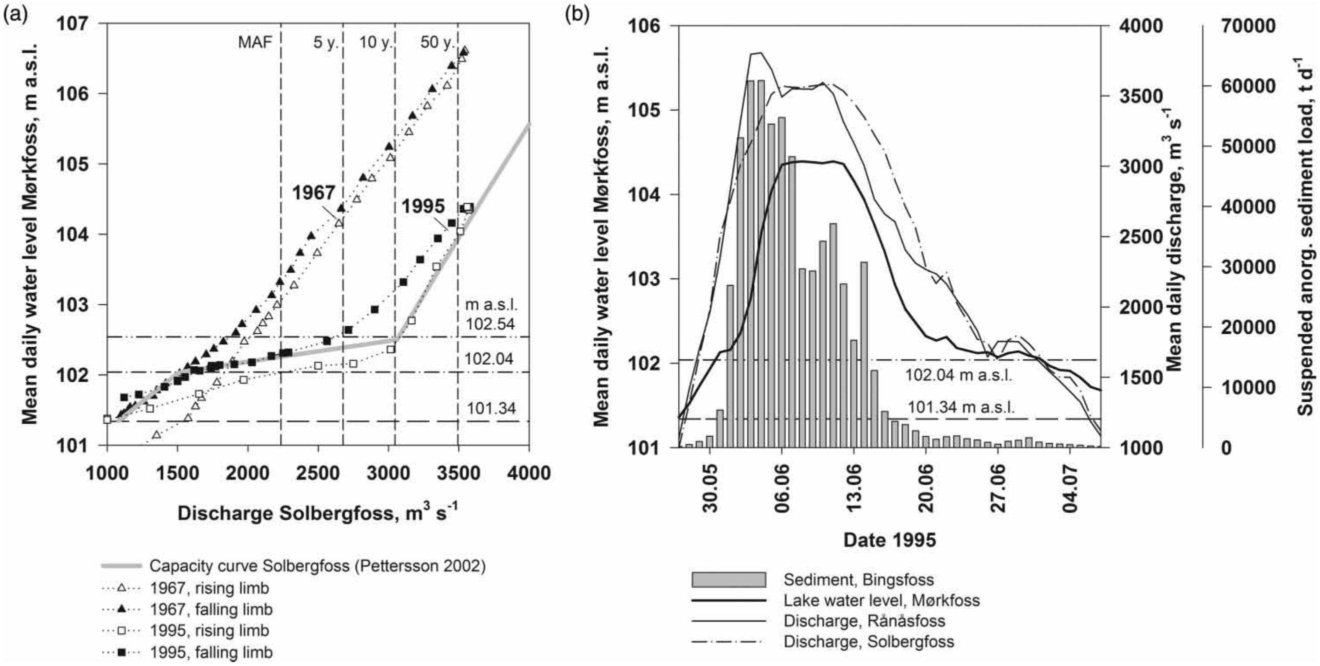

Figure 4 | Flooding practice during extreme floods. (a) Stage-discharge relationship at Mørkfoss during the extreme flood in 1967 and the 1995 flood, together with flood frequencies for Solbergfoss according to Pettersson (2002). (b) Lake stage, discharges and suspended sediment load of the Glomma River during the 1995 flood.

Table 1 | Recurrence interval estimates for maximum instantaneous values according to Pettersson (2002); *Q*: discharge; *W*: water level; MAF: mean annual flood

Recurrence interval (years)	2 (MAF)	5	10	20	50	100	200
Q (m^3 s^{-1}), inflow (Fetsund)	2,180	2,640	3,030	3,310	3,720	4,020	4,320
Q (m^3 s^{-1}), outflow (Solbergfoss)	2,235	2,677	3,046	3,217	3,492	3,722	3,957
W (m a.s.l.), Mørkfoss	102.26	102.39	102.50	103.02	103.93	104.68	105.43

Figure 5 | Development of the delta islands over time according to Bogen *et al.* (2002) and data from the Norwegian Mapping Authority.

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Measurements of incoming sediments have been available since 1990 for the Leira River and since 1995 for the Glomma River. The mean suspended sediment transport from the Glomma, Leira and Nitelva rivers into Lake Øyeren is approximately 500,000, 90,000 and 18,000 t yr^{-1}, respectively. Bed load transport is assumed to account for 10–20% of the total sediment transport (Bogen *et al.* 2002). During the extreme flood of May and June 1995, the suspended sediment transport of the Glomma at Bingsfoss was estimated to be 700,000 t, i.e. 93% of the total suspended sediment load for that year. The sediment load reached its maximum during the first days of the flood, when the incoming discharge was also at its maximum (Figure 4). The maximum mean daily suspended sediment concentration was 188 mg L^{-1}, recorded on 3 June 1995.

Sediment thickness on the delta islands following the 1995 flood was measured by the Norwegian Water Resource and Energy Directorate (NVE) during field work throughout summer and autumn of 1995. The greatest thicknesses were accumulated as levees built up on lateral channels, especially in the eastern and lower parts of the delta plain. Thicknesses in these regions were between 20 and 30 cm, and decreased markedly with increasing distance from the river bed. The mass of the measured overbank sediments was estimated as 400,000 t (Bogen *et al.* 2002; Zinke *et al.* 2011).

DATA AND METHODS

For the present study, we analysed the morphology of the delta islands, compiled measured hydrological data and used a CFD model to investigate the effect of hydropower regulation on water levels and overbank deposition during the 1995 flood.

A digital elevation modelling (DEM) of the deltaic islands was performed based on an aerial image taken during flight number 11722 on 13 April 1995. The black-and-white aerial photograph had a flight scale of 1:10,000, and was chosen for photogrammetry because it was taken immediately before the occurrence of the 1995 flood.

The database held by NVE provided mean daily values of water level and discharge, which were analysed for the period 1986–2005. Since 1852, the water levels at Lake Øyeren have been measured at Mørkfoss, approximately 25 km south of the delta (Figure 1). Gauge observations of incoming water from the Glomma River were made at station Fetsund Bru. Data from this station were available for the period 1995–2004, but for the period 1995–1997 and for 2003 data were only available for selected days. Discharge data for the Glomma River were available from the Rånåsfoss hydropower plant upstream from the delta, and from the Solbergfoss hydropower station downstream from the lake.

The numerical modelling was performed using the three-dimensional finite-volume model SSIIM. It solved the Reynolds-averaged Navier–Stokes equations with the k–ε turbulence closure on a 3D unstructured grid using predominantly hexahedral cells and wetting and drying algorithms. The free water surface was calculated from the 3D pressure field, with reference to a given point at the outflow boundary. For model cells covered with vegetation, a volume-averaged sink term conforming to the classical drag force approach (e.g. Munson *et al.* 2002) was introduced into the Navier–Stokes equations. Sediment transport was computed using the convection–diffusion equation for sediment concentration, applying the empirical Van Rijn's (1984) formula for pick-up rate from the bed and employing multiple grain sizes. Bed elevation changes were calculated from sediment continuity in the bed cell. The model accounted for the cohesiveness of sediments, shear-stress induced erosion and sand-slide processes. It did not include a geotechnical bank stability analysis. For a full description of the modelling tool, the reader is referred to Olsen (2010).

The morphology data which provided input to the modelling were accumulated from a combination of bed level data from a 2004 side-scan sonar investigation of the deeper channels, NVE's digital bed level data for parts of the delta platform, the DEM from April 1995 for the delta islands, some aerial image-based modifications in areas subject to high frequency changes and geographic information system (GIS)-supported interpolations. On the basis of a previous grid dependency study, and taking into account the limited accuracy of this combined dataset, a horizontal grid resolution of about 10 m (for steady computations) or 20 m (for the flood wave) was chosen. The performance of the flow model was tested and verified using data from Acoustic Doppler Current Profiler (ADCP) measurements (Zinke *et al.* 2010). The morphological capabilities of the model and the influence of uncertainties regarding model parameters and

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boundary conditions were investigated using comparisons with the measured levee deposits resulting from the 1995 flood. These results, together with detailed information about model settings, its sensitivity in relation to the flood case and the influence of model uncertainties are described by Zinke *et al.* (2011).

The modelling results presented here include steady flow simulations for selected flow situations (1996/1997), together with flow and sediment transport computations for the entire 1995 flood (see Table 2). The latter were performed using a quasi-steady flow approach, which approximates the flow hydrograph as a sequence of steady flow discharges. The flood computation consists of a model investigating the real flow situation conforming to actual regulation practice, and a hypothetical scenario in which water levels were regarded as behaving in response to the previous flood regulation practice as it was prior to 1978, i.e. conforming to a stage-discharge relationship as shown in Figure 4(a) (for 1967). These two model variants are referred to as the '1995-Real' case and the '1995-fHW' (1995 fictive high water level) case.

RESULTS

Morphology and growth of the delta plain

Figure 6 shows the morphology of the delta islands as they appeared in 1995. Some levees associated with the upper islands in the northern part were higher than 105 m a.s.l. For the most part, the islands in the southern part of the delta exhibited lower elevations. The elevations of islands in close proximity to the banks, which have largely developed after 1952 (at Storsand, Bukkesand and Årnestangen) were mostly between 102.5 and 103.5 m a.s.l. The elevations in the most downstream parts of the islands did not exceed 102.5 m a.s.l.

Based on Figure 6, the total land area of the delta islands and shore zones (elevations between 101.5 and 105.5 m a.s.l.) in 1995 was 8.7 km^2. Table 3 provides estimates of the growth in area of the exposed part of the delta during different time periods. These estimates are based on data illustrated in Figure 5 and available publications. These growth rates must be regarded as coarse approximations, because the historical maps of the islands displayed a variety of scales and were made for different and partly unknown water levels. According to Figure 5, the mean annual rate of land area increment from the beginning of regulation until the year 2000 was approximately 2 ha yr^{-1}, which is similar to the estimate arrived at by Pedersen (1981). The net growth in area between 1976 and 1994 was estimated by DN (2007) as 20.4 ha (resulting from 77.7 ha aggradation counterbalanced by 57.3 ha erosion) and gives a lower annual growth rate of about 1 ha yr^{-1} for this period.

Overbank deposits laid down during extreme floods account for only a small part of the sediment budget. If the overbank sediment mass resulting from the 1995 flood (400,000 t) is divided by the flood frequency (50–100 years),

Table 2 | Description of the simulations. Nos I–III were available from previous studies (Zinke *et al.* 2010, 2011), No. IV was performed for the current investigation

No.	Simulation	Type of computation	Major boundary conditions	Note
I	22 October 1996	Steady flow computation	$Q = 712$ m^3 s^{-1}, $W = 101.37$ m a.s.l. at Mørkfoss	Compared with ADCP measurement data from 22 October 1996 (Zinke *et al.* 2010)
II	9 July 1997		$Q = 1{,}496$ m^3 s^{-1}, $W = 101.97$ m a.s.l. at Mørkfoss	Compared with ADCP measurement data from 9 July 1997 (Zinke *et al.* 2010)
III	1995-Real	Time-dependent flow and sediment computation	Measured hydrograph and sediment concentrations during the 1995 flood, as shown in Figure 4(b). W–Q relationship '1995' in Figure 4(a). Other parameters as for the base scenario in Zinke *et al.* (2011)	Calculated levee deposition tested against measured data (Zinke *et al.* 2011)
IV	1995-fHW (fictive high water level)		Same parameters as for 1995-Real, but water levels as for the earlier regulation practice (W–Q relationship '1967' in Figure 4(a))	Hypothetical scenario; no data available for verification

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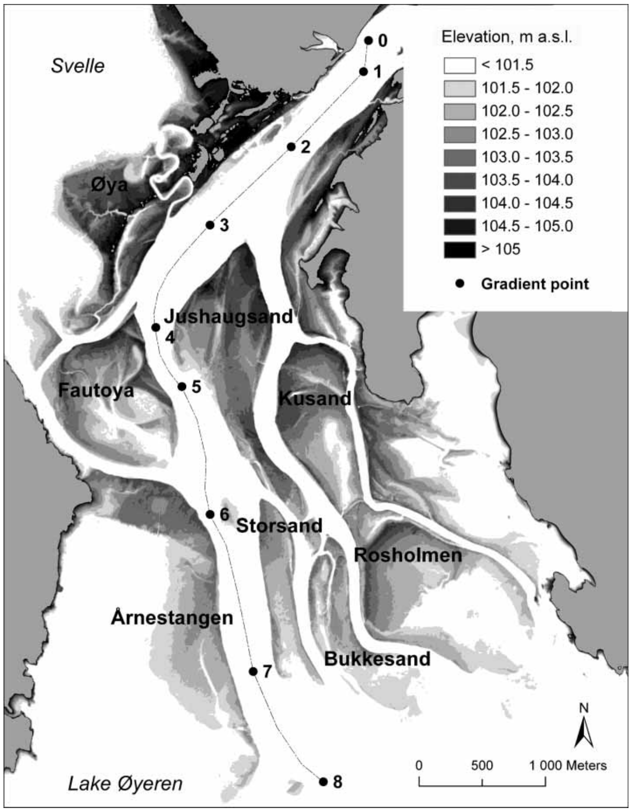

Figure 6 | Elevations of delta islands as derived from a digital elevation model from 1995, and the positions of the gradient control points shown in Figure 10.

we obtain a mean annual overbank sedimentation rate of 4,000–8,000 t yr^{-1}. This represents only about 1% of the mean annual total sediment inflow, which is estimated to be approximately 700,000 t yr^{-1} (the sum of suspended sediment load from the three rivers and bed load).

Water levels and gradients within the delta

Figure 7 shows stage–discharge plots for Fetsund Bru and Mørkfoss for the current regulation regime, which reveal mean daily discharges of up to 2,000 m^3 s^{-1}. The highest point density is concentrated around and slightly above the upper regulation limit of 101.34 m a.s.l. The two density fields below this value represent winter lowering (steep drawdown for low discharges; see Figure 3) and rising during spring floods. For discharges exceeding 1,300 m^3 s^{-1}, the data arrange to a single stage–discharge relationship. Between 102.04 and 102.54 m a.s.l. the stage–discharge relationship at Mørkfoss is very flat because of the successive opening of the spillways in compliance with current regulation rules. The high levels of scatter in the data result from the influence of wind, seiches and other factors which can also influence water levels at Lake Øyeren. Figure 8 shows typical water level differences between the Mørkfoss and Fetsund Bru stations for summer and autumn flow conditions with water levels above 101.34 m a.s.l., based on linear regressions derived from hydrological data shown in Figure 7. The average water level difference between inflow into the delta and outflow from the lake was 0.3–0.4 m.

Figure 9 shows the stage–discharge plot for the 1995 flood. As for the hydrometric station at Fetsund Bru, the NVE database provided reliable data only for the period after 16 June. These data were supplemented by spot observations of water levels provided by NVE, combined with the results of the numerical simulations (ranges of the sensitivity tests described in Zinke *et al.* (2011)). The assumed curve is what we regard as the most likely behaviour associated with the rising limb.

Figure 10 presents simulated gradients along the main delta channel between Fetsund Bru and Mørkfoss for nearly mean flow conditions (712 m^3 s^{-1}), a higher discharge rate (1,495 m^3 s^{-1}) and for selected dates during the extreme flood of 1995. The positions of the control points are shown in Figure 6. The combination of hydrological data and

Table 3 | Estimated growth in area of the subaerial delta for different periods, together with data sources

Period	**Years**	**Land area increment (ha)**	**Mean annual land area increment (ha yr^{-1})**	**Reference**
1874–1952	78	151.5	1.94	Derived from Figure 5
1952–2000	48	95.0	1.98	Derived from Figure 5, including deposition in areas outside the frame
1868–1974	106	238.4	2.25	Pedersen (1981)
1976–1994	18	20.4	1.13	Norwegian Mapping Authority, published by DN (2007)

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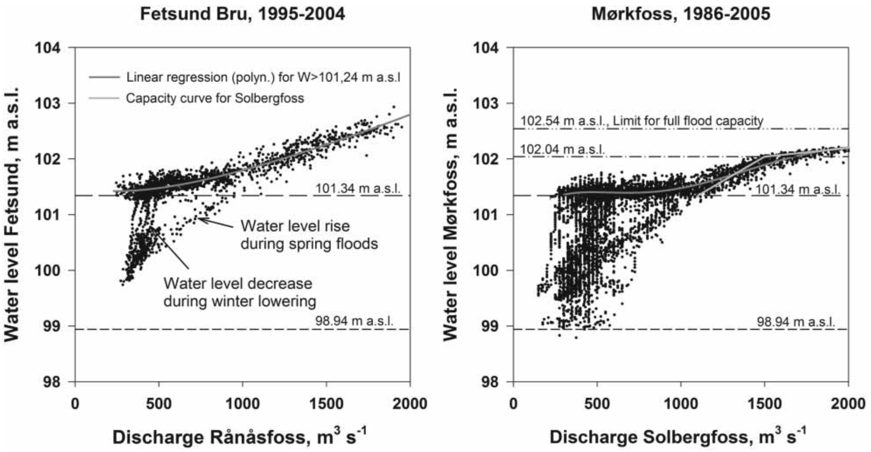

Figure 7 | Stage–discharge plots for mean daily values at Mørkfoss and Fetsund Bru.

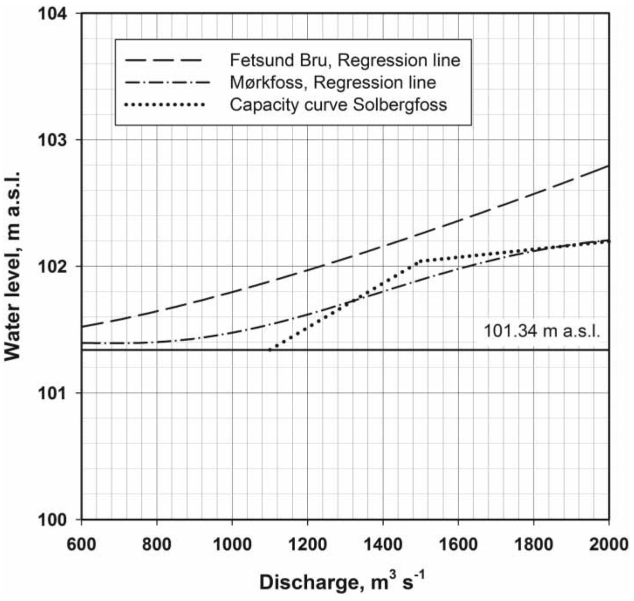

Figure 8 | Regression plots for the stage–discharge relationships at Mørkfoss and Fetsund Bru for water levels above 101.34 m a.s.l., and the capacity curve for Solbergfoss (the latter taken from Pettersson (2002)).

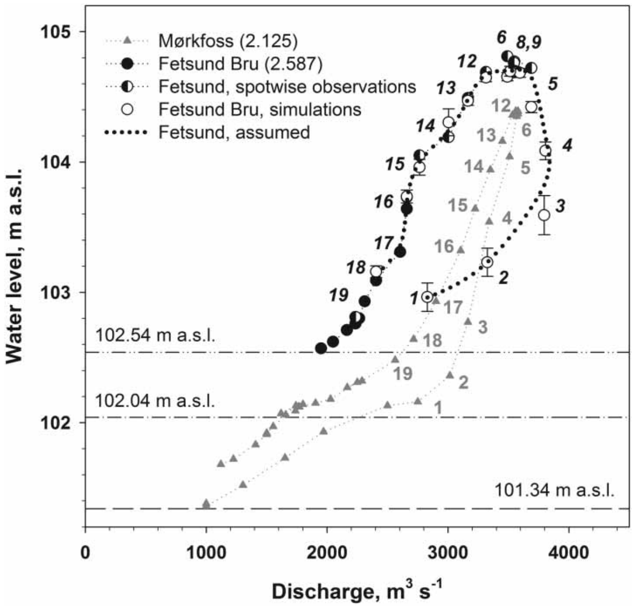

Figure 9 | Stage–discharge plot for the 1995 flood. Measured mean daily values for the Mørkfoss and Fetsund Bru stations, supplemented by spot observations of water levels and simulated values for Fetsund Bru. The numbers refer to the date during June 1995 (italics for Fetsund, roman for Mørkfoss).

modelling results implies that the height difference between Mørkfoss and Fetsund Bru ranged from 0.3 to 0.5 m both for the period 6–12 June 1995, when the maximum water level in the lake was reached (*cf*. Pettersson 2002), and for the falling limb of the flood hydrograph after 13 June.

For the rising limb of the flood wave on 2 and 3 June 1995, differences of more than 0.7 m between the mean daily water levels at Mørkfoss and Fetsund Bru occurred, corresponding to mean daily gradients of >0.10‰ between Fetsund and Årnestangen (Figure 10). This was the period during which water levels on the delta plain varied between 102.5 and 103.5 m a.s.l., such that the islands were successively inundated (Figures 6 and 11). The complex interactions between sinuous channels and the vegetated floodplain resulted in additional head losses, especially during the first phase of overbank flow. Figures 10 and 11

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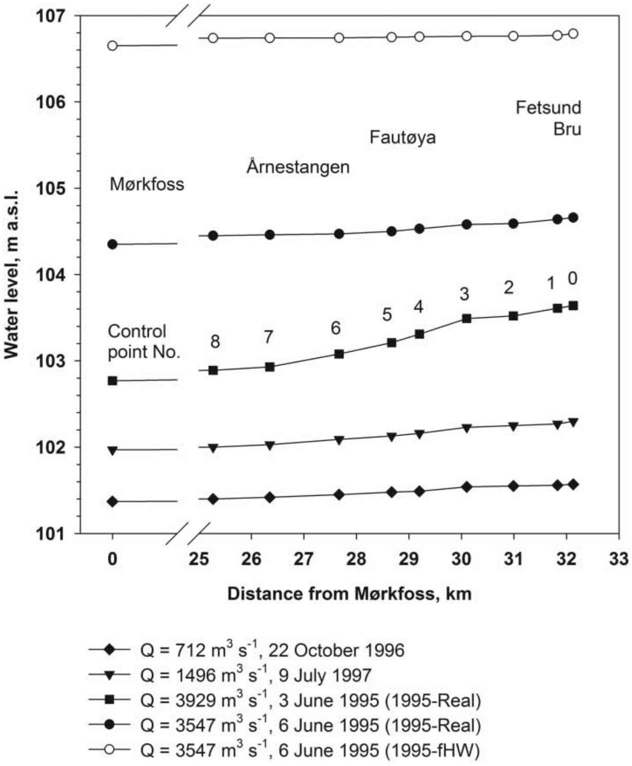

Figure 10 | Simulated gradients along the main delta channel between Fetsund Bru and Mørkfoss.

demonstrate that the gradients after inundation of the entire delta on 6 June were lower (about 0.036‰ between Fetsund Bru and Årnestangen) due to the massive increase in flow area and the slightly reduced incoming discharge. Even lower gradients were simulated for the maximum water level of the 1995-fHW scenario.

Flow and levee deposition phenomena for the investigated 1995 flood scenarios

The influence of regulation on levee deposition during the extreme flood of 1995 was studied by qualitatively comparing simulated flow patterns and overbank deposition for the 1995-Real and the 1995-fHW cases, respectively (Table 2). In the 1995-fHW scenario, all the islands became completely inundated until 2 June, i.e. prior to peak maximum discharge and sediment load. The real scenario (1995-Real) was characterized by high water level gradients and flow velocities at near bankfull discharge in the channels until 4 June. During the early stages of the flood, passive back-pounding occurred prior to overbank spillage while inundation directly from the channels was

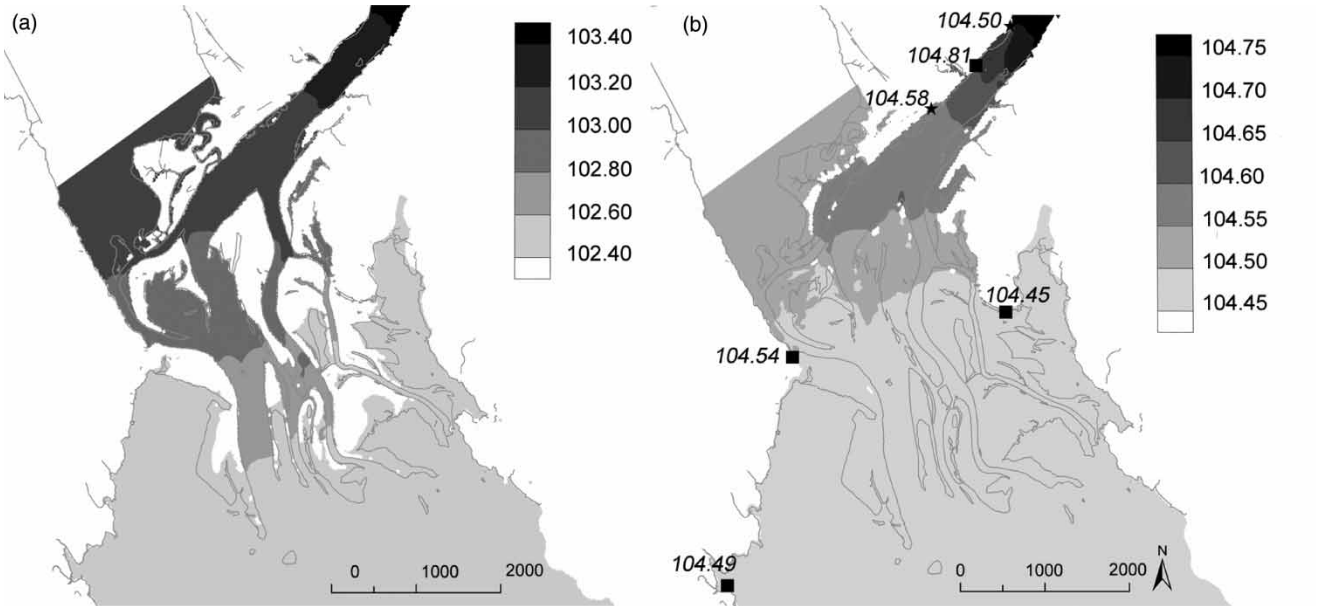

Figure 11 | Simulated mean daily water levels in the delta for 2 June and 6 June 1995 (1995-Real), compared with spot observations provided by the Norwegian Water and Energy Directorate for 6 June.

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restricted by the levees. Consequently, overbank flow and deposition were restricted to the lower parts of the islands at periods when the inflow of water and sediment were at their maximum. Comparatively high flow velocities and shear stresses within the channels resulted in high suspended sediment concentrations, providing material for levee deposition from the channel beds. The maximum water level was not reached before 6 June, when all the deltaic islands became almost completely inundated (Figure 11). The period of deposition on the upper parts of the islands was thus restricted to the water level culmination period between 6 and 11 June 1995.

The calculated sediment deposition on the islands for the 1995-Real and the 1995-fHW cases are shown in Figure 12, together with a difference map. The 1995-Real case resulted in levee-like morphologies along the channel banks at many locations, especially in the east and lower part of the delta plain. This phenomenon is similar to observational data (*cf.* Zinke *et al.* 2011). For the 1995-fHW case, the total area covered by levee-like morphologies was much smaller and restricted to the upper part of the delta plain. However, in the 1995-fHW case more widespread deposits of restricted thickness arose covering the entire island, as shown in the difference map (Figure 12c).

DISCUSSION

Water level regulation and morphological development of the islands

A comparison of the island map (Figure 5) and the elevation map (Figure 6) demonstrates that the highest elevations correspond to the oldest parts of the islands. These areas developed in part during the pre-1860 flood regulation regime, which was characterized by much higher flood water levels which attained levels greater than 109 m a.s.l. during extreme floods (Figure 2).

Figures 4(a) and 7 clearly indicate that the new post-1978 flood regulation rules have influenced water levels in the delta for all discharges greater than 1,500 m^3 s^{-1}, i.e. discharges lower than MAF levels (Table 1). Water levels associated with the MAF are expected to correspond to average bank elevations of mature delta channels developed during a given hydrological regime (Axelsson 1967; Dahlskog & Johansson 1977). Under the current regulation regime, they are maintained at about 1 m lower than under the previous regime (Figure 4(a)). The recently deposited tongues and levees in the southern part of the delta will therefore probably remain at distinctly lower elevations than the older islands as the channels continue to mature.

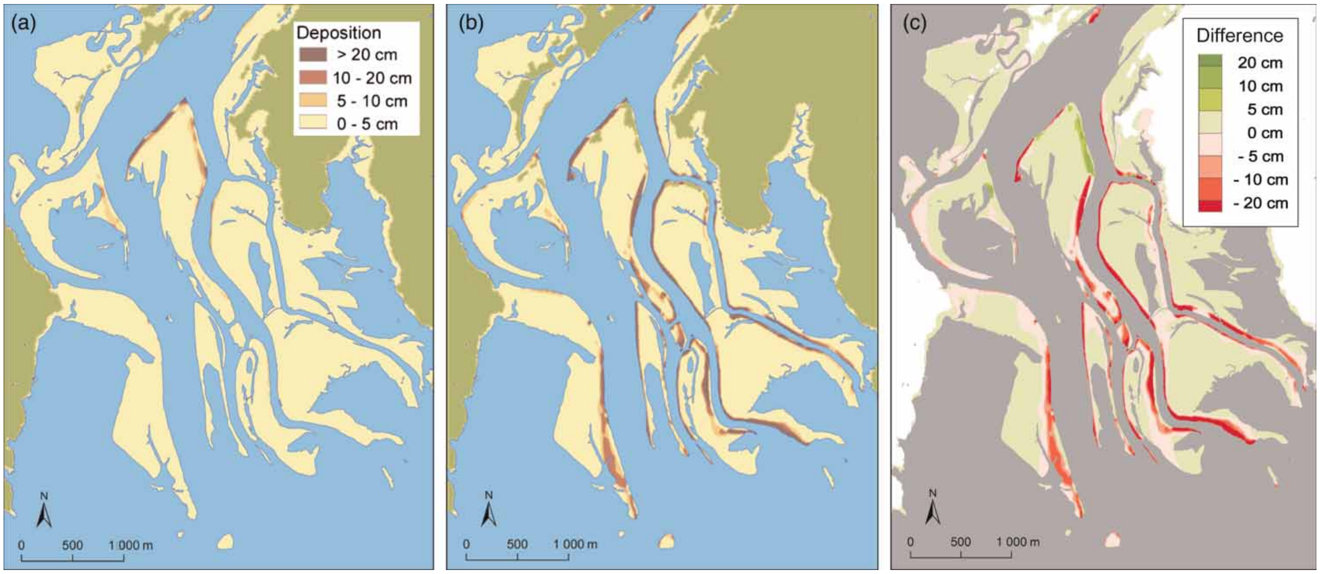

Figure 12 | Simulated overbank deposition (a) for the 1995-fHW case, (b) for the 1995-Real case and (c) difference map (1995-Real subtracted from 1995-fHW).

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The new flood regulation regime introduced after 1978 resulted in reduced flooding frequencies and shorter inundation periods for the deltaic islands when compared to the previous practice. Prior to 1978, the frequency of almost complete inundation of the entire delta ($W > 105$ m a.s.l.) was about 5–10 years. Today this happens with a frequency of 50–100 years, i.e. only during extreme floods (Figure 4(a)).

We believe that the simulated differences in depositional behaviour between the 1995-Real and 1995-fHW cases help to explain some of the tendencies observed in the morphological development of the delta, despite the relatively minor importance of overbank deposition related to extreme floods for the mean sediment budget. Our simulations demonstrated that reduced water levels during floods in the presence of the older islands extended the period of in-channel flow and promoted the deposition of levee-like features in the lower part of the delta plain. We expect similar behaviour in response to more frequently flooding events, including the MAF. In the juvenile part of the delta plain, subaqueous levee deposition constitutes part of the river mouth bar formation process. Lower water levels under given flood discharge conditions permit a larger volume of sediment to be transported to the channel mouths and contribute towards the acceleration of mouth bar maturation and subaqueous levee formation processes (*cf.* Edmonds & Slingerland 2007). This explains the increased number of lagoons which arise in response to a greater number of tongues and exposed levees.

The generally lower flow velocities and longer pondage periods associated with the previous flood regime (case 1995-fHW) favoured the deposition of thin layers of fine-grained sediment on the mature islands. Indeed, soil samples taken from the older island deposits at Fautøya, Kusand and Jushaugsand islands confirm the predominance of silt with grain diameters (D_{50}) between 0.02 and 0.05 mm at depths of 0.2–2 m. In contrast, the observed and simulated levee deposits in the Lake Øyeren delta in 1995 were characterized by fine sands (Zinke *et al.* 2011).

Deposition and erosion processes on the delta topsets

The morphological pattern developed on the delta plain is determined by the interplay of accumulation and erosion processes. It is known that bank erosion has been an important process on the delta plain during many decades and that it is influenced by factors such as frost action, wind, waves, vegetation, navigation and groundwater flow (e.g. Pedersen 1981; Bogen & Bønsnes 2002).

Since 1978, the maximum water level during floods has decreased. This may have resulted in increased levels of erosion in the upstream part of the delta. The observed decrease in the net land area increment rate from about 2 ha yr^{-1} to about 1 ha yr^{-1} since 1976 (Table 3) may be an indication of enhanced erosion processes. Moreover, new regulation practices after 1978 meant that the duration of very low water stages during winter were extended. Bogen & Bønsnes (2002) argued that this practice resulted in increased bank erosion because the river banks became more exposed to frost action and subsequent weakening of the soil structure.

The numerical model used to simulate the flood event accounted for fluvial (shear-stress induced) erosion, but not for mass failures. Our modelling results for the 1995-Real case suggest that there was only limited fluvial bank erosion of the cohesive islands during the 1995 flood, characterized by its short-lived high-gradient properties. Erosion was concentrated along the sandy beds of the channels, and the levee deposits probably originated mainly from material derived from the channel beds (Zinke *et al.* 2011). For the 1995-fHW case, the calculated levels of fluvial erosion were lower, as expected.

Flood-related bank (mass) failures of cohesive sediments associated with high pore-water pressure typically occur some time after the peak stage, during the inversion of groundwater flow from the bank towards the river. A major bank failure, probably resulting from this phenomenon, was recorded on the northeast margin of Fautøya island on 27 June 1995, more than two weeks after the peak stage at Lake Øyeren (Bogen *et al.* 2002). This event did not contribute to the sediment balance during the overbank flows, i.e. it was not relevant to the levee modelling study. However, such mass failures should be taken into account when considering the development of the delta as a whole.

Uncertainties and recommendations for future research

The morphological simulations of the 1995 flood event were influenced by many uncertainties related to model assumptions and boundary conditions, and were discussed in

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detail in Zinke *et al.* (2011). In particular, these refer to uncertainties concerning the model representation of natural vegetation, which were found to have a major impact on calculated overbank deposition patterns. Other limitations may have arisen from limitations in the resolution of the models imposed by the quality of the input data (Zinke *et al.* 2010). All these factors also affected the simulation of the hypothetical 1995-fHW scenario presented in this study. Our simulation of the 1995-fHW case was carried out by varying water levels only, whereas all other input data were kept constant. In practice, however, altered regulation practices have influence not only on isolated events, but also in the longer term. This means that the fluvial system would adapt to some degree, possibly leading to the creation of different boundary conditions in terms of factors such as the distribution of riparian plant communities, incoming sediment concentrations and grain size distributions on the river bed. Additional uncertainties resulting from these adjusted boundary conditions are unknown, and it is difficult to obtain data retrospectively regarding the situation prior to 1978.

The levee deposition during the 1995 flood appeared as a process where fine sand (mainly originating from the channel bed) was brought into suspension and deposited on the floodplain (Zinke *et al.* 2011). However, the channel bed changes immediately after the 1995 flood were not documented. This makes it very difficult to establish sediment balances of the distribution of the incoming sediments in the delta during the 1995 flood.

Future studies of the effects of water level regulation on morphological processes in the delta should therefore focus on detailed investigations and the recording of ongoing changes and their relation to current regulation practice and modifications thereof. More and better field data including water level measurements at different locations throughout the delta, high-resolution terrain models of both subaerial and subaqueous parts, vegetation maps and sediment data recorded at different times must be obtained in order to address these phenomena. Such data also provide essential input to future modelling studies simulating the morphological changes in the entire delta or effects of longer-term phenomena such as frequent floods and the winter lowering period. This will also require the development of modelling tools to simulate bank erosion resulting from mass failures.

CONCLUSIONS

Water level changes resulting from hydropower regulation has influenced water flow, gradients and sediment processes in the Lake Øyeren delta for about 150 years, resulting in a complex pattern of channels, islands and lagoons.

The flood regulation regime introduced since 1978 has affected water levels in the delta for all discharges greater than approximately 1,500 $m^3 s^{-1}$. Under current regulation practices, water levels during the MAF (about 2,200 $m^3 s^{-1}$) are maintained at about 1 m lower than during the previous regime. We assume that as the channels continue to mature, recently deposited tongues and levees in the southern part of the delta will remain at distinctly lower elevations than the older islands in the upper delta.

The influence of water level regulation on levee deposition during the extreme 1995 flood is demonstrated in the different depositional patterns resulting from two CFD modelling scenarios. Reduced water levels under extreme flood conditions in the presence of older islands prolonged the period of in-channel flow and promoted the development of levee-like morphologies in the lower part of the delta plain. In general, lower water levels for a given flood discharge accelerate mouth bar development and levee formation processes, especially in the distal part of the delta plain. This phenomenon explains some features observed in the morphological development of the delta, in particular the increased number of lagoons resulting from a higher proliferation of levees.

The morphological simulations were affected either by uncertainties inherent in the model assumptions or insufficient data regarding boundary conditions. Future studies addressing the effects of water level regulation on morphological processes in the delta must include the acquisition of more and better field data and the development of more advanced modelling tools.

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