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3D modelling of the flow distribution in the delta of Lake Øyeren, Norway

Peggy Zinke, Nils Reidar Bøe Olsen, Jim Bogen and Nils Rüther

ABSTRACT

A 3D numerical model was used to compute the discharge distribution in the channel branches of Lake Øyeren's delta in Norway. The model solved the Navier–Stokes equations with the k–ε turbulence model on a 3D unstructured grid. The bathymetry dataset for the modelling had to be combined from different data sources. The results for three different flow situations in 1996 and 1997 showed a relative accuracy of the computed discharges within the range of 0 to ± 20% compared with field measurements taken by an ADCP at 13 cross sections of the distributary channels. The factors introducing the most error in the computed results are believed to be uncertainties concerning the bathymetry. A comparison between the computational results of the older morphology data from 1985–1990 and the model morphology from 1995–2004 indicated that morphological changes in this period had already had consequences for the flow distribution in some channels. Other important error sources were the inevitable use of averaged water level gradients because of unavailable water level measurements within the delta.

Key words | CFD modelling, delta, flow distribution, Øyeren, 3D numerical model

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INTRODUCTION

Deltas form where rivers enter standing bodies of water such as the sea, lakes and reservoirs. Based on the forces and processes determining the delta morphology, they are often classified into tide-dominated, wave-dominated and fluvial-dominated deltas (Galloway 1975). Wright (1985) subdivided deltas into several physiographic zones, among them the distributary network on the delta plain. It is characterized by a number of bifurcating channels which carry sediment to the delta front. The number of these distributary channels can be predicted using the maximum monthly discharge (Syvitski 2005).

In Scandinavia, some fluvial-dominated deltas are situated on elongated freshwater lakes. Typical morphological features of their distributary networks are bifurcations, confluences and river bends (Dahlskog 1966; Axelsson 1967). These structures implicate complex turbulent flows. As a consequence, the computation of the flow distribution between the distributary channels is not trivial. Some existing approaches are based on empirical and semi-theoretical methods for the calculation of the discharge distribution among the various delta channels (Mihajlov *et al.* 1986; Andrén 1994).

With the increasing power of computers, it has become feasible to use 3D numerical flow models for calculation of the flow distribution in deltas. These models have been successfully used for natural rivers with single complex flow features (e.g. Dargahi 2004; Fischer-Antze 2005), although there is little experience with the use of these models in delta applications.

The objective of the present study was to therefore test the performance of a 3D numerical flow model for the computation of the flow distribution between the channel branches of a fluvial-dominated delta. For this investigation, the delta of Lake Øyeren in eastern Norway was chosen. This delta is the largest freshwater delta in Northern Europe and an important nature protection area. The water level of

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the lake is regulated by a hydropower plant, and there is a need to evaluate changes in the operational directives for the power station on the processes of both delta erosion and sedimentation. For that reason, much environmental data about the delta, including bed sediment mappings and discharge measurements, was acquired within a large multidisciplinary project led by Berge (2002). The available bathymetry and terrain surveys were, however, conducted at different times and with different methods. The uncertainties arising from that are addressed in this paper by means of comparative computations.

FIELD DATA

The area of investigation

Lake Øyeren, covering approximately 85 km^2, is situated about 25 km east of Oslo, Norway. The sediments of the three incoming rivers, the Glomma, Leira and Nitelva Rivers, have formed a group of islands with lagoon-like structures. The complete delta including the subaqueous sediments covers ca. 56 km^2 and was divided into several morphological units by Bogen & Bønsnes (2002): the *delta plain* composed of vegetated islands and interjacent distributary channels, the *delta platform* extending approximately 9 km downstream, *the foreset slope* and the *bottom set beds* of the deep basin (Figure 1).

The lagoons, mud flats and grass meadows of the delta plain are important habitats for waterfowl nesting and provide a staging area for bird migration. The delta was protected in 1975, and in 1985 it was recognized as a wetland of international significance under the Ramsar Convention (UNESCO 1994).

Lake Øyeren has been affected by water level regulation since 1862. In the beginning, 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 Solbergfoss hydropower plant. The actual rules for the regulation of Lake Øyeren were enacted in 1934 and updated in 1981 (GLB 2000). They include year-round water level regulations according to upper and lower regulation limits and flood regulations of water level and discharge.

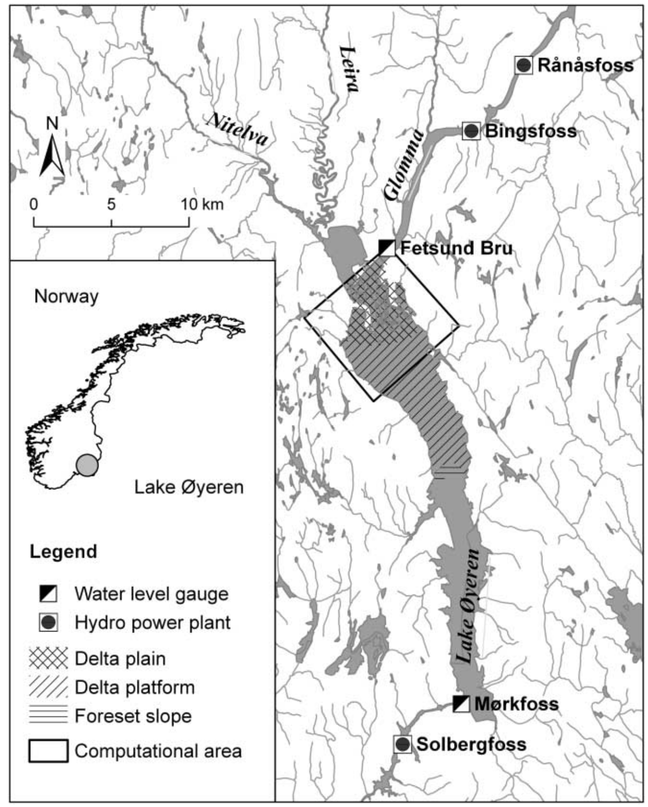

Figure 1 | Overview map with measurement stations.

Water level and discharge data

So far, the Glomma River accounts for the largest inflow into the delta, since its basin represents 97% of the delta's total catchment area of 40,055 km^2 (Bogen *et al.* 2002). Regular discharge measurements at Glomma were conducted upstream of the delta at the Rånåsfoss and Bingsfoss hydropower stations and downstream of the lake at the Solbergfoss hydropower station (Figure 1). The discharge values of these stations were highly correlated because of the limited potential for discharge regulation since the storage capacity of 145 million m^3 at Lake Øyeren is relatively low compared to the annual inflow of approximately 22,000 million m^3. For the time period from 1986–2005, the mean discharge at Solbergfoss was 700 m^3/s.

Between 1996 and 1998, the Norwegian Water Resource and Energy Directorate (NVE) conducted a series of Acoustic Doppler Current Profiler (ADCP) discharge measurements in the delta. The position of selected ADCP measurement profiles is shown in Figure 2. For the present study, three different flow situations with water levels above the upper regulation limit were chosen. The results of the measurements are shown in Table 1.

The ADCP raw data was analysed using the program AGILA (Adler & Nicodemus 2000). Each of the observed discharges for P1–P9 in Table 1 is the mean of 2–8 ADCP moving-vessel transects and represents the average discharge over the time period required to make the measurements (typically between 5–30 min). The standard deviations of the measurements ranged between 1–7%, and only 2 of the 39 measurements exceeded a standard deviation of 4%.

Since 1852, the water level of Lake Øyeren has been measured at Mørkfoss, which is approximately 30 km south of the delta plain (Figure 1). For the time period from 1986–2005, the median water level at Mørkfoss was 101.37 m asl. Between 1995 and 2004, gauge observations of the incoming Glomma River were also made at the station at Fetsund Bru (Bridge). However, for the years 1996 and 1997, the database of this station provided mean daily values only for specific days. For the time period when the ADCP measurements were conducted, no data from this gauge was available. As a result, the water level for the Fetsund Bru in Table 1 was estimated based on typical water level gradients between Mørkfoss and the Fetsund Bru for the given discharges. The data of another temporarily driven station (Nordhagan) was not used for this study because of uncertainties about the accuracy of the absolute reference height.

The ADCP measurement campaigns usually took two to three days each, and the water level in Table 1 is the water level of the first day of the campaign when most of the profiles were taken. Figure 3 shows the hydrograph during the measurements. The conditions changed only slightly during the campaigns of October 1996 and July 1997. For the measurement series of June 1997, two of the cross sections (P6a and P6b) were measured 5 days later on 30 June when the water level was 23 cm higher and the discharge had increased by approximately 11%. These values are set in brackets in Table 1.

Table 1 | Discharge distribution within the delta due to ADCP measurements on different dates. In square brackets: delayed measurement

Date	21–23 October 1996	24–25 [30] June 1997	9–10 July 1997
Lake stage (m asl)			
Mørkfoss	101.37	101.49	101.97
Fetsund Bru*	101.57	101.82	102.30
Measured discharges (m^3/s)			
P1	662	1,024	1,475
P2	708	1,032	1,460
P3a	482	724	1,022
P3b	212	313	446
P4a1/4	423	639	889
P4b	156	233	339
P4c	46	73	96
P5b	114	178	210
P6a	385	[683]	778
P6b	120	[205]	234
P6c	149	233	297
P8	64	92	141
P9	36	84	112

*Water levels derived from mean gradients.

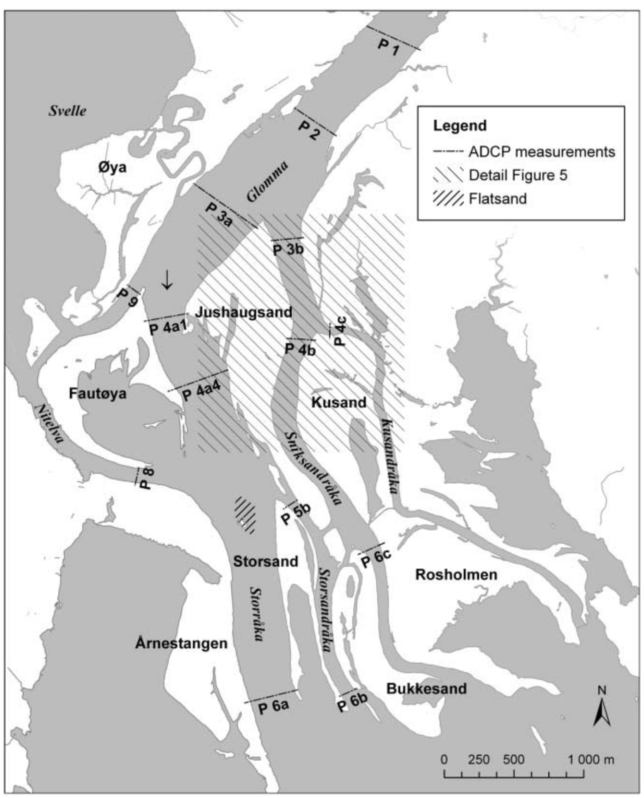

Figure 2 | ADCP measurement profiles in the delta of Lake Øyeren.

Bathymetry data

Pedersen (1981) constructed a bathymetric map for the river reach of the Glomma and Storråka within the delta by combining echo sounder data from 1974 and 1980. Another dataset based on echo sounder profile measurements provided contour lines for the entire lake including the delta for the period from 1985–1990 (NVE 2007). In 2004, the Geological Survey of Norway (NGU) conducted interferometrical sonar measurements to obtain high resolution bathymetrical data. This dataset provided data for the deeper parts of the channels in the delta, but not for the shallow water zones (Eilertsen *et al.* 2005).

The three different datasets were analysed using a geographical information system (GIS). Figure 4 illustrates typical features of these datasets from the Storråka channel that point to some general tendencies of local morphological changes, e.g. progressing erosion at the northeast part of Fautøya Island with a side erosion rate of between 0.5 to 5–6 m/yr (Bogen *et al.* 2002). They may also indicate bed accretion from 1974–1980 (after an extreme flood in 1967) to 1985 and later, before another extreme flood in 1995 caused some new erosion. The floods of 1967 and 1995 had a recurrence interval of 50–100 years according to Erichsen (1995).

However, comparisons and plausibility tests using GIS demonstrated that the differences between the datasets are probably not only caused by morphological changes, but to a high degree also reflect uncertainty due to different and partly unknown measurement techniques, sample designs and compilation methods over the 30-year period. This made the detection of temporal changes and therefore a temporal interpolation very difficult–a problem which has also been noted in other areas with a changing morphology (Van der Wal & Pye 2003).

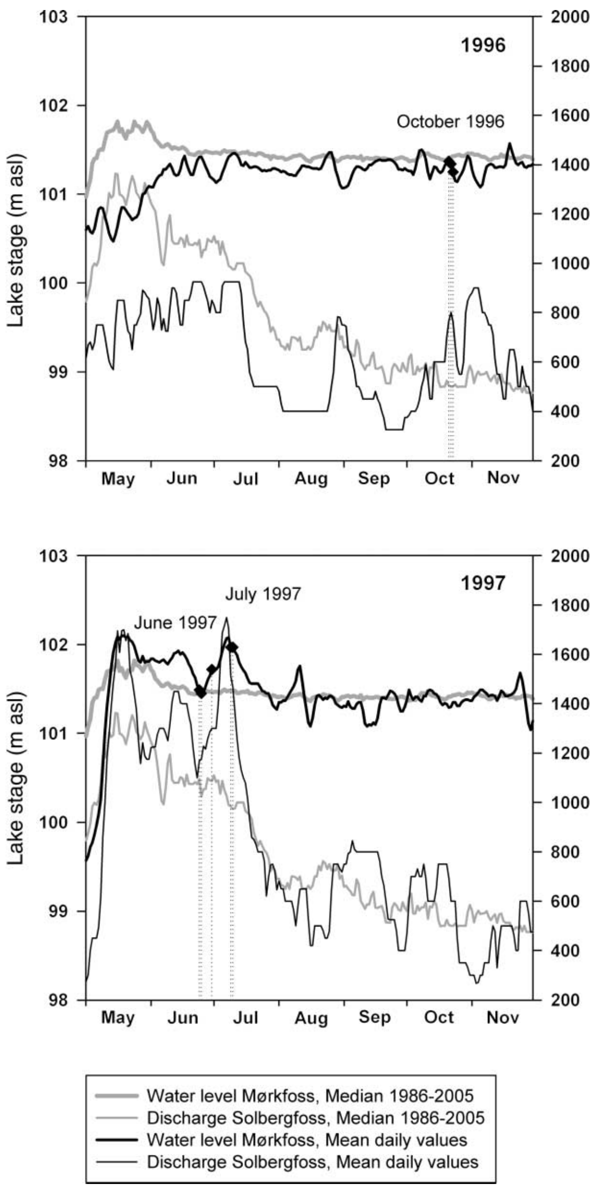

Figure 3 | Hydrograph during the measurement campaigns from 1996 and 1997 based on NVE's database.

METHODS FOR NUMERICAL MODELLING

Model and boundary conditions

The three-dimensional numerical finite-volume model SSIIM developed by Olsen (2009) was used in the current study. It solved the Reynolds-averaged Navier–Stokes equations for each cell and used the standard $k-\varepsilon$ model with the five constants as recommended by Rodi (1984) for turbulence closure. The pressure term was computed with the SIMPLE method (Patankar 1980). The free water surface was calculated using the 3D pressure field which referred to a given reference point at the inflow or outflow boundary. The model applied wall laws (Schlichting 1979) for rough boundaries in the cell bordering the channel boundary. At the water surface, zero-gradient boundary conditions were used for all variables with the exception of the turbulent kinetic energy which was set to zero.

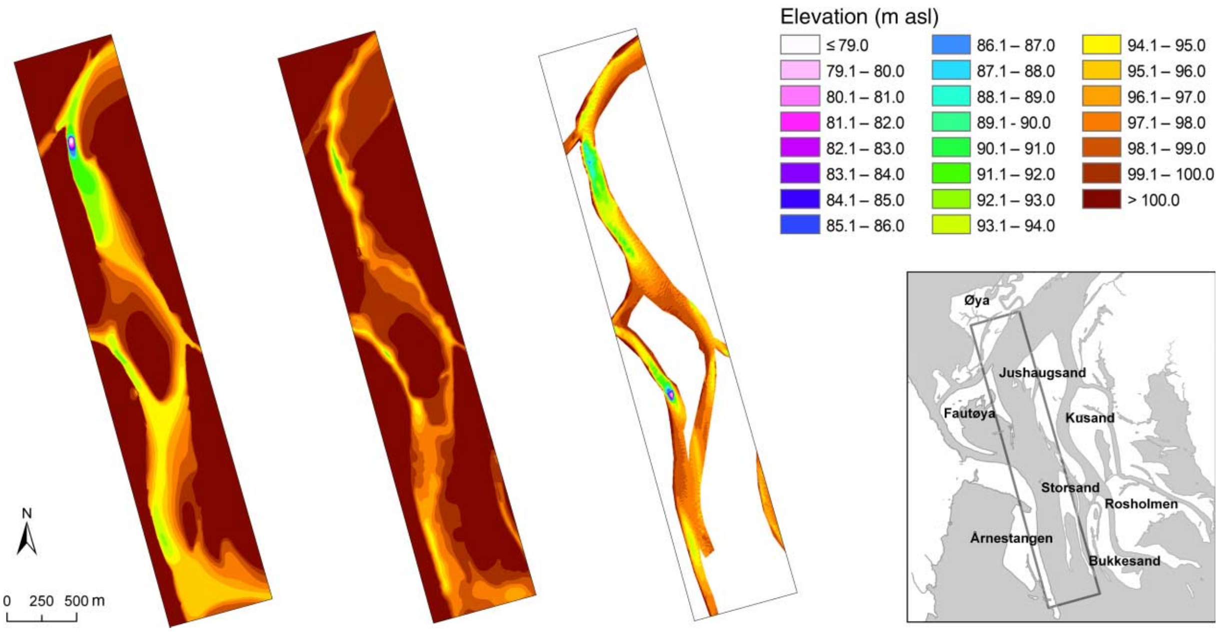

Figure 4 | Bed levels of the Storråka channel during various periods: 1974–80 (Pedersen 1981, left), 1985–90 (NVE 2007, middle) and 2004 (Eilertsen *et al.* 2005, right; only available for the shown corridors).

The model simulations were conducted as stationary flow computations for the three flow situations shown in Table 1. The discharge values were taken from the ADCP measurements and given as constant values at two inflow areas (Glomma and Svelle) and one outflow area at the southeast model border. The numerical discharge data were extracted from the computation results at the same locations as the field measurements.

In addition to the line-like ADCP profiles, there was no bathymetry data available for the years 1996–1997. A correlation analysis between the bed levels measured during the campaign of June 1997 and the documented bed levels for 1985–1990 (NVE 2007) and 2004 (Eilertsen *et al.* 2005) showed a better correlation with the data from June 2004. In general, the bathymetry for the numerical modelling was therefore based on the assumption that the morphological channel data from 2004 represented the situation between 1996 and 1997 better than the basic map from 1985–1990 (see Figure 4), and that this morphology can be used together with an adaption due to the documented rates of change in highly changing areas. The final morphology data set "Model morphology 1995–2004" was a combination of the 2004 bed level data from NGU for deeper channels of the delta plain, NVE's digital bed level data 1985–1990 (NVE 2007) for parts of the delta platform, a digital elevation model from 1995 for elevations higher than 100.12 m asl, handmade interpolations northeast of Fautøya and GIS-based nearest-neighbour interpolations in between. The channels of the delta were mostly between 2–8 m deep, and at some sites up to a depth of 20 m.

Roughness

The channel beds in the distributaries consisted mainly of medium sand ($D_{50} \approx 0.4$ mm) whereas fine sand ($D_{50} \approx 0.1$ mm) dominated the Nitelva River and lower Kusandråka channels (Bogen *et al.* 2002). The side scan sonar investigations by Eilertsen *et al.* (2005, 2008) showed a large range of bed forms with different scales, reaching from 3–53 m in length and from 0.14–2.24 m in height, while bed forms with lengths between 10–20 m occurred most frequently. Consequently, the roughness in the delta was mainly influenced by the bed forms.

The equivalent roughness heights k_s (Nikuradse 1933) for sandy rivers with bed forms were often taken as the mean bed form heights (Dittrich 1998). For numerical models with a spatial resolution finer than the length of the largest bed forms, the roughness effects of the bed forms are segregated depending on the mesh size, with sub-grid scale roughness representing the use of the wall function approach and larger-scale roughness elements are being incorporated within the model mesh (Nicolas 2001).

In the present study, the equivalent roughness heights k_s were separately calibrated for the three flow situations as constant values for all of the channels based on a 10 m mesh and the water surface gradients between Mørkfoss and Fetsund Bru, as shown in Table 1. The optimal values found were: $k_s = 0.5$ m for the flow situation of October 1996 (overall discharge 712 m^3/s), $k_s = 0.2$ m for the flow situation of June 1997 (overall discharge 1,036 m^3/s) and $k_s = 0.1$ m to 0.2 m for the flow situation of July 1997 (overall discharge 1,496 m^3/s). A decreasing roughness height with increasing discharges agreed with the results of some other studies, e.g. Paarlberg (2008). The calibrated roughness heights have to be interpreted as rough upper estimations since the real water level gradients during the

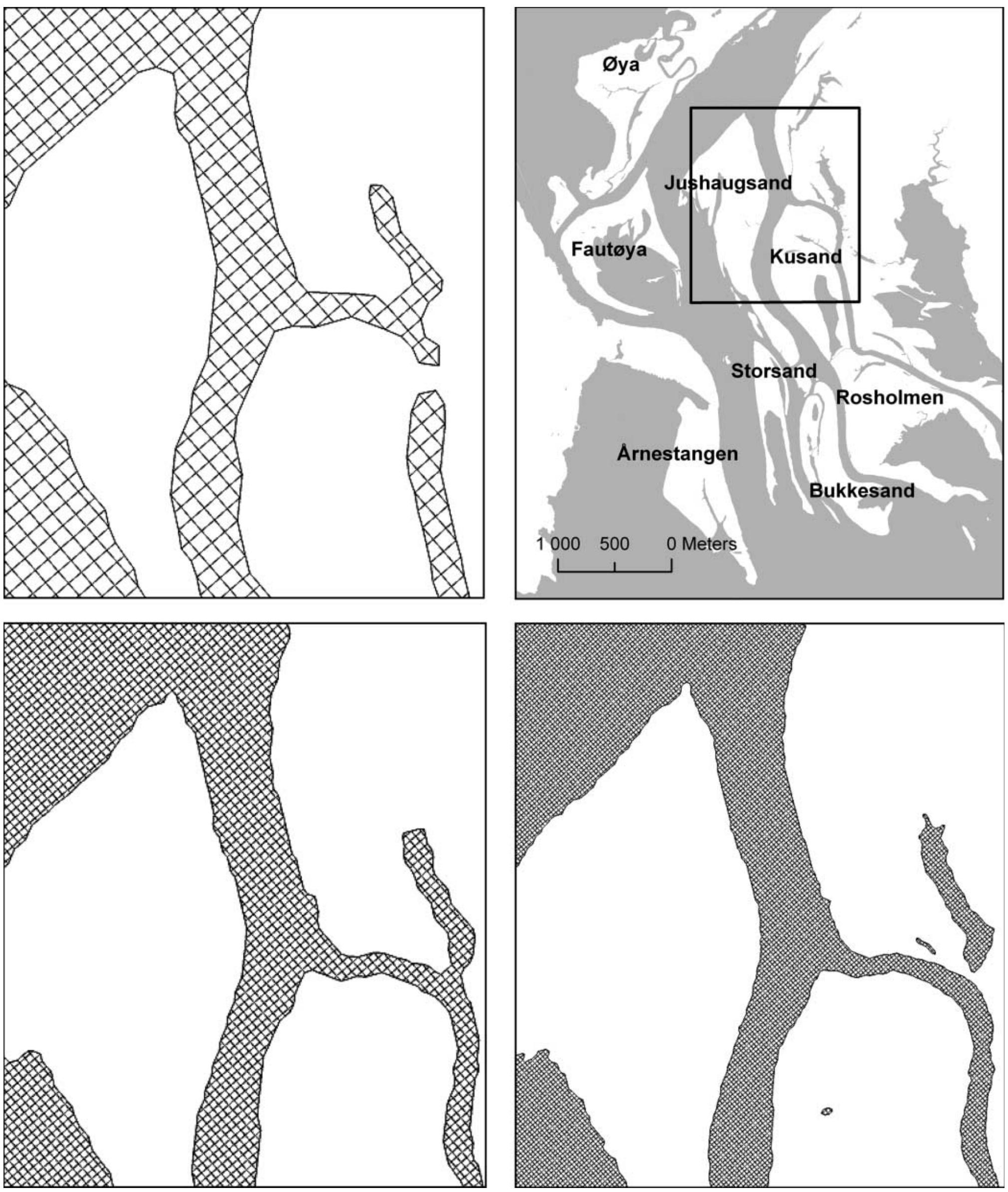

Figure 5 | Spatial structure of the grid for a grid resolution of 50 m, 20 m and 10 m and a water level of 101.47 m asl.

measurements were not known, and the calibration was done assuming a negligible gradient between the outflow region of the model and the Mørkfoss gauge station.

Grid

The grid algorithms were based on a 2D structured grid covering the entire delta plain, both dry and wetted areas (50 km^2, "computational area" in Figure 1). In this grid, the water depth was computed in each cell based on the bathymetry and the water level, and varying numbers of 3D grid cells were added in the vertical direction depending on the depth. The cells were then connected forming an unstructured grid, and afterwards an algorithm was used to smooth the edges of the grid. The shape of the cells on the border between water and dry land were changed as a function of the positive and negative depths of the corners. In dry areas, no 3D cells were generated. A detailed description of the grid algorithms was given by Olsen (2003).

A grid dependence study was carried out with spatial mesh resolutions of 50, 20, 10 and 7 m for the flow situation from October 1996 (see the following section). If not otherwise mentioned, the results presented in this paper were computed with a horizontal mesh resolution of 10 m and a maximum of 10 or 20 cells vertically, resulting in a vertical number of grid cells between 6–10 in the larger and 4–6 in the smaller channels for the lowest computed water depth. The maximum vertical cell numbers were only applied locally at some deeply eroded sites. The number of active cells in the grids was approximately 1.3 million for a mesh size of 10 m and the given water levels. The computational time for the calculation including the free water surface for the 10 m mesh was approximately 17 h. The computations were run on a 16-processor 1.9 GHz PowerPC node of the IBM P575 cluster at the Supercomputing Centre of the Norwegian University of Science and Technology.

RESULTS AND DISCUSSION

Grid dependence study

Figure 5 shows the spatial structure of the grid for a mesh resolution of 50, 20 and 10 m for the flow situation from October 1996. The 50 m grid resolution evidently appeared to be too coarse, producing a cutoff in the Kusandråka channel which is locally only 40 m wide.

Figure 6 presents the computational results for different grid resolutions for the flow situation in October 1996, which was chosen for the grid dependence study. The relative errors were obtained by taking the difference between the numerical and the average of the measured

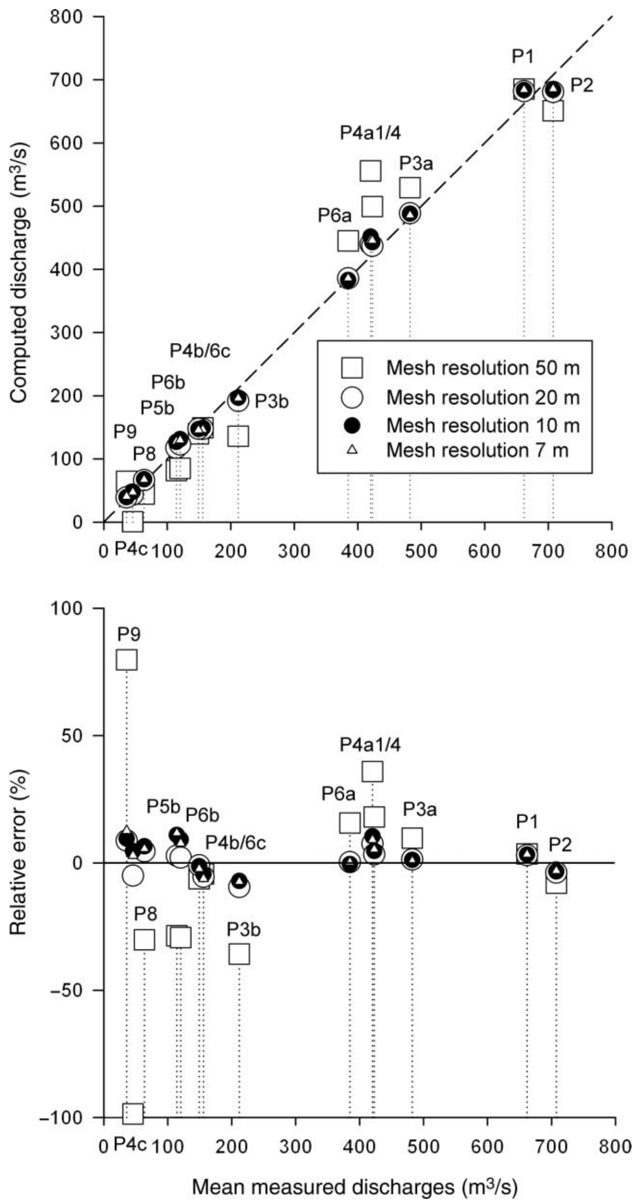

Figure 6 | Computed versus measured discharges and relative errors for the flow situation from October 1996 for different spatial grid resolutions (fixed water surface at 101.47 m asl, $k_s = 0.5$ m, maximum of 10 vertical cells).

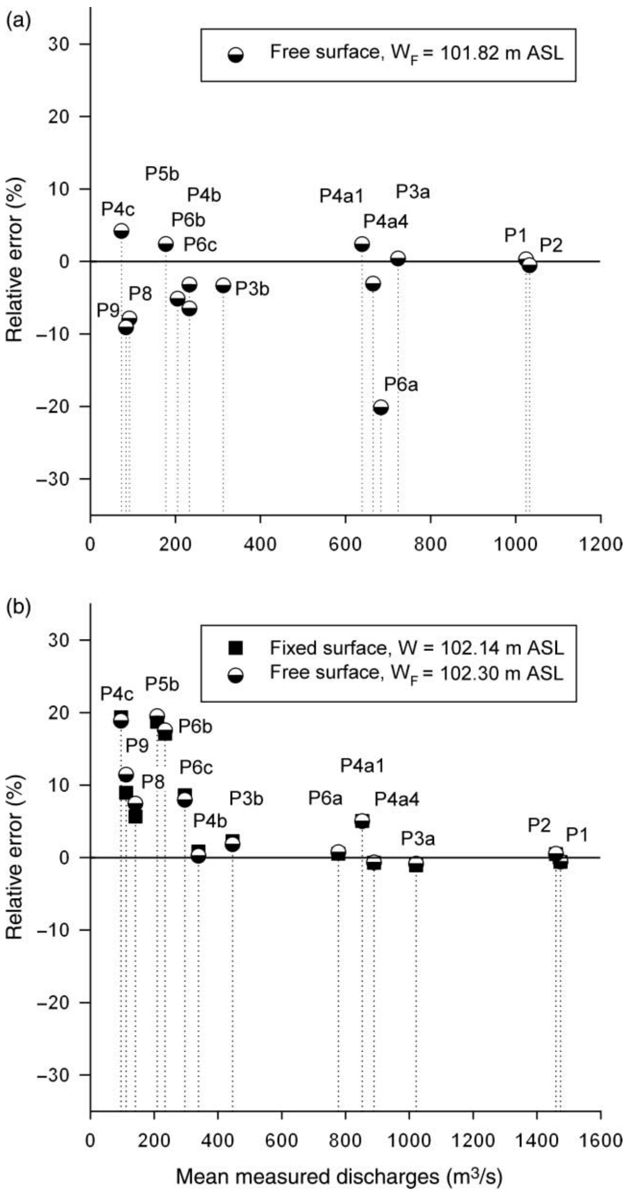

Figure 7 | Relative errors of the computed discharges for the flow situation from (a) June 1997 and (b) July 1997; $k_s = 0.2$ m, a maximum of 20 cells in vertical direction; W_F = water level at Fetsund Bru.

discharge values and then dividing the results by the average of the measured values.

For the 50 m mesh, the relative errors were between ± 4 and ± 36% in the large channels and reached ± 80–99% in some small channels. The extreme deviations in the small channels were caused by the cutoff effects for profile P4c in the Kusandråka channel and imperfect reproductions of the island plan forms, especially at bifurcations as it was for profile P9 near Fautøya. As expected, the accuracy of the computed discharges in the delta channels initially increased with successive mesh refinement. The relative errors in all the channels were already less than 11% for the 20 and 10 m mesh, and the further refinement gave no improvement concerning the average error for all of the measurements. The sensitivity of the results to vertical mesh resolution was also tested, and there was no trend for indicating any improvement for very fine vertical mesh resolutions.

Flow distribution in the delta

For all three flow situations with a spatial mesh resolution of 10 m, the measured discharges in the various channels were simulated with a relative accuracy within the range of 0 to ± 20% (see Figures 6 and 7). The highest errors usually corresponded to the smallest channels, whereas the relative errors of the large channels were in the range of 0–7%. The high deviation for cross section P6a for the flow situation from June 1997 could be explained by the delay in the date of this measurement. The measurements of the cross sections P6a and P6b were conducted five days later than the other measurements during higher discharges (see Table 1 and Figure 2).

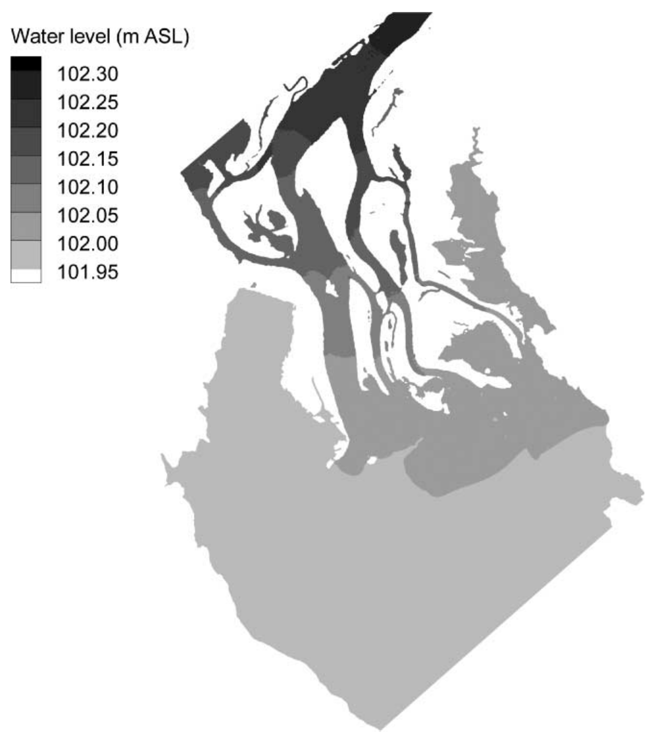

Figure 8 | Computed water levels for the flow situation of July 1997; free surface computation.

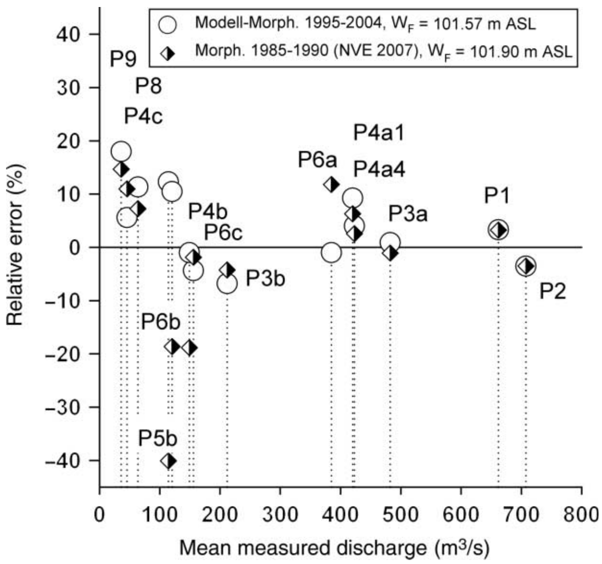

Figure 9 | Relative errors of the computed discharges for different morphology datasets, flow situation from October 1996; for free surface and a maximum of 10 cells in vertical direction, W_F = water level at Fetsund Bru.

Figure 7(b) shows the results of a free surface and fixed surface calculation for the flow situation with the highest gradients among the three investigated cases. For the fixed surface calculations, the average of the water levels at Mørkfoss and Fetsund Bru was given as a constant value for all channels. The error plot indicates a relatively low influence of this factor on the computed discharges, reflecting the generally low water level gradients in the delta under the flow conditions that were investigated (see Figure 8).

To investigate the influence of the uncertainties in the bathymetry data, some calculations were conducted using the older 1985–1990 bathymetry dataset. This bathymetry data was available only for bed elevations ≤ 102 m asl, so as a result, the flow situation from October 1996 was chosen.

The calculations for the 1985–1990 morphology dataset were done with the calibrated roughness value $k_s = 0.5$ m from the model morphology from 1995–2004. However, the gradient was not expected to be completely the same because of the generally lower water depth of the 1985–1990 data (see Figure 4). A free surface computation with the same roughness value led to a considerably higher gradient, resulting in a computed water level at Fetsund Bru that was 0.3 m higher as compared to the model morphology from the 1995–2004 dataset. For most channels, the relative accuracy of the computed discharges with the older bathymetry dataset was again within the range of 0 to ± 20% as shown in Figure 9. An exception was the Storsandråka channel, characterized by profiles P5b and P6b where the simulations underestimated the measured discharges. At the same time, the discharge in the neighbouring Storråka channel (profile P6a) was too high. This could be explained by the accretion of the small island between Årnestangen and Storsand in the middle of the Storråka channel (Figure 2), leading to a reduced discharge in the lower parts of the Storråka channel and an increased discharge through the Storsandråka channel.

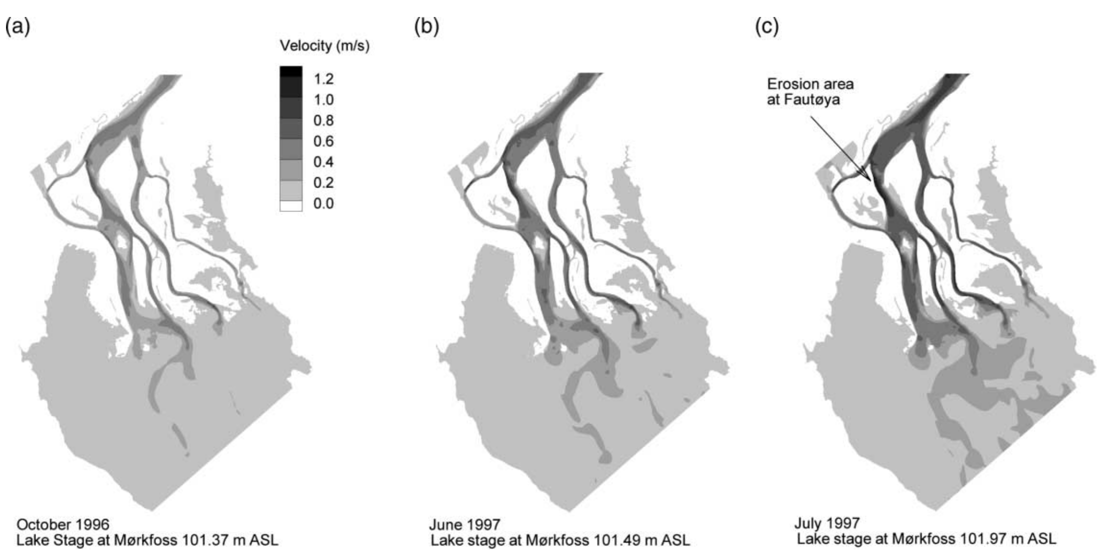

Figure 10 | Computed flow velocities on the water surface for the flow situation of (a) October 1996, discharge 712 m^3/s, (b) June 1997, discharge 1,036 m^3/s and (c) July 1997, discharge 1,496 m^3/s; free surface computations.

Bogen *et al.* (2002) reported remarkable changes in this area ("Flatsand") between 1985 and 1995 which they ascribed to the earlier winter lowering of Lake Øyeren in the years after 1979. The stepwise shifting of some discharge portions from the Storråka channel to the Storsandråka channel had probably continued during the following years since the computed discharges of profiles P5b and P6b were too high in all of the computations with the model morphology from the 1995–2004 dataset, which was mainly based on the 2004 bed level data.

Flow velocities

Figure 10 illustrates the computed mean flow velocities on the water surface for the three flow situations. For October 1996, these flow velocities were between 0.2 and 0.6 m/s in most of the channels in the delta. For higher discharges and water levels, the flow velocities on the water surface increased to more than 1 m/s at some locations in the delta.

The known erosion areas such as the east bank of Fautøya were characterized by the highest computed flow velocities.

The accuracy of the velocity computations was inspected by a direct comparison with the measured values of the cross sections. The measured instantaneous flow velocities of the individual ADCP measurement cruises per cross section showed a high variation due to the turbulence of the flow, the random measurement error and the positional error of the boat course. To acquire sufficient data about the mean current velocities from moving-vessel

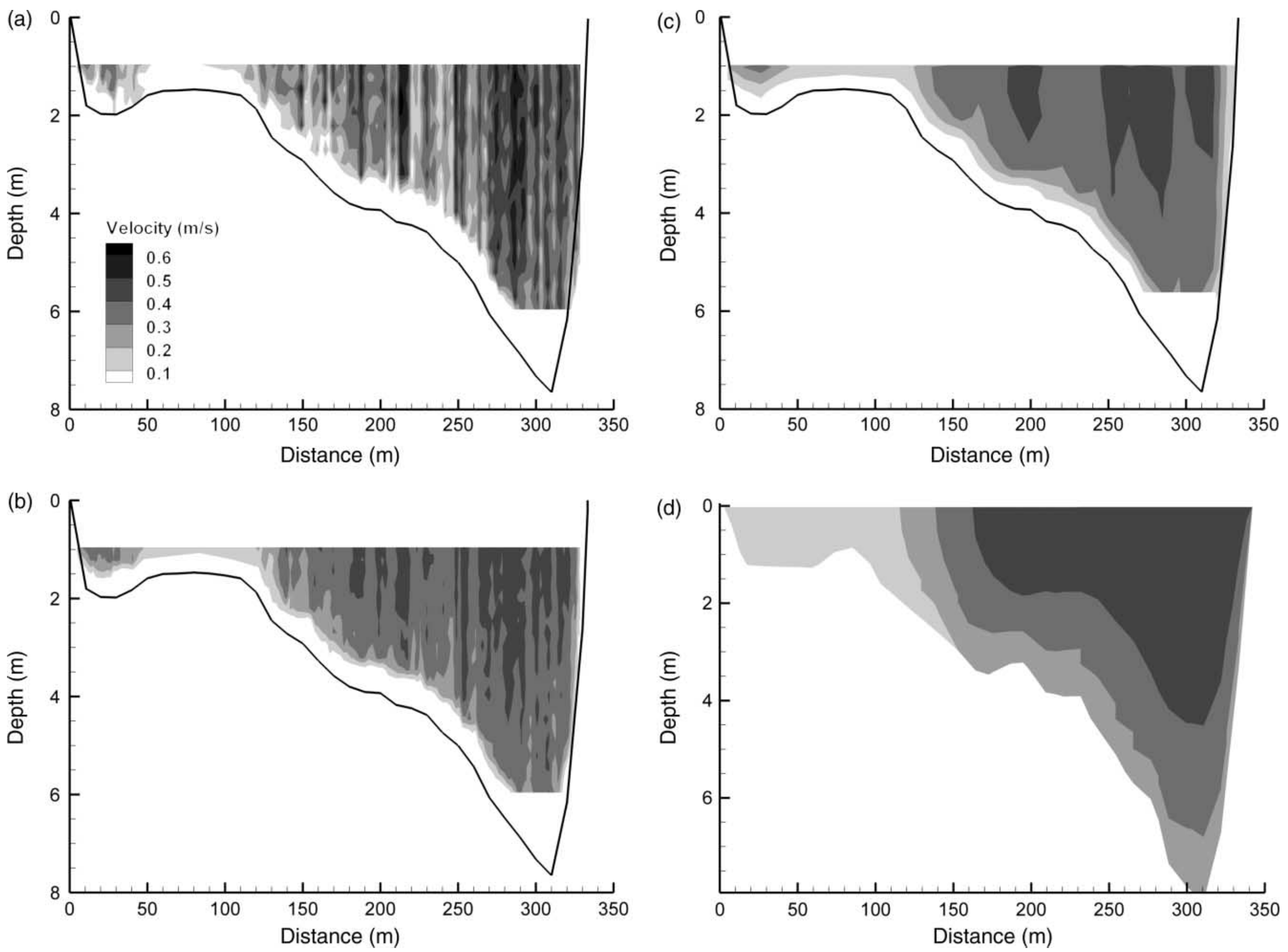

Figure 11 | Flow velocities at profile P6a for the flow situation of October 1996: (a) average of two ADCP measurements, (b) average of eight ADCP measurements, (c) spatial aggregation of the average of eight ADCP measurements using a raster of 31 horizontal and 12 vertical cells and (d) mean flow velocities, computed with SSIIM for the model morphology from 1995–2004 (free surface computation).

ADCP measurements, it is recommended to average at least five (Szupiany *et al.* 2007) or 10 moving-vessel transects (Muste *et al.* 2004). The averaging over the existing velocity data sets–mostly three to five per cross section–was therefore not expected to yield a completely correct distribution of the mean flow velocities over the cross sections, although it undoubtedly contained some information in regard to the flow velocities which could be used for comparison.

For profile P6a, eight moving-vessel transects were available for October 1996 (Figure 11). For Figure 11(a, b), the velocity ensemble data from the ADCP measurements of this profile were scaled by the average length of all boat cruises and then averaged. Averaging over all transects (Figure 11(b)) obviously much better approximates the mean flow distribution than averaging over only two cross sections (Figure 11(a)). In Figure 11(c), the data from Figure 11(b) was further averaged, aggregating data from the small ensemble cells into a larger cell raster. All these ADCP data-based figures contain blank zones without signal below the water surface and near the bottom. The computed mean flow velocities (Figure 11(d)) seem to be slightly higher than the measured ones, but reflect the measured velocities relatively well.

This was not the case, however, for all of the computed profiles, and neither was it expected, due to high uncertainties in the bed level data and the calibrated roughness values. In addition, the flow resistance in some small channels was probably influenced by vegetation. Macrophytes such as *Potamogeton perfoliatus*, *P. gramineus*, *Ranunculus peltatus* and *Myriophyllum alternifolium* were typical species in the shallower areas of the river banks (Rørslett 2002). These species were known to exert additional resistance to the flow (Green 2005; Sand-Jensen 2008), but their local influence was not reflected in the calibrated overall equivalent roughness height.

CONCLUSIONS

The three-dimensional numerical model was successfully used to compute the discharge distribution in the various branches of the Lake Øyeren delta for three different flow situations with a relative accuracy within the range of 0 to ± 20%, using existing bathymetry and hydrological data from the years 1985–2005. The factors introducing the most error and uncertainty in the computed results are believed to be the inaccuracies of the morphological dataset, which was combined from different data sources and did not belong exactly to the flow situation to be modelled. A comparison between the computational results of the older morphology data from 1985–1990 and the model morphology from 1995–2004 indicated that morphological changes in this period had already had consequences for the flow distribution in some channels. This fact is also reflected in the missing model sensitivity to further grid refinement. Other important error sources were the inevitable use of the averaged water level gradients due to unavailable water level measurements within the delta. This did not allow for the specification of locally varying roughness values or vegetation resistance exerted by aquatic macrophytes.

Thus, in the present study, the accuracy of the modelling results was restricted by the quality of the input data, and a final assessment of the accuracy that can be generally achieved with the numerical model was not possible. For that reason, the performance of the model should be further investigated using a delta bathymetry dataset which belongs exactly to the time of the discharge measurements. This can either be done for the delta of Lake Øyeren or another fluvial-dominated delta.

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