Bedform evolution in distributary channels of the lake Øyeren delta, southern Norway, revealed by interferometric sonar.

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ABSTRACT: High-resolution bathymetric data from interferometric sonar surveys conducted in June 2004, June 2007 and Oct/Nov 2007 were used to investigate the river bed of distributary channels of the Øyeren delta plain, the largest freshwater delta in northern Europe.

The data shows that the dominant bedform is dunes, and that the dune morphology is complex with large variations in wavelength, height, leeside angles, scour depth and crest line curvature. Heights range between 0.14 and 2.24 m, and lengths between 3.9 and 52.9 m. The leeside angles range from 1.1 to 34 degrees. A prominent feature is localized scours that occur at the lee sides of some dunes, often extending well into the stoss side of the downstream dune and with prominent spurs on the flanks. Their presence seems related to increased curvature and 3-D appearance of the dunes. Changes in planform morphology of the crest line with time may suggest that the dunes developed towards a more 3-D appearance with persistent flow level. Erosion of the bed is at its highest during lake level lowstand when the discharge in the distributary channels is high. Deposition and migration rates of dunes are also relatively high during lake level highstand. Superimposed bedforms are rare.

1 INTRODUCTION

Dunes are one of the most common bedforms in rivers (Bridge, 2003), and their presence influences the nature of flow structure and exerts a strong control on the entrainment, transport, and deposition of sediment (Parsons et al., 2005). Thus, understanding the nature and origin of dunes may help predicting flow resistance, sediment transport, and deposition within many rivers (Best, 2005). For instance, cross stratification formed from migration of dunes is the most common sedimentary structure of many ancient alluvial successions. These deposits may be of varying and complex geometries, and thus may cause heterogeneous and anisotropic permeability fields in the subsurface, complicating prediction of subsurface flow in both aquifers and hydrocarbon reservoirs (Weber, 1980, 1986; Van de Graff and Ealey, 1989; Best, 2005). The study of river dune dynamics has mainly focused on small-scale laboratory experiments and with small field sites and 2-D survey tools (e.g. single beam echo sounders). However, new geophysical equipment designed to obtain swath bathymetry in shallow waters enables detailed imaging that provides new information on dune morphology and causative processes (e.g. Parsons et al., 2005; Eilertsen & Hansen, 2008). It is the aim of this paper to describe and interpret: 1) bed forms in distributary channels on a lacustrine delta plain at Øyeren, South Norway, and 2) changes to these bedforms occurring over a 3-year period. To our knowledge this is the first time river bed dunes have been described from this type of setting using swath bathymetry data.

2 SETTING

The Øyeren delta is the largest freshwater delta in northern Europe (56 km^2; Berge et al., 2002). It is situated at the northern end of the regulated Lake Øyeren, an 87.4 km^2 large lake having a normal water level 101 m above present sea level (Fig. 1). The delta was divided into 4 morphological units by Bogen and Bønsnes (2002); 1) the delta plain positioned between the 103 and 101 m contours, composed of vegetated islands and intermittent distributary channels; 2) the delta platform positioned between the 101 and 96 m contours and extending about 9 km downstream; and 3) the foreset slope that grades into; 4) the delta bottomset around contour 36 m.

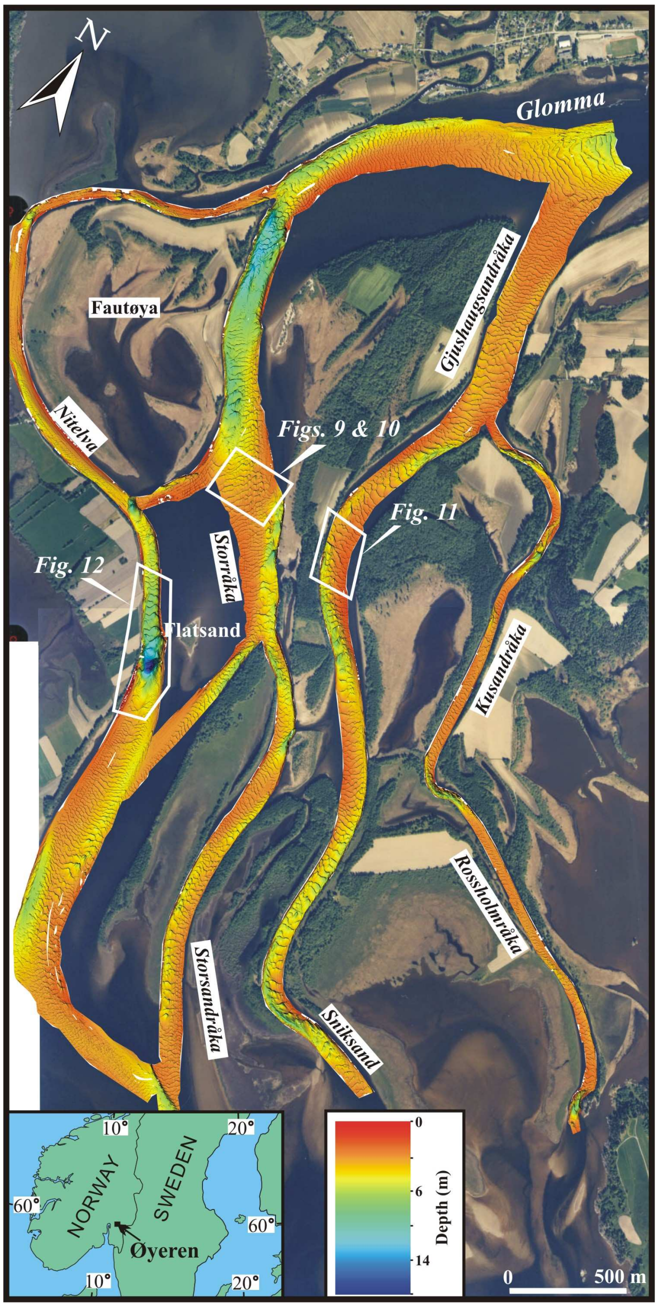

Figure 1. Overview of the Lake Øyeren delta plain with the Oct/Nov 2007 dataset shown.

Three rivers feed the delta: Leira, Nita and Glomma. The Glomma River is the largest, having a mean annual discharge of 630 m^3/s measured at Bingsfoss, 13 km upstream of the study area. It delivers a mean-yearly suspended-load and bed load of 500 000 tons and 75 000 - 150 000 tons $year^{-1}$ to the lake delta, respectively (Bogen et al., 2002). The smaller rivers Leira and Nitelva deliver suspended loads of 90 000 and 18 000 tons $year^{-1}$, respectively. The total catchment area draining into Lake Øyeren is ca. 40 000 km^2 (Pedersen, 1981). The area has a mean annual precipitation and temperature of 820 mm and 4.1° C (Norwegian Meteorological Institute, http://met.no/index.shtml).

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 lowstand during the winter, with a mean fluctuation of 8 m. At present the water level rarely fluctuates more than 4 m between seasons (Fig. 2; Bogen et al., 2002). Sediments were transported and deposited at the delta front before regulation. 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 (Longva, 1991). The channel beds in the distributaries consist of mainly coarse sand, with fine sand dominating in the Rossholmråka and Nitelva channels (Bogen et al., 2002).

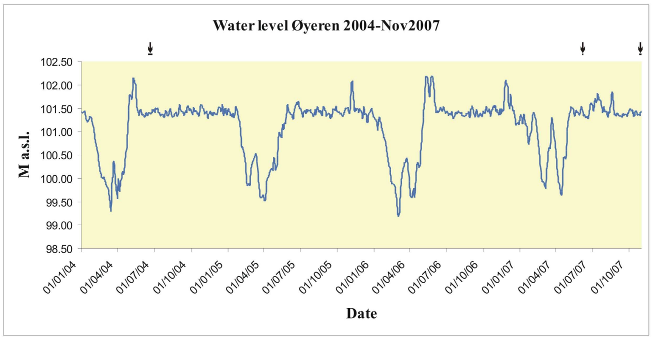

Figure 2. Lake level during 2004-Nov. 2007. Arrows marks the survey dates.

3 METHODS

During 10 days in June 2004, 3 days in June 2007, and 5 days in Oct/Nov 2007, high-resolution bathymetric data were collected using a 250 kHz GeoSwath interferometric sidescan sonar from GeoAcoustics. The 2004 and late 2007 cruises measured the whole delta plain, while the June 2007 cruise only measured parts of the Storråka, Nitelva, and Gjushaugsandråka channels. In addition, parts of the Kusandråka channel were measured twice in Oct/Nov 2007 with one day in between. Two types of data were recorded, bathymetric and backscatter data. The former gives high-resolution depth information, the latter gives information about the riverfloor reflectivity, which depends on the bed character (e.g. grain size, bedrock, roughness). 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 a fixed station measured by Glomma og Lågen Brukseierforening (ww.glb.no). Water level in Øyeren varied in total between 101.34 and 101.41 m a.s.l. during the survey (Fig. X). All datasets have been adjusted to the same water level (101.35 m a.s.l.), which is roughly 1 m below bankfull level. Mean lake level is ~101 m a.s.l. (Bogen et al., 2002). Differential GPS was used for positioning, giving an accuracy of ± 1 m. A gyroscope was also used for navigation. The accuracy of depth measurements during data acquisition was in cm-dm scale. Processing was conducted using the GeoSwath software, and included sound velocity correction and calibration to reduce signal-to-noise ratios. Multiple overlapping runs over the same area were one of the methods used to test the accuracy of the equipment.

4 RESULTS

4.1 *Dune morphology*

The dune morphology within the distributary channels is rather complex with a domination of transverse dunes with well defined crest lines in the more shallow and straight reaches and more complex 3-D forms in the deeper parts and bends. The dunes have individual wavelengths between 3.9 and 52.9 m (average 18.2 m; Fig 3) and heights between 0.14 and 2.24 m (average 0.7 m; Fig 4). Typically the dune size (length and height) increases with depth, although exceptions do occur (Figs. 5 & 6). The dunes are asymmetric with lee-side angles between 3 and 25 degrees (average 11°), although individual dunes with angles of as low as 1.1 and as high as 34.3 degrees also exist (Fig. 7). The high values typically occur where there are prominent local scour on the leeside of the dunes (see below). The stoss slope shape is planar to more commonly concave up, with angles between 1.4 and 6.3 (average 2.9). Superimposed bed forms are rare, however, smaller bed forms like ripples or small dunes may be present but not visible due to the resolution of the dataset.

The dune crest lines can be followed for up to 200 m, and their planform curvature (sinuosity) varies between 1.04 and 1.63 (average 1.18 for the Oct/Nov 2007 dataset; Fig. 8). Commonly, the dunes exhibit crestbrink parting with gentle, rounded dips at the crest followed by a sharper break of slope into the lee. Also, the heights of individual dunes may vary quite strongly along individual crest lines. Bifurcations and discontinuous crest lines also occur. order in which reference is made to them in the text, making no distinction between figures and photographs. Figures should fit within the column width of 90 mm (3.54") or within the type area width of 187 mm (7.36").

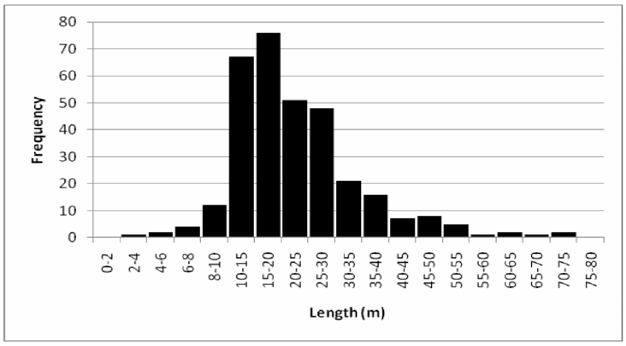

Figure 3. Histograms of dune length for the Oct/Nov 2007 dataset (N=324).

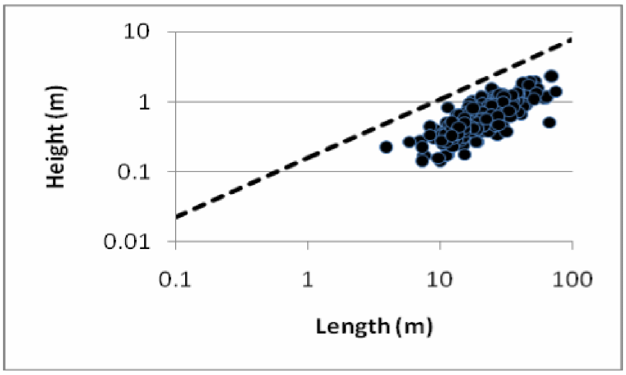

Figure 4. Relation between height and length of dunes from the distributary channels for the Oct/Nov 2007 dataset (N=290). Note the general increase in height with depth. The values are well inside the 'equilibrium' dune function of Ashley (1990) indicated by the stippled line ($H=0.16L^{0.84}$).

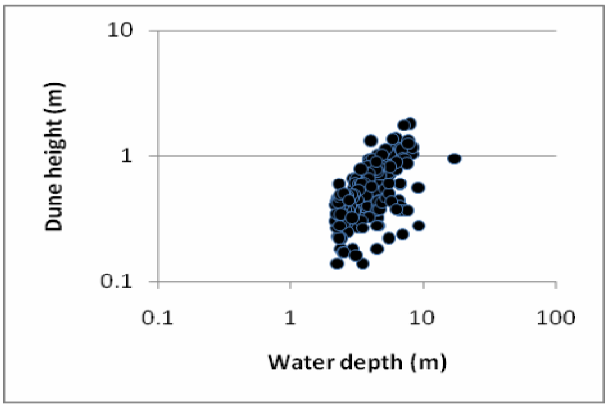

Figure 5. Relationship between dune height and water depth for the Oct/Nov 2007 dataset (N=195).

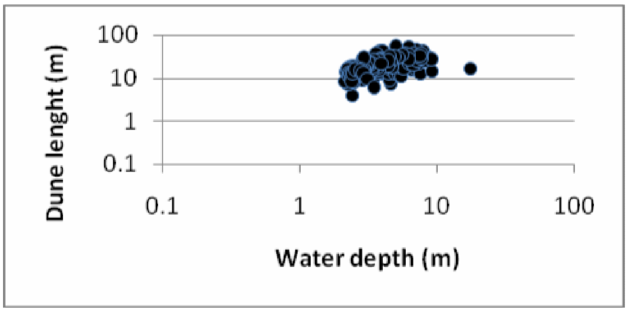

Figure 6. Relationship between dune length and water depth for the Oct/Nov 2007 dataset (N=195).

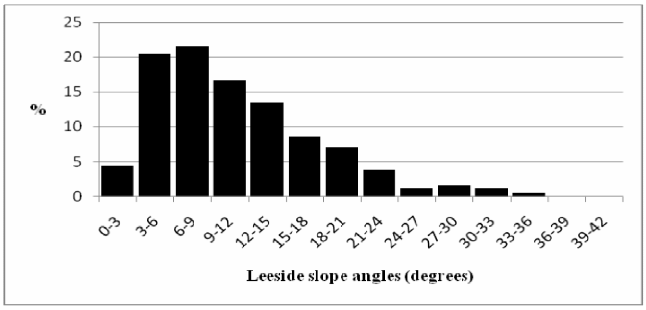

Figure 7. Histograms of leeside slope angles for the Oct/Nov 2007 dataset (N=186).

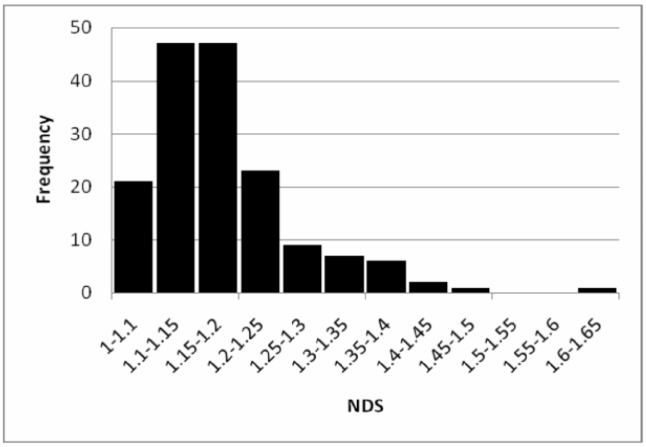

Figure 8. Histograms of dune crest line sinuosity for the Oct/Nov 2007 dataset (non-dimensional span (NDS) sensu Venditti, 2003. N=164).

Occasionally, local scours are present on the lee-side of dunes (Figs. 9 & 10). They are up to 20 m long, 10 m wide, and more than 1 m below mean bed level, and may extend almost to the crest line of the downstream dune. Spurs along the scour margins may be up to 50 cm high (Fig. 11).

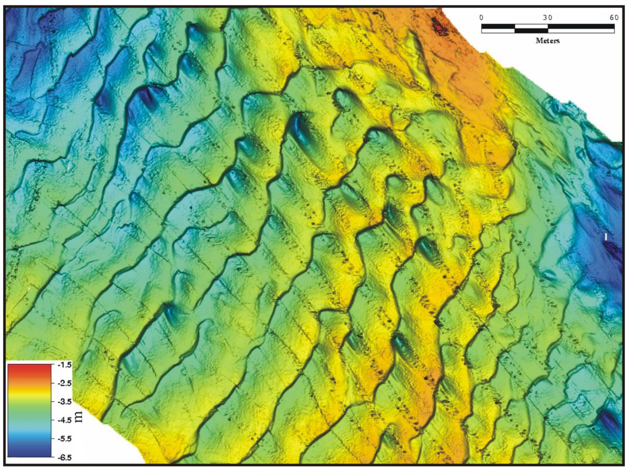

Figure 9. Shaded relief map of a section of the Storråka channel from the Oct/Nov 2007 dataset (see Fig. 1 for location). Note the pronounced local scours, some with spurs, on the leeside of the dunes. Flow from upper left to lower right.

The crest lines of the dunes are often highest and have the largest leeside angles at the scour location (22 to 34 degrees). Crest line curvature also appears to increase at localities with scours, and the scours are often associated with saddle shaped (concave downstream) crest lines, although this is not always the case. Often, the scours and the associated spurs appear to be aligned in 'bands' at the leeside of successive dunes downstream. This is also evident in channel bends (e.g. Fig. 11).

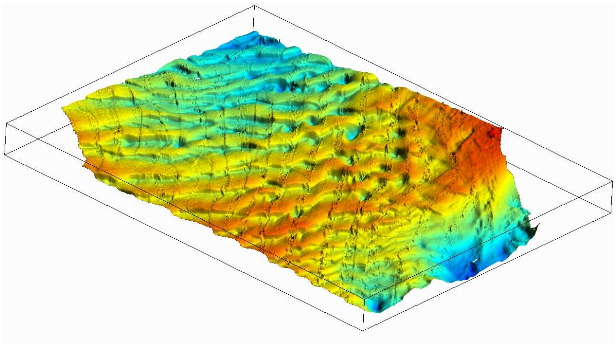

Figure 10. 3-D view of the same area as shown in figure 9. Note the pronounced local scours, some aligned in 'bands' at successive dunes downstream, and the difference in crest line height. Flow is out of page.

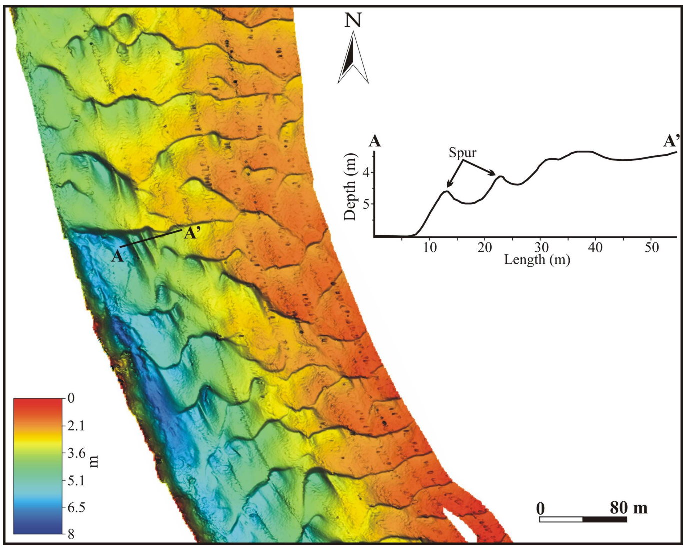

Figure 11. Shaded relief map of a section of the Gjushaugsandråka channel from the Oct/Nov 2007 dataset (see Fig. 1 for location). Note the pronounced local scours and associated spurs. Flow from top to bottom.

4.2 *Bedform evolution*

The three data sets allow us to observe changes of the river bed within several time scales (Fig. 12). However, the time span between the datasets, apart from the two-day survey at Kusandråka channel, is too large to recognize the individual dunes and their migration.

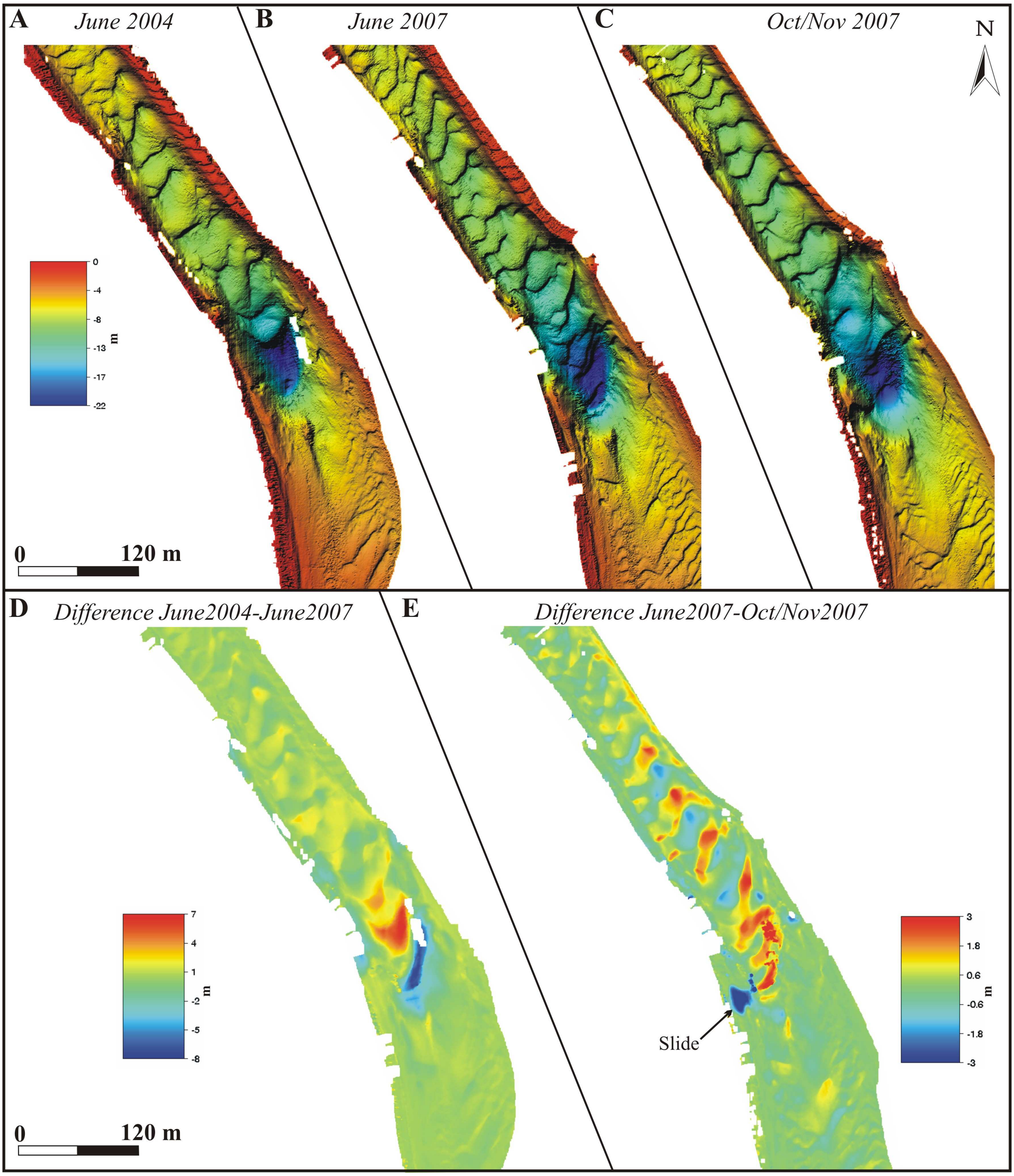

Figure 12. Bathymetry of the Storråka channel at Flatsand at three different periods (A-C), and changes that have occurred over a 3 year and 4-5 month period (D and E, respectively). See Fig. 1 for location. Flow is from top to bottom of page.

Figure 12D shows the difference in bathymetry in parts of the Storråka channel between June 2004 and June 2007. Here the 23 m deep scour, which probably appeared during a major flood in 1995 (Eilertsen & Hansen, 2008), has migrated more than 20 m downstream and up to 8 m of sediments have been removed. Over the same period, 7 m of vertical deposition has taken place at the upstream end of the scour. Between June and Oct/Nov 2007, the data shows that relatively little erosion has taken place, apart from a bank collapse at the scour margin. In contrast, evidence of dune migration is clearly visible in the upstream channel, and more than 3 m of sediments were deposited at the upstream part of the scour (Fig. 12E).

The changes observed at the Kusandråka channel with one day apart are difficult to distinguish due to the resolution of the dataset. However, it appears as most changes have occurred on the lee side of scours and along the river banks.

The crest line curvature (sinuosity) measured over the same reach of the Gjushaugsandråka channel in June 2004, June 2007, and Oct/Nov 2007 show relatively small differences, with mean curvature of 1.13, 1.16, and 1.18 respectively.

5 DISCUSSION

Although more than 50% of the leeside angles are lower than 10°, such low angle dunes may possess intermittent separation in the dune lee (Best & Kostaschuk, 2002). Dunes with larger leeside angles, on the other hand, may generate permanent flow separation. Highest angles are normally found in combination with the more prominent scours, although the leeside angle may be half or less laterally of the same individual dune crest. This, in combination with variability in crest line height, would cause an important topographic steering of the flow that significantly affects the distribution of shear stresses and sediment transport over the dunes (Maddux et al., 2003). The crest line parting observed at some dune crests may also significantly influence shear and turbulence in the leeside (Best & Kostaschuk, 2002).

The prominent local scours and associated spurs would suggest that a narrow zone of high turbulence is operating at specific locations, probably related to some kind of topographic steering. The convergence of flow in the lee of saddle shaped dunes may explain some of the scours, but not all are related to saddles. Also, Venditti (2003) argued that the convergence of flow in the lee of saddle shaped dunes would reduce the turbulence intensities but increase the average flow velocity. Another important aspect is how the prominent scour relates to the dune migration subsequent to its formation, whether the scour will enhance the 3-D shape as the dune migrates around it or if it migrates at the same pace as the lateral dune crest. The alignment of prominent scours in successive dunes and the alongside spurs suggest that these features are related to a 'local' turbulence phenomena.

The lack of erosion between June and Oct/Nov 2007 observed in the Storråka channel (Fig. 12E) contrast the relatively high sedimentation rates within the same period. This suggests that most of the erosion takes place during the lake level lowstand when the discharge is at its highest, supporting the conclusions made by Bogen et al. (2002). However, the flow velocities are still high enough to transport and deposit substantial amounts of sediments (mainly medium sand) during the lake level highstand.

The difference in crest line curvature between the datasets where small, only from 1.13 to 1.18. This is slightly lower than the value of 1.2 which Venditti et al. (2005) defined as the boundary between 2-D and 3-D bedforms. However, the lowest values occurs early in a period of a more stable lake level following lake-level lowstand, and the higher value occurs in late fall after a period of relatively stable lake level. This may suggest that the dunes were adjusting from initial 2-D to a more 3-D appearance as the water flow was relatively steady for a longer period of time (Fig. 2). If a flow persists for a sufficiently long period, a transition from 2D to 3D bedforms will occur (Baas et al., 1993; Baas, 1994, 1999; Venditti et al., 2005).

6 CONCLUSIONS

Detailed bathymetry data from distributary channels on a lake delta plain was collected over three time periods by using interferometric sonar.

The data shows that the dune morphology is complex with large variations in wavelength, height, leeside angles, scour depth and crest line curvature. Superimposed bedforms were rarely found on the dunes.

A prominent feature is localized scours that occur at the lee sides of some dunes, often extending close to the crest line of the downstream dune and with prominent spurs on the flanks. Their presence seems related to increased curvature and 3-D appearance of the dunes. However, more work is needed to monitor these features and how they relate to the migration of the dunes.

Changes in planform morphology of the crest line with time suggest that the dunes will develop towards a more 3-D appearance with persistent flow level.

Erosion of the bed is at its highest during lake level lowstand when the discharge in the distributary channels is high. Deposition and migration of dunes are also prominent during lake level highstand.

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