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# 3D numerical modeling of morphodynamics in deltas due to hydro power regulation

Dresdner Wasserbauliche Mitteilungen

# 3D numerical modelling of morphodynamics in deltas due to hydro power regulation

Peggy Zinke, Nils Rüther, Nils R. B. Olsen and Raymond S. Eilertsen

The paper introduces a three-dimensional numerical model being able to calculate flow and morphological changes in a delta due to hydropower regulations. The numerical model solves the Navier-Stokes equations with the k-epsilon turbulence model on an unstructured grid. The same grid is also used to compute sediment transport by solving bed load equations together with the convection-diffusion equation for suspended material and the Exner equation. The grid is regenerated as the bed level changes. The bed movements over time can thereby be computed. The model has been tested on the delta of Lake Øyeren, the largest fresh water delta in northern Europe. The sediments of the three incoming rivers Glomma, Leira and Nitelva have formed a group of islands with lagoon-like structures covering an area of about 9 km$^2$. Following the onset of regulation in 1862, 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. The paper presents preliminary simulation results of the flow distribution in the delta and a comparison with measured discharge data, and it shows preliminary results of a bed change simulation. Detailed bed form movement was simulated and compared to multi-beam side scan sonar measurements.

## 1 Introduction

To assess the environmental impacts of the hydropower regulations, there is a need to evaluate the impact of changes in the operational directives for the power station on the processes of delta erosion and sedimentation. The current project develops a three-dimensional numerical model to simulate how the geomorphology of the delta in the reservoir changes over time, due to different regulations of the water level and the inflowing water and sediment discharge. The model was tested against field data from Lake Øyeren in Norway.

Lake Øyeren, covering approximately 85 km$^2$, is situated about 25 km east of Oslo in southern Norway (Fig. 1). The sediments of the three incoming rivers

Glomma, Leira and Nitelva have formed a group of islands with intermittent channels and lagoon-like structures covering an area of about 9 km$^2$. It is the largest freshwater delta in northern Europe. The lagoons, mud flats and grass meadows of this nature-protected area are an important habitat for waterfowl nesting and provide a staging area for bird migration. The delta was recognized in 1985 as a wetland of international significance under the Ramsar Convention.

The complete delta including the subaqueous sediments covers ca. 56 km$^2$ and was divided into four morphological units by Bogen and Bønsnes (2002): $1_)$ the delta plain composed of vegetated islands and intermittent distributary channels; $2_)$ the delta platform extending about 9 km downstream; $3_)$ the forest slope and $4_)$ the delta bottom set. The latter is situated ca. 3 km upstream of gauge station Øyeren 2. The current study focuses only on the delta plain.

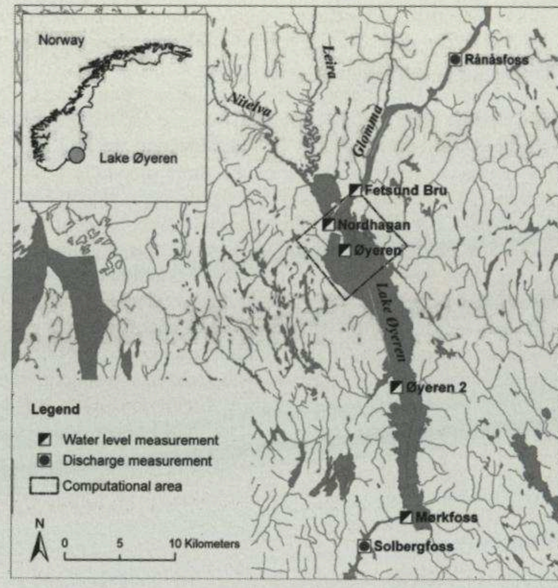


**Figure 1** Overview map with measurement stations

River Glomma accounts for the largest water inflow into the delta, since its basin represents 97 % of the delta's total catchment area of 40055 km$^2$. It delivers a mean-yearly suspended-load and bed load of 500 000 tons and 75 000 to 150 000 tons per year to the lake delta, respectively (Bogen et al., 2002).

Prior to the onset of river regulation in 1862, natural water levels in the lake varied by up to 14 m between spring flood and low stand during the winter, with a mean fluctuation of 8 m. In the beginning of the regulation, the need for flood control and a constant water level for navigation and lumber transport were the main incentives. During the 20th century further regulations were initiated for hydropower development. Since 1924, the water level has been regulated by the hydro power plant Solbergfoss (Bogen and Bønsnes, 2002).

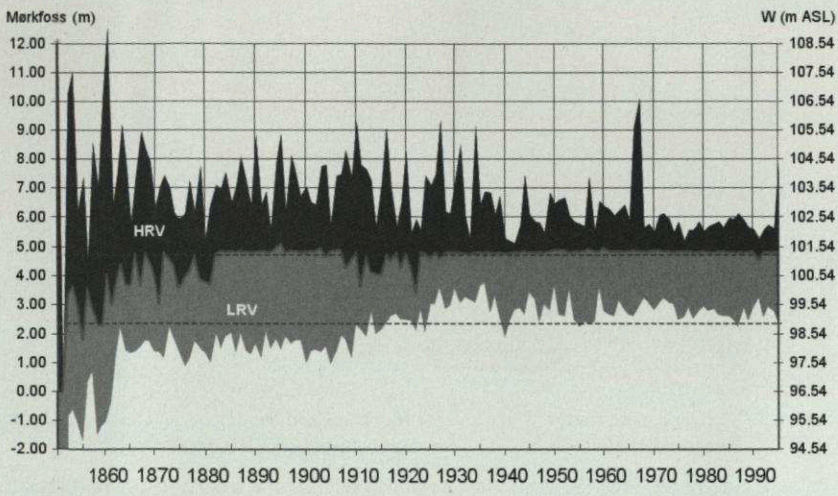


**Figure 2** Highest and lowest water levels at Mørkfoss 1852-1995; the grey line in the middle shows the median water level (GLB, 2000)

At present the water level rarely fluctuates more than 4 m between seasons (Fig. 2). Before regulation, sediments were transported and deposited at the delta front. As a consequence of regulation, sediments are being deposited on the delta platform at present. The deltaic sediments are up to 60 m thick in the study area, and are underlain or flanked mainly by glaciofluvial sands and gravels, and glaciomarine sands, silts and clays. The channel beds in the distributaries consist of mainly medium sand, with fine sand dominating in the lower Kusandråka and Nitelva channels (Bogen et al., 2002).

The regulation rules define an upper regulation limit (HRV) of 101.34 m ASL and a lower regulation limit (LRV) of 98.94 m ASL at gauge station Mørkfoss. During the summer and autumn season it is not allowed to decrease the water level below HRV or to increase it over HRV, as long as the discharge at Solbergfoss is lower than 1070 $m^3/s$. During the following winter months the water level is lowered, reaching a minimum in March/April before the spring flood (Fig. 3). Since 1978, new flood regulation rules after the opening of Bingsfoss hydro power plant have been used. According to them, the spillways at Solbergfoss have to be opened step by step for water levels higher than 102.04 m ASL at Mørkfoss, and they have to be completely open when the water level exceeds 102.54 m ASL.

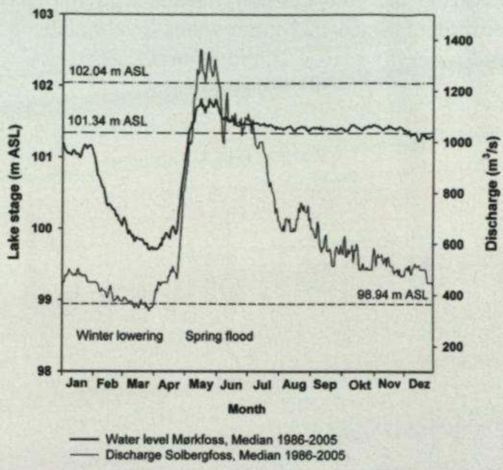


**Figure 3** Median curves for the water level at Mørkfoss and the discharge at Solbergfoss for the period 1986-2005, based on the daily values of NVE's database

An assessment tool for the environmental impacts of the hydropower regulations would have to combine the simulation of several physical processes. In the following the paper attempts to validate the flow model and the sediment transport routine when modelling alluvial roughness.

# 2 Database

## 2.1 Water level and discharge measurements

The water level of Lake Øyeren has been measured since 1852 at Mørkfoss, ca. 25 km south of the delta. Since 1998, this station has been supplemented by station Øyeren 2 in the middle of the lake. Gauge observations of the incoming river Glomma were made at station Fetsund Bru. In the delta, water level measurements were impeded by ongoing morphological changes, and the two stations Nordhagan and Øyeren were only intermittently used between 1994 and 2001 (Fig. 1).

Regular discharge measurements at Glomma have been conduced upstream of the delta at the hydro power station Rånåsfoss and 40 km downstream of the delta at hydro power station Solbergfoss. The discharge values of these stations are highly correlated because of the limited potential for discharge regulation, since the storage capacity of Lake Øyeren with a volume of 145 million $m^3$ is relative low compared to the annual inflow of about 22000 million $m^3$. The median discharge at Solbergfoss for the time series 1986-2005 was 550 $m^3/s$ and the median water level at Mørkfoss 101.37 m ASL.

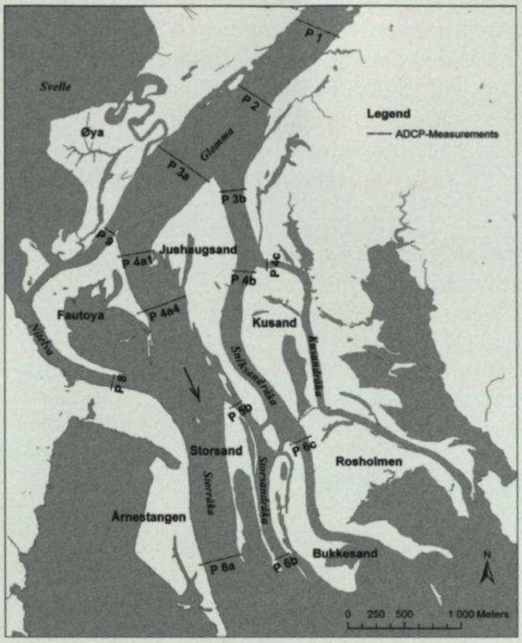


**Figure 4** Map of the delta plain showing the positions of the ADCP-measurements

Between 1996 and 1998, the Norwegian Water Resources and Energy Directorate (NVE) performed a series of Acoustic Doppler Current Profiler (ADCP) discharge measurements in the delta at four different times and flow situations. The position of the ADCP measurement profiles (P1 to P9) is shown in Fig. 4.

## 2.2 Bathymetry and bed changes

Bathymetry data of the delta gained by echo sounder profile measurements was available for the years 1974/80 (Pedersen, 1981) and 1985 (Bogen et al, 2002).

In 2004, the Geological Survey of Norway (NGU) started to conduct interferometrical sonar measurements to obtain high resolution bathymetrical data. For these investigations, which were conducted also in June 2007 and October/November 2007 (Eilertsen et al, 2008), the swath bathymetry system scanned the bed topography in a line perpendicular to the track of the survey vessel, typically with a width several times the water depth. The bathymetry was determined by measuring the phase differences between multiple receive staves within a transducer from a returning acoustic wave. Vessel speed was around 4 knots, and depending on the width of the swath, 16 to 30 pps were used, giving a reading for every 6 to 12 cm of the river bottom. Sound velocity profiles (SVP) were measured using a Valeport 650 SVP. The water level during the survey was measured digitally using a submerged Valeport 740 instrument that was calibrated with water level measurements at gauge station Øyeren 2. Differential GPS was used for positioning, giving an accuracy in the horizontal direction of ± 1 m. A gyroscope was also used for navigation. Multiple overlapping runs over the same area revealed an accuracy of the depth measurements in cm-dm scale.

To investigate the progression of alluvial bed forms, parts of the Kusandråka channel were measured twice in Oct/Nov 2007 with one day in between. The measured bed changes are displayed in Figure 8a.

## 3 The numerical model

### 3.1 Model cases and methods

The present study included:

a) the stationary flow modelling of the whole delta plain for mean flow conditions (flow situation during the ADCP discharge measurements from 21$^{st}$ to 23$^{rd}$ October 1996, water level at Mørkfoss 101.37 m ASL, discharge 712 $m^3/s$)

b) the transient modelling of bed changes during one day in a 50 m long part of the Kusandråka channel (flow situation during the side scan sonar investigations of Oct/Nov 2007).

In both cases, the flow field for the three-dimensional geometry was determined by solving the continuity equation and the Reynolds-averaged Navier-Stokes equations. The control volume method was used as discretisation method (Olsen, 2004). The Reynolds stress term was modelled by the k-ε turbulence model (Rodi, 1980). An implicit method was used for transient terms and the pressure field was computed with the SIMPLE method (Patankar, 1980). The free surface was modelled using the 3D pressure field.

For case b), the grid was also used to compute sediment transport by solving bed load equations together with the convection-diffusion equation for suspended material. The bed changes were computed from sediment continuity in the bed cell, as the difference between the inflowing and out flowing sediment fluxes. The defect was converted into a vertical bed elevation by dividing it by the submerged density of the sediments, 1320 kg/m³, to find the volume of the deposits for each time step. This volume was then transformed into bed level changes for the grid. The grid was regenerated as the bed level changed. Both the sedimentation and erosion processes were modelled using the same approach.

## 3.2 Grid

The computation of the discharge distribution in the delta (case a) was done with an unstructured grid (Olsen, 2000). The number of grid cells in the vertical direction varied according to the water depth, from a maximum of 20 in the deepest parts of the geometry (depth ca. 20 m) to 1 in the shallowest areas. A grid dependency study with mesh sizes (cell lengths) of 50, 25, 10 and 7 [m] was conducted (See Chapter 4). The number of active cells in the grid was about 1.3 million for the 10 m mesh.

For the calculation of the transient bed changes (case b), a three-dimensional, structured, non-orthogonal, vertically adaptive and curvilinear grid with a non-staggered variable placement was used. The grid consisted of 520 hexahedral cells in the stream wise, 220 cells in the lateral and 40 cells in the vertical direction, resulting in a cell size of approximately 0.22 m x 0.22 m x 0.065 m.

## 3.3 Boundary conditions

The upstream velocities as well as the incoming sediments were defined by a Dirichlet boundary condition. Wall law functions for rough boundary introduced by Schlichting (1979) were used for the side walls and the bed. In case a) for the flow modelling of the delta, the equivalent roughness height $k_s$ was calibrated as a constant value for all of the channels based on the water surface gradient. The roughness in the delta was mainly influenced by bed forms, in some regions also by vegetation. The optimal value found was $k_s = 0.5$ m for the flow situation of October 1996 (discharge 712 $m^3/s$, spatial mesh resolution 10 m). In case b) for the dune modelling, $k_s$ was set to 3 times the $d_{50}$. In the default configuration, the model computes the bed roughness as a function of the grain size distribution on the river bed. The boundary conditions at the bed for the sediment concentration were given by the sediment transport relations for bed load. Sediment transport was computed by the bed load transport formulas of van Rijn (1984) applied individually for each size fraction.

For case a), there was no bathymetry data available for the year of the ADCP-measurements. Therefore the bathymetry data set for the model was a combination of the 2004 bed level data from NGU, a digital elevation model from 1995 and hand-made interpolations in highly-changing areas.

# 4 Results of the numerical simulation

## 4.1 Flow distribution in the delta

Fig. 5 shows the computed versus measured discharges for the profiles P1 to P9 for the flow situation of October 1996. The relative errors were obtained by taking the difference between the numerical and the average of the measured discharge values and then dividing the results by the average of the measured values.

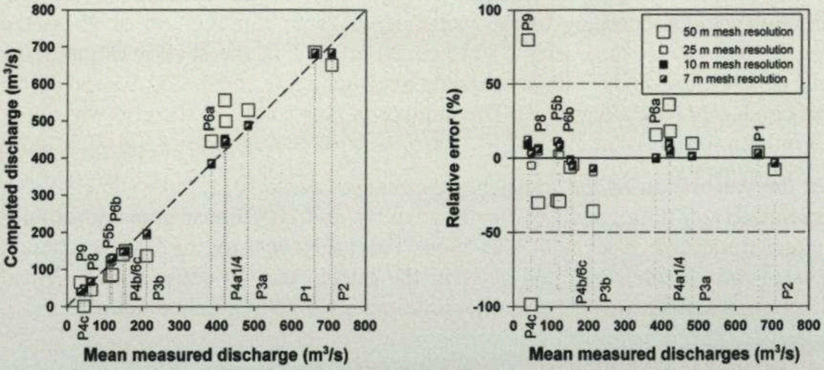


**Figure 5** Computed versus measured discharges for the flow situation from October 1996, computed with different spatial grid resolutions

In the grid dependency study, the 50 m grid resolution appeared evidently too coarse, producing cut-offs in small channels (profile P4c) or imperfect reproductions of island plan forms especially at bifurcations (profile P9). As expected, the accuracy of the computed discharges in the delta channels increased with successive grid refinement. For the 10 m grid, the relative errors in all channels were less than 11 %. The 7 m mesh gave slightly different values compared to the 10 m mesh, but no general improvement. The missing model sensitivity to further grid refinement reflects the inaccuracies of the bathymetry data set, which did not exactly belong to the flow situation to be modelled. Hence, the mesh resolution and the quality of the results were restricted by the quality of the input data.

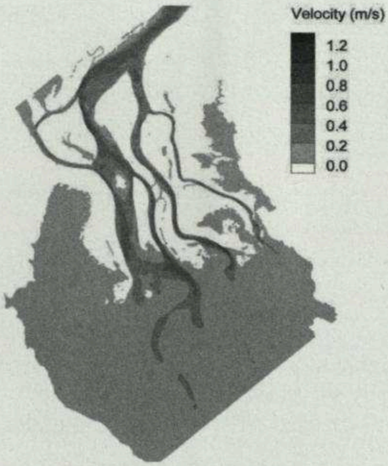


**Figure 6** Computed flow velocities on the water surface for October 1996: Lake stage 101.37 m ASL at Mørkfoss, Discharge 712 $m^3/s$; spatial mesh resolution 10 m

Fig. 6 shows the plan view of the calculated surface velocities in the delta. For discharges of ca. 700 $m^3/s$ and water levels around the upper regulation limit, these flow velocities were between 0.2 and 0.6 m/s in the most channels of the delta. Some known erosion areas like the east bank of Fautøya were characterized by the highest computed flow velocities.

## 4.2 Flow and sediment transport over 3D dunes

Fig. 7a shows a two-dimensional contour plot of the longitudinal velocities over a row of three-dimensional dunes. An accelerated water body over the crest of the dunes is visible. Here the mean flow velocity is above 0.75 m/s, whereas on the lee side of the dune, the mean velocity decreases to 0.3 m/s. Classical flow separation behind a single dune could not be identified. One possible reason is that the grid is very coarse compared to the size of the reattachment bubble, causing false diffusion. Another possible reason can be the fact that for dunes with a lee angle lower than 11° no fully recirculation zone occurs. Classical approaches (Engel, 1981) and recent laboratory experiments (Coleman et al, 2006) to determine the length of the reattachment bubble over two dimensional dunes showed that for dunes with a lee angle of 20 to 25° the length of the bubble is 5x the height of the dune.

Fig. 7b shows the computed turbulent kinetic energy in the same longitudinal plots as the mean velocities. One can see a peak of the shear stress at the crest of the dune, whereas low values are observed at the bottom of the lee side of the dune.

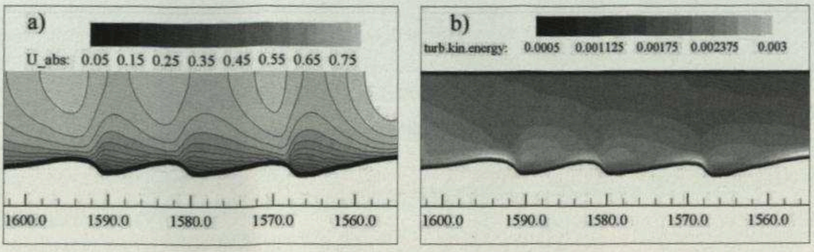


**Figure 7** a) Simulated velocity field [m/s] and b) turbu-lent kinetic energy [N/m$^2$]

Transient bed changes of the initial geometry were simulated with the previously described numerical model. For the simulation, a transient time step $\Delta t = 10$ sec and a roughness $k_s = 0.0012$ mm was chosen. The bed roughness was therefore defined by the grain roughness equal to $3xD_{50}$. The form roughness of the dunes was discretised directly in the grid of the CFD model.

The initial geometry was taken from the high resolution interferometric sonar scan. The simulated results were tested against another measurement series taken 24 hours later. The resulting bed changes after 24 hours are shown in Figure 8b.

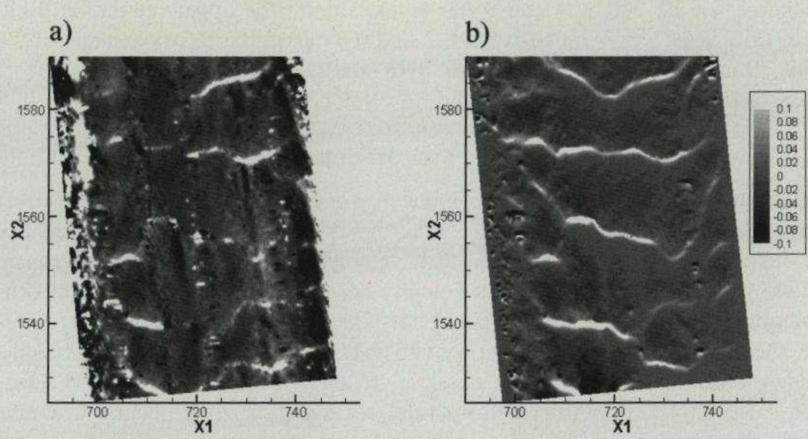


**Figure 8** Comparison of measured (a) and simulated (b) bed changes.

The general agreement between measurements and computations was good. Differences were especially observed near the river banks and might be caused by vegetation. It is known that macrophytes like *Potamogeton perfoliatus*, *P. gramineus*, *Ranunculus peltatus* and *Myriophyllum alternifolium* were typical species of the shallower areas at the river banks (Rørslett, 2002). Their local presence was not included in the model so far.

# 5 Conclusion and further research

A three-dimensional numerical model was successfully applied to compute the flow distribution in a complex delta geometry using an unstructured grid. The computations were compared with ADCP field measurements. Already for a spatial mesh resolution of 25 m, good agreement was found between computed and measured discharge distributions in the different branches of the delta. Theoretically, finer meshes would introduce less false diffusion in the results and resolve a larger part of the bed form spectrum, improving the accuracy. However, a grid resolution finer than 10 m gave no further improvement because of the limited accuracy of the bathymetry data set, which did not exactly pertain to the date of the flow measurements. The advantages of 3D numerical models will only reach its full potential with a corresponding high spatial and temporal resolution of the input data. In the future, this can be achieved by using airborne laser hydrography systems, allowing Lidar measurements of both the water depth and the island topography of the delta at the same time.

The flow and sediment transport over naturally formed, three-dimensional dunes were simulated using a numerical model for a single channel of the delta. Although the measured bed changes were small, dune characteristics as well as dunes migration speed could be identified from the data. The comparison between the numerical model and the field data shows that it is possible to compute migration of dunes in a natural river bed. However, to make a complete validation of the numerical method, simulation with a finer grid and a higher order discretisation scheme should be performed.

Further research will focus on the influence of vegetation on flow and sedimentation processes in the delta, especially during floods. Another task is the bank erosion at specific locations to evaluate the long term morphological changes in the delta.

One of the objectives of the current project is to implement physical processes like steady and unsteady three dimensional flow processes, bank erosion, sediment deposition in vegetated areas, and macro roughness development due to bed forms, into the numerical model in order to investigate their combined influence on the development of the delta. All of these processes are directly or indirectly influenced by the hydropower regulation.

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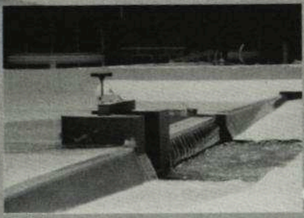

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