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3D MODELING OF THE FLOW DISTRIBUTION IN THE DELTA OF LAKE ØYEREN (NORWAY)

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ABSTRACT

The delta of Lake Øyeren is 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.

A 3D computational fluid dynamics model was used to compute the distribution of the water discharge in the channel branches of the delta. The numerical model solved the Reynolds-averaged Navier-Stokes equations for the water flow. An unstructured 3D grid based on a morphological map of the area was used together with the finite volume method and the k-ε-model for the turbulence. Different grid resolutions and varying roughness parameters were tested.

The results were compared with field measurements taken by an ADCP instrument. Good agreement was found between the results of the computations and the field data, for varying discharges and water levels. As expected, the finer grid resolutions gave the better results. The results were not very sensitive to varying bed roughness values.

Keywords: delta, flow distribution, CFD modelling

1. INTRODUCTION

Lake Øyeren, covering approximately 85 km^2, is situated about 25 km east of Oslo in southern Norway. 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. By far the largest discharge (95 %) and sediment inflow comes from the river Glomma. The delta of Lake Øyeren is the largest fresh water delta in Northern Europe. It is an important bird habitat and nature protection area.

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 is regulated by the hydro power plant Solbergfoss (Bogen and Bønsnes 2002). The regulation regime is characterized by an upper regulation limit (HRV) of 4.8 m (101.34 m ASL) and a lower regulation limit (LRV) of 2.4 m (98.94 m ASL) at the gauge station Mørkfoss. In summer and autumn until the ice period starts, it is not allowed to decrease the water level more than 10 cm below the LRV or to increase the water level more than 20 cm over HRV, as long as the discharge at Solbergfoss is lower than 1200 m^3/s. According to Bogen et al (2002), 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.

Figure 1 The delta of Lake Øyeren (Foto: Fjellanger Widerøe AS).

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 goal of the present study was to compute the flow distribution in the delta with its complex structure as a first step on the way to model these processes.

2. FIELD DATA

Water levels and discharges

A long data series for the water level of Lake Øyeren was available at Mørkfoss, ca. 25 km south of the delta. Regular discharge measurements are performed at the hydro power stations Rånåsfoss (at the Glomma River, 20 km upstream) and Solbergfoss (40 km downstream of the delta). The discharge values of both 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.

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. The position of selected ADCP measurement profiles is shown in Figure 2. For the present study, three different flow situations were chosen to test the numerical model (Table 1). The flow situation of October 1996 represents mean conditions. In June 1997, discharge and water level were increased within the normal regulation limits, whereas the HRV limit was exceeded during a flood situation in July 1997. The measured discharges in Table 1 are averages of 2 to 8 measured ADCP profiles at each cross-section.

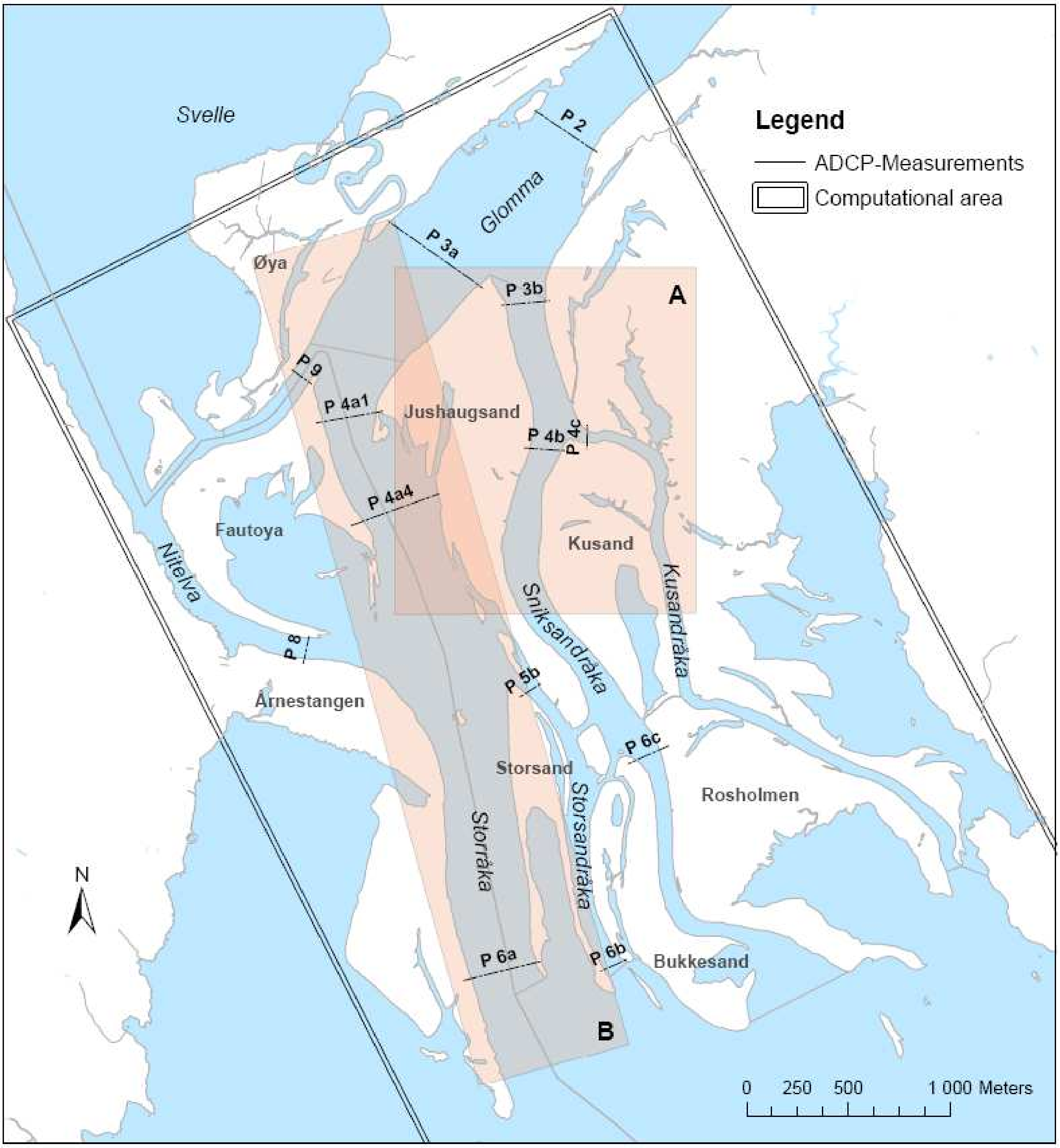


Fig. 2 Measurement cross-sections and locations mentioned in the paper, with frames A and B for Figure 3 and 4.

The ADCP measurement campaigns usually took two to three days, and the water level in Table 1 is the water level of the first day of the campaign when the most profiles were taken. During the measurement periods in October 1996 and July 1997, the water levels and discharges changed only marginally.

For the measurement series of June 1997, two of the cross-sections (P6a and P6b) were measured 5 days later on 30th June, when the water level was 23 cm higher and the discharge had increased by approximately 11 %. Since the measured discharge values at these cross-sections might be not representative for the flow situation during the days before, they are set in brackets in Table 1.

Table 1 Discharge distribution within the delta due to ADCP-measurements at different dates

Date	21^{st}-23^{rd} October 1996	$24^{th}/25^{th}$ (30^{th}) June 1997	$9^{th}/10^{th}$ July 1997
Lake stage (m ASL)			
Mørkfoss	101.37	101.49	101.97
Mean daily discharges (m^3/s)			
Rånåsfoss	No data	1110 to 1173 (1280)	1397 to 1453
Solbergfoss	763 to 800	1169 to 1175 (1300)	1467 to 1513
Measured discharges (m^3/s)			
P1/2	684	1028	1467
P3a	482	724	1022
P3b	212	313	446
P4a1 / P4a4	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

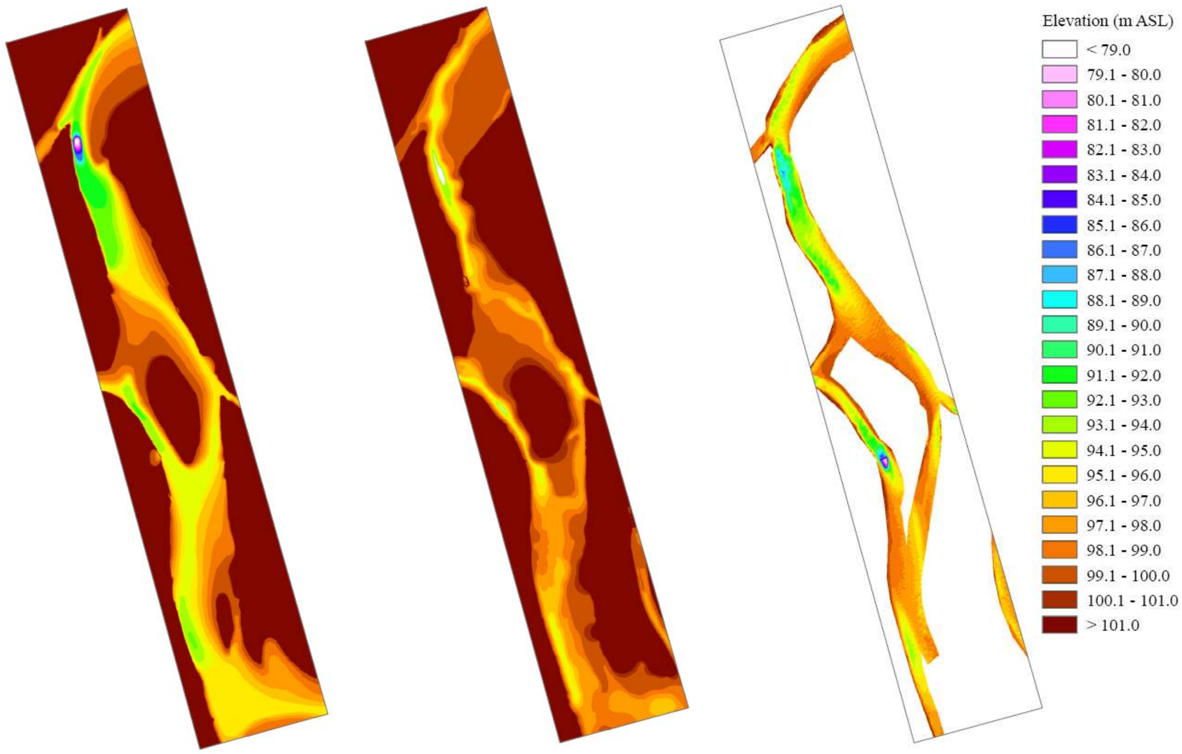
Bathymetry data

An investigation of the existing delta bathymetry data showed that there was no data available for the years when the ADCP measurements were done. Therefore it was necessary to include data from the years before and after, in order to get a proper morphological data set by studying changes and performing a temporal interpolation. In this connection we had to take in mind two big floods from 1967 and 1995 with a 50 to 100 years frequency.

Pedersen (1981) constructed a bathymetric map for the river reach of Glomma and Storråka within the delta for a water level of 101.55 m ASL, combining data from 22 profiles measured by NVE 1974 and 11 own profiles measured with echo sounder in 1980. Another data set – the so-called basic map from 1985 – was published in Bogen et al (2002) and gives contour lines for the whole lake including the delta.

In 2004, the Geological Survey of Norway (NGU) started to perform interferometrical sonar measurements to obtain bathymetrical data of high resolution. This investigation was reported by Eilertsen et al (2005) and provided data for the deeper part of the channels in the delta, but not for the shallow water zones, since a minimum water depth had to be observed.

The three different data sets were analyzed using a geographical information system (GIS). Figure 3 illustrates typical features of them for the Storråka channel. They point to some general tendencies for local morphological changes, for example progressing erosion at the northeast part of the Fautoya Island. They may also indicate a bed accretion (after the 1967's flood) from 1974/80 to 1985 and later, before the 1995 flood caused new erosions.



1974/80 (Pedersen 1981) 1985 (Bogen et al 2002) June 2004 (Eilertsen et al 2005)

Figure 3 Bed levels of the Storråka channel at different times (See frame B in Figure 3).

However, comparisons and plausibility tests using GIS demonstrated that the differences between the data sets are probably not only caused by morphological changes. They reflect also a high degree of uncertainty due to different and partly unknown measurement techniques, sample designs and compilation methods over the 30 years period. This makes the detection of temporal changes and therefore a temporal interpolation very difficult – a problem which has been noted also at for other areas with changing morphology. Van der Wal et al (2003), for example, investigated sources of error and uncertainty in connection with the use of bathymetric charts for the study of morphological changes in estuaries. They found that the charts were suitable for studying *patterns* of long-term morphological change in estuaries. However, when it comes to *quantify* long-term morphological development, errors due to measurement technique, sampling strategy, and errors made during compilation of the charts may exceed the actual change.

The bathymetry for the numerical modelling was therefore based on the assumption that the morphological channel data from 2004 represents the situation between 1996 and 1997 in general better than the basic map from 1985, and that this morphology can be used for the flow modelling if we perform an adaption due to the documented rates of change in highly changing areas.

The final morphology data set was performed as raster with a 2 m grid resolution and is a combination of the 2004 bed level data from NGU (for deeper channels), a digital elevation model from 1995 (for elevations over ca. 100.12 m ASL), own hand-made interpolations northeast of Fautoya and GIS interpolations in between.

3. NUMERICAL MODELLING

Numerical model, model cases and boundary conditions

A three-dimensional numerical finite volume model was used for this study. It solved the Reynolds-averaged Navier-Stokes-Equations for each cell and used the standard k-ε-model with the 5 constants recommended by Rodi (1984) for turbulence closure. The pressure term was computed with the SIMPLE method (Patankar 1980). The model applied wall laws for rough boundaries in the cell bordering the channel boundary. At the water surface, zero gradient boundary conditions were used for all variables except the turbulent kinetic energy, which was set to zero.

The modelling was performed for the three flow situations shown in Table 1. The water level was fixed in the computations. The discharges were given as constant values at two inflow areas (Glomma and Nitelva) and one outflow area at the south-east lake border. The discharge values for the inflow- and outflow areas were taken directly form the ADCP measurements, using the value of P1/P2 for Glomma and the difference between P9 and P8 for Nitelva as inflow and the sum of both values as outflow (see Figure 2 and Table 1). For the Manning-Strickler value at the river bed we tested numbers between 25 and 40 $m^{1/3}/s$.

Computational grid

The grid algorithms are based on a 2D structured grid covering the whole delta, both dry and wetted areas. In this grid, the water depth is computed in each cell based on the bathymetry and the water level. A varying number of 3D grid cells in the vertical direction is added, depending on the depth. In dry areas, no 3D cells are generated. The cells are then connected, forming an unstructured grid. Afterwards, an algorithm is used to smooth the edges of the grid. The shape of the cells on the border between water and dry land are changed as a function of the positive and negative depths of the corners. The algorithm thereby removes sharp corners in the grid. A detailed description is given by Olsen (2003).

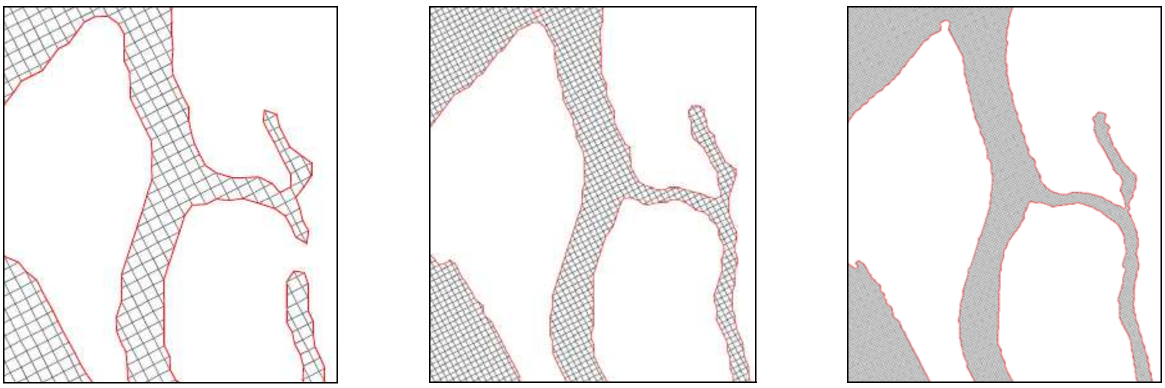


Figure 4 Spatial structure of the grid for a grid resolution of 50 m, 25 m and 10 m and a water level of 101.37 m ASL. The position of the depictured area is shown in frame A in Figure 2.

The grid resolution was restricted by the size of the model area (21 km^2) and the processing power of the computer. Grids with a spatial resolution of 50, 25 and 10 m were tested. The 50 m grid resolution appeared to be evidently too coarse, producing a cut-off in the Kusandråka-channel, which is locally only 40 m wide (Figure 4). For the final computations, a spatial grid resolution of 10 m and a vertical discretisation with max. 20 cells over the depth were chosen. The number of active cells in the grids was about 0.5 million.

The computational time for the finest grid was under 2 hours on a 16 processor 1.9 GHz PowerPC node of the IBM cluster at the supercomputing center of the Norwegian University of Science and Technology.

4. RESULTS AND DISCUSSION

Grid sizes and roughness values

Figure 5 presents the computational results for different grid resolutions and Manning values for the flow situation in October 1996. As expected, the accuracy increased with increasing grid resolution. With the coarser grids, the discharges at channel bifurications were often overestimated in the larger channels (for example P3a) and underestimated in the smaller channels (for example P3b).

The different Manning values were tested with a spatial grid resolution of 10 m. Manning values between 25 $m^{1/3}/s$ and 40 $m^{1/3}/s$ are typical for natural rivers with sandy bed. For the case of investigation, a Manning value of 25 $m^{1/3}/s$ gives slightly improved results, but the difference between the two values was very low. With a constant grid resolution, the Manning value seems to have a relatively low influence on the computed discharges.

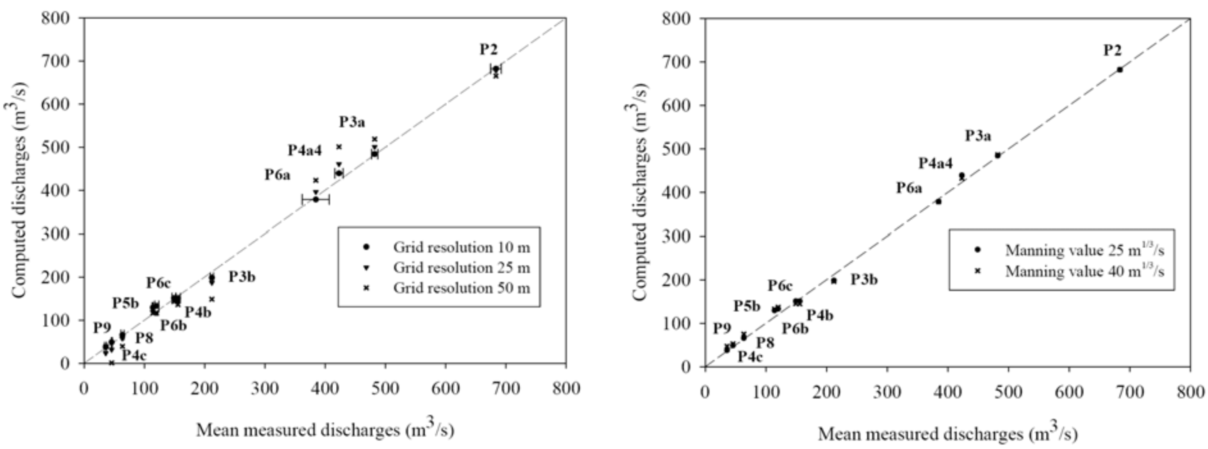


Figure 5 Computed versus measured discharges for the flow situation from October 21st to 23rd 1996, for different grid resolutions (left) and Manning values (right).

However, the roughness in the delta is mainly influenced by the bed forms. The side scan sonar investigations showed a large range of bed forms with different scales, reaching from 3 to 300 m in length and from 0.15 to 2 m in height. Hence, a finer grid resolution gives a more detailed description of the real bed roughness than a coarser one, because the number of the included bed forms increases and their direction can be reflected more correctly. In further investigations it has to be tested whether a further refinement can give improved results for separate parts of the delta.

Flow distribution

Figure 5 and 6 show the computed versus measured discharges for the three different flow situations together with the error bars for the standard deviation of the ADCP measurements. They show a good agreement for a grid resolution of 10 m.

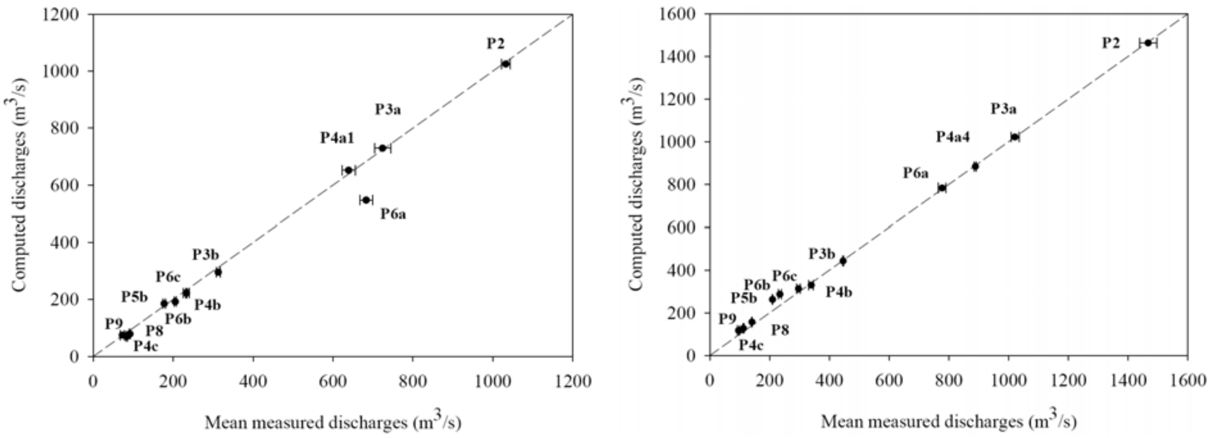


Figure 6 Computed versus measured discharges for the flow situation from 24th/25th (30th) June 1997 (left) and 9th/10th July 1997 (right), computed with a grid resolution of 10 m.

The high deviation for cross-section P6a for the flow situation from June 1997 can be explained with the delayed date of this measurement compared to the other ones. The measurements of the cross-section P6a and P6b were performed 5 days later than the other measurements and during higher discharges (see Chapter 2).

For the flow situation from July 1997, the computed discharges at cross-section P5b and P6c are slightly too high. Both cross-sections are situated at the Storsandråka channel, which is characterized by comparatively high morphological changes. Therefore the real bed morphology especially in the inflow area of the channel during the measurements might have been different form that in the morphology data set used for the computations.

Flow velocities

Figure 7 demonstrates the three-dimensional character of the flow field, showing both the computed mean flow velocities and the measured flow velocities for one of four ADCP measurements at profile P6a. The ADCP figure contains only the measured ensembles, since there are no values available for the blanked areas near the water surface and closed to the river bed.

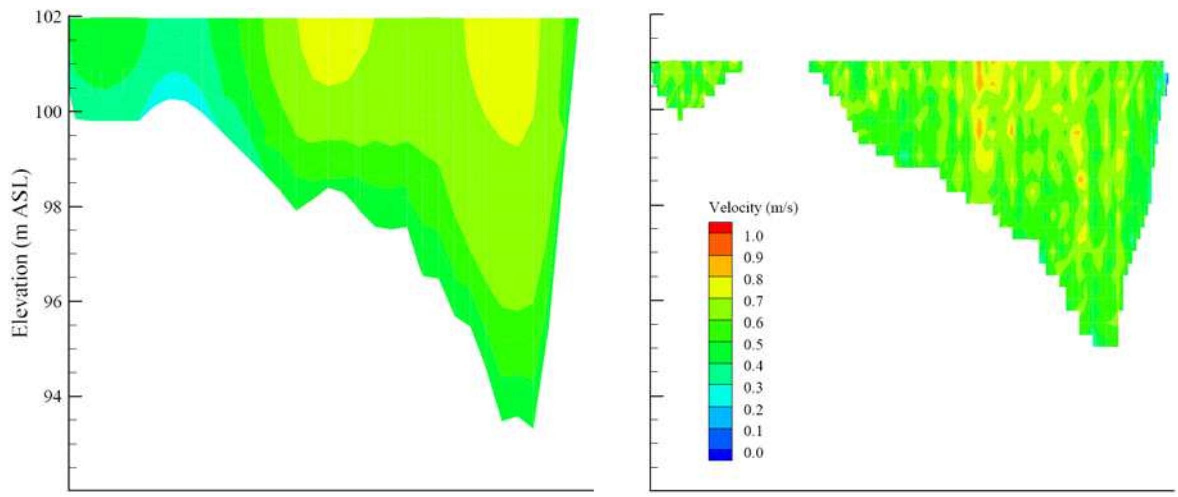


Figure 7 Flow velocities at cross-section P6a for the flow situation on 9th/10th July 1997, left computed with SSIIM, right for one of four ADCP measurements of the profile.

Figure 8 and 9 illustrate the computed flow velocities on the water surface for the three flow situations. Under mean conditions with discharges of ca. 700 m^3/s (i.e. October 1996), these flow velocities are between 0.3 and 0.6 m/s in the most channels of the delta.

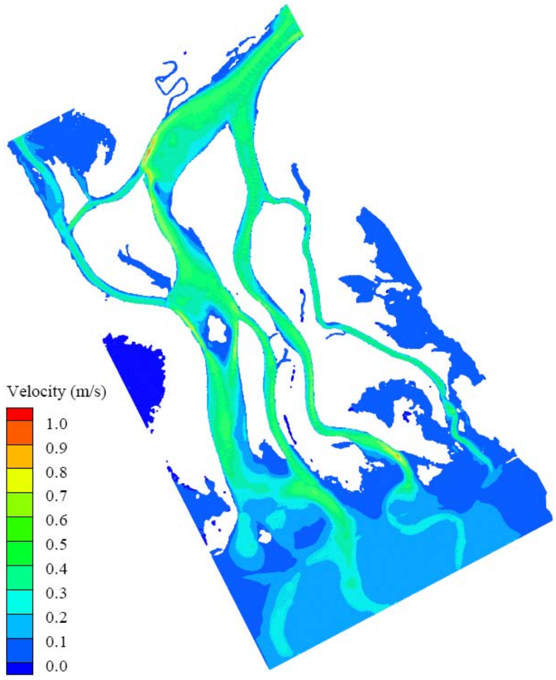
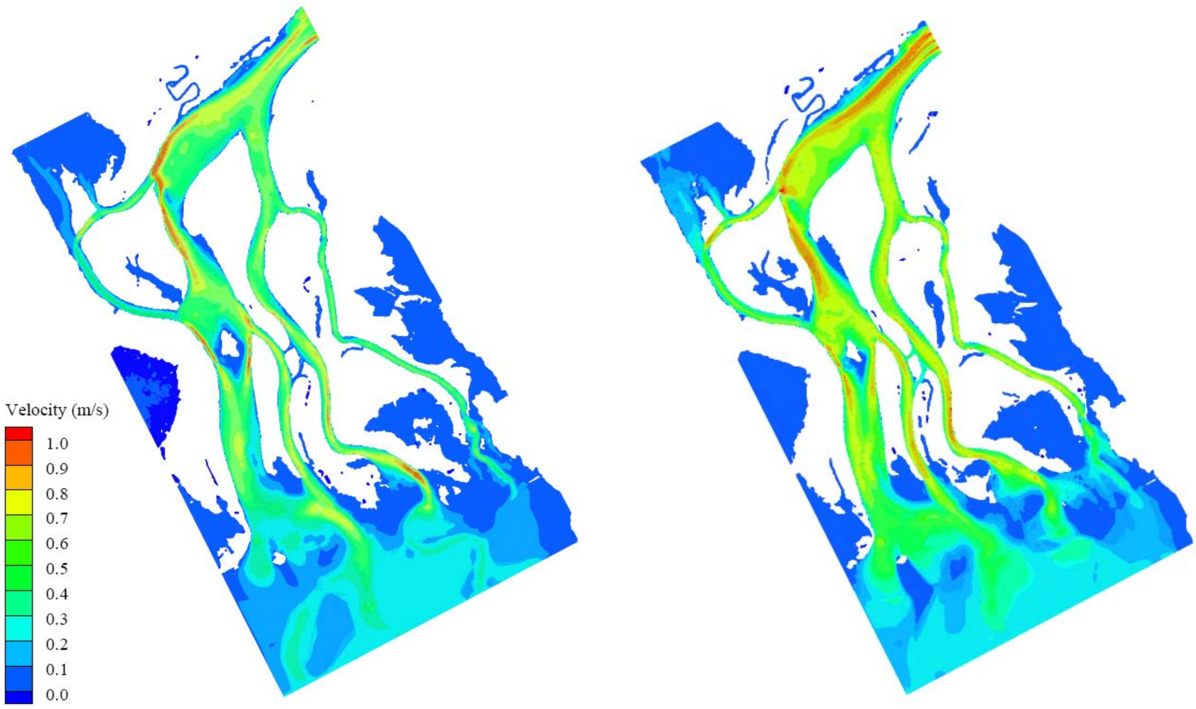


Figure 8 Computed flow velocities on the water surface for the flow situation of 21st to 23rd October 1996, Lake stage 101.37 m ASL, Discharge 712 m^3/s.



June 1997: Lake stage 101.49 m ASL, Discharge 1036 m^3/s

July 1997: Lake stage 101.97 m ASL, Discharge 1496 m^3/s

Figure 9 Computed flow velocities on the water surface for the two other flow situations.

For the higher discharges and water levels, the flow velocities on the water surface become locally more than 1 m/s. The known erosion areas like the east bank of Fautoya are characterized by the highest flow velocities. The flow velocities during a flood situation (July 1997) are generally higher than under mean conditions (October 1996, June 1997). However, locally the flow velocities can be higher for lower discharges, as between Rosholmen and Bukkesand in June 1997 compared to July 1997. This demonstrates that even small water level regulations within the allowed regulation limits can change the locations of higher velocities and thereby influence the erosion and deposition processes within the delta.

5. CONCLUSIONS

A three-dimensional numerical model has been applied successfully to compute the flow distribution in a complex delta geometry using an unstructured grid. The computations were compared with ADCP field measurements. Good agreement was found between computed and measured discharge distributions in the different branches of the delta. Computations with different spatial resolutions of the grid show that the finer grids produce results with better agreement than the coarse grid. The finer grid will also introduce less false diffusion in the results, improving the accuracy. The results were not very sensitive to variations in the bed roughness value.

The computational time for the finest grid of half a million cells was under two hours on a cluster at the supercomputing center of the Norwegian University of Science and Technology, showing that such computations are feasible for practical predictive purposes.

ACKNOWLEDGMENTS

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