Impact of Improvement of the Entrance Channel on the Rate of Sediment Deposition into the Dar es Salaam Harbour

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Abstract: The study reported here sought to investigate the effect that the dredging of the harbour basins and the entrance channel has had on sediment deposition rate into the Dar es Salaam harbour. Echo-sounding was carried out along berths No 2, 3, 4, 6, 7 and 8 as a means of detecting changes to their bathymetry in the four years since 1998, when the dredging commenced. Concentrations of transported sediments into and out of the harbour were determined using sediment traps. Short-term measurement of waves and currents were also carried out. Sediment traps, a wave-gauge and a current-meter were deployed in the entrance channel during the South East and North East monsoon seasons respectively.

Our results reveal that the sedimentation rates after improvement of the channel are between 13 and 43 cm/year. Rates of sedimentation before dredging were relatively low, at between 7 and 25 cm/year. There are two reasons for the difference in rates. First, the settling of fine particles as a result of dredging activities, and second, the change of channel alignment and subsequent erosion on Ras Makabe. The eroded sediments were probably deposited into the harbour basin by the flood tide. This trend has the implication that the harbour basin will need more frequent dredging than it did before improvement of the entrance channel: In the past, with a maximum sedimentation rate of 25cm/year, it took 20 years before the harbour basin needed to be dredged. At the present sedimentation rate (maximum of 43cm/year), it will take only 11 years before re-dredging is necessary.

INTRODUCTION

Worldwide, sedimentation is one of the outstanding problems in port planning and operations. Port installations are generally associated with improvements in harbour accessibility. Dredging of entrance channels and harbour basins encourages the deposition of sediments in these channels, because when water currents pass over a dredged channel, the flow transport intensities are weakened and the ability to transport sediment decreases. This results in increased deposition of sediments in the newly dredged channel (Bruun, 1990; Mead, 1999; van Rijn, 1991).

In planning and executing dredging works, it is important to have an indication of sedimentation rates prior to commencement of the operations. Unexpectedly high rates of sedimentation can lead to the necessity of frequent dredging, which could have a high cost implications to the port operations. Therefore, extensive research has been carried out on sediment transport mechanics in dredged trenches and channels, and scientists and engineers have come up with mathematical models, including numerical, empirical and semi-empirical approaches to predict the rate of sedimentation in these excavations (e.g. van Rijn, 1991; Mead, 1999; Greimann, et al., 1999; Leenknecht, et al., 1992; Lumborg & Windelin, 2003).

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Siltation is a major problem in Dar es Salaam harbour (Scott Bertlin Consulting Engineers and Planners, 1991). Before dredging the berths basin and the entrance channel in 1998, the controlling water depth below chart datum in the entrance channel was 7.4 meters. In accordance with the Dar es Salaam pilotage rules, underkeel clearance is 0.7 meters, which means that the allowable maximum draft at low tide was 6.7 meters (Jan de Nul, 1991; SLI Consultants, 1994). Ships with greater draft were forced to make use of tides to enter and leave the harbour. Numerous bends in the entrance channel hindered navigation at night, resulting in delays to most of the larger vessels and higher cost for such vessels entering and leaving the port (Tanzania Harbours Authority, 1998/99). Therefore, it was necessary to improve the entrance channel. Apart from the limitation of the entrance channel, the inner harbour also was silted to the extent that underkeel clearance for larger vessels was insufficient. Pilots of larger ships frequently reported their ships touching the harbour's floor during low tides. Bathymetric surveys carried out in 1993 showed that in some areas the sedimentation layer was up to 3.7 meters thick (SLI Consultants, 1994).

In 1998, the Tanzania Harbours Authority (THA) improved the harbour basin and the entrance channel. The harbour basin was improved by dredging it to a designated depth. In the entrance channel, works carried out include straightening, widening and deepening the channel. The depth of the channel now is 10.2 meters below chart datum and the width is 120 m, which is 20 m wider than it was before. This improvement, together with installation of the navigation aids, has made it possible for vessels of up to 40,000 DWT and 225 meters overall length to enter the port without relying on the tides, and at any time of day or night (Tanzania Harbours Authority, 1998/99). These improvements, however, altered the alignment of the channel which in turn has altered its hydraulic parameters.

The aim of the study reported here was to look at the impact that the improvement carried out in the entrance channel has had on the rate of sediment deposition in the harbour and in the entrance channel.

Study area

The port of Dar es Salaam is located along the shore of western Indian Ocean at latitude 6° 50' S and longitude 39° 18' E (Fig. 1). The inner harbour is a tidal basin with a deepwater area of approximately 96 hectares with a narrow opening to the sea. The tides are semidiurnal with two high tides and two low tides daily. The harbour is well sheltered from strong winds and waves. Three small, seasonal rivers namely Yombo, Mbagala and Mzinga drain into the head of the southern creek.

MATERIALS AND METHODS

Field activities included echo-sounding surveys in the berth basins and in the entrance channel. Because of authoritative constraints, only berths 2, 3, 4, 6, 7 and 8 were surveyed. A current-meter and wave-gauge were used for measurement of currents and waves respectively. Sediment traps were used for collection of sediment transported into and out of the harbour. The traps were fixed on a 25-mm-diameter galvanised pipe and deployed together with the instruments in the entrance channel at the West ferry beacon (6°49.10 S, 39° 17.89 E) during both NE and SE monsoon winds (Fig. 1). Current data recording frequency interval was 10 minutes.

2001. During the NE monsoons sediments were collected in February, for 6 hours during flood tide and 4 hours 55 minutes during ebb tide. During the SE monsoon sediments were collected in August, for 6 hours. Currents and waves were recorded for 48 hours.

2002. During the SE monsoon sediments were collected in August, for 6 hours 2 minutes during flood tide and for 4 hours 27 minutes during ebb tide. Currents and waves were recorded for 25 hours.

Sediment traps were arranged and fitted to a galvanised pipe at levels 1.0 metre apart, and the bottom traps were deployed at least 1.0 m above the seabed. These traps captured vertical settling sediments and horizontally transported sediments respectively. A total of 60 samples from both vertical and horizontal traps were collected and later transported to the laboratory, where they were oven-dried at 60 °C, then weighed.
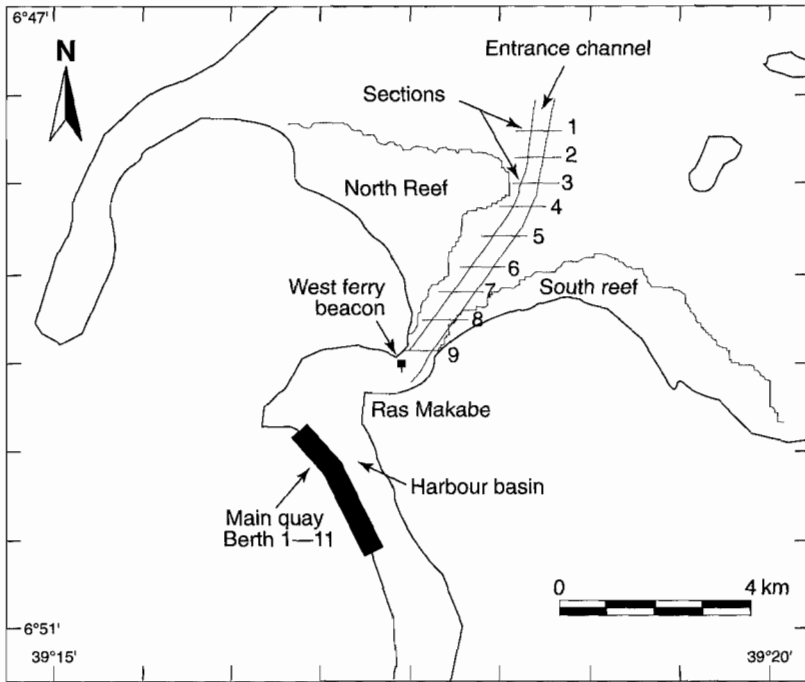
Fig. 1. Layout of Harbour basin and entrance channel where hydrographic parameters were taken at the Dar es Salaam Harbour

Data analysis

Simulation of water discharge and therefore evaluation of suspended sediment concentration entering the harbour basin was carried out based on the following theoretical background. The volume of water that passes through the sediment traps is directly proportional to the weight of sediment captured. From this relationship the concentration of sediment deposition is computed from the volume of water passing through the sediment traps. The volume of water through a trap in time (t) is given by

$$V = avt \qquad [1]$$

where

   a = base area of a sediment trap (m^2)
   v = longitudinal current velocity at the height z above the bed (m/s)
   t = time taken to capture the sediments.

   The discharged volume of water into and out of the harbour through the entrance channel is computed using spatially integrated momentum equations (Leenknecht, et. al., 1992).

$$\frac{dQ}{dt} = I_g\left[\left(\frac{1}{A_b^2} - \frac{1}{A_s^2}\right)Q^2 - g(h_b - h_s) - F\right] \qquad [2]$$

where

$$I_g = \frac{1}{\int_{xs}^{xb}\frac{dx}{A_c}} = \frac{1}{\sum\limits_{i=1}^{IC}\dfrac{\sum\limits_{j=1}^{IC}\dfrac{L_{ij}}{IC}}{\sum\limits_{j=1}^{IC}A_{ij}}} \qquad [3]$$

and

$$F = \sum_{i=1}^{IS=1}\frac{1}{\sum\limits_{j=1}^{IC}A_{ij}}\sum_{j=1}^{IC}\frac{gn_{ij}^2|W_jQ|W_jQB_{ij}L_{ij}}{\kappa d_{ij}^{\frac{3}{1}}A_{ij}^2} \qquad [4]$$

where

$$W_j = \frac{C_j}{\sum_{i=j}^{IC} C_j} \tag{5}$$

and

$$C_j = \frac{A_j^2 d_j^{\frac{1}{3}}}{n_j^2 Q^2 B_j L_j} \tag{6}$$

in which Q = inlet flow passes through a channel at an instant in time

t = time

I_g = geometry integral

A_b = cross-sectional area of the inlet at the bay boundary

A_s = cross-sectional area of the inlet at the seaward boundary

g = gravitational acceleration

h_b = water levels at the bay boundary

h_s = water levels at the seaward boundary

F = total bottom friction

x = distance along the main axis of the inlet

A_c = inlet cross-section flow area at x

IS = last cross section at the bay end of the inlet

i = the inlet flow grid of cross sections

IC = last grid along the channel indexed from left to right across the inlet from seaward perspective

L_{ij} = mean cell length

j = the inlet flow grid along the channel indexed from left to right across the inlet from seaward perspective

A_{ij} = cross-sectional area of the cell perpendicular to flow

n_{ij} = Manning's coefficient for a cell

W_j = weighting function for a cell

B_{ij} = mean cell width

6 = conversion factor to adapt Manning's equation to the application system of units

d_{ij} = mean instantaneous water depth in a cell

A_j = channel cross-sectional area

d_j = water depth of the channel

n_j = Manning's coefficient of friction

B_j = channel width

L_j = channel length.

RESULTS

Currents

The measured short-term current velocity and water level in the entrance channel at west ferry beacon are superimposed with the simulated ones as shown in Fig. 2a, while the simulated discharge volume of water that passes through the entrance channel is shown in Fig. 2b. It can be seen that measured flooding current speed is in the order of 20 cm/s while the ebbing current speed is between 50 and 60 cm/s. Current velocities measured during the NE monsoon season at spring tide are stronger during ebb tide compared to those during flood tide, whereas simulated current velocities match with those during flooding but are weaker during the ebb tide. The noted differences could be due to the input in the models applied, which has not incorporated local geometry and some meteorological parameters, which are likely to influence the measured current velocity. Surface elevation for both measured and simulated data are the same. The tidal range is about 4 meters.

Sedimentation

Figure 3 shows cross-sections 1 to 9 of the entrance channel measured from the sea to the harbour basin. It can be seen that after dredging in 1998, the entrance channel has experienced scouring. Bathymetry along the berth basins, as shown in Fig. 4, indicates that sediment deposition in some areas has reached up to 1.7 m in thickness. The trend of sediment deposition shows that there is scouring in the entrance channel where the magnitude differs from section to section and in the harbour basin, sedimentation is seen closer to the quays. However, berth 6 is experiencing scouring.

Figure 5 shows the results of laboratory tests for trapped sediments. Fig. 5a and 5b show that the concentration of suspended sediments for sediment trapped during flood tide is higher compared to those collected during ebb tide, except Fig. 5c, which shows the contrary. From the Figures we see that the concentration of collected sediment does not depend on the level of the trap.

The simulated discharged volume of water that
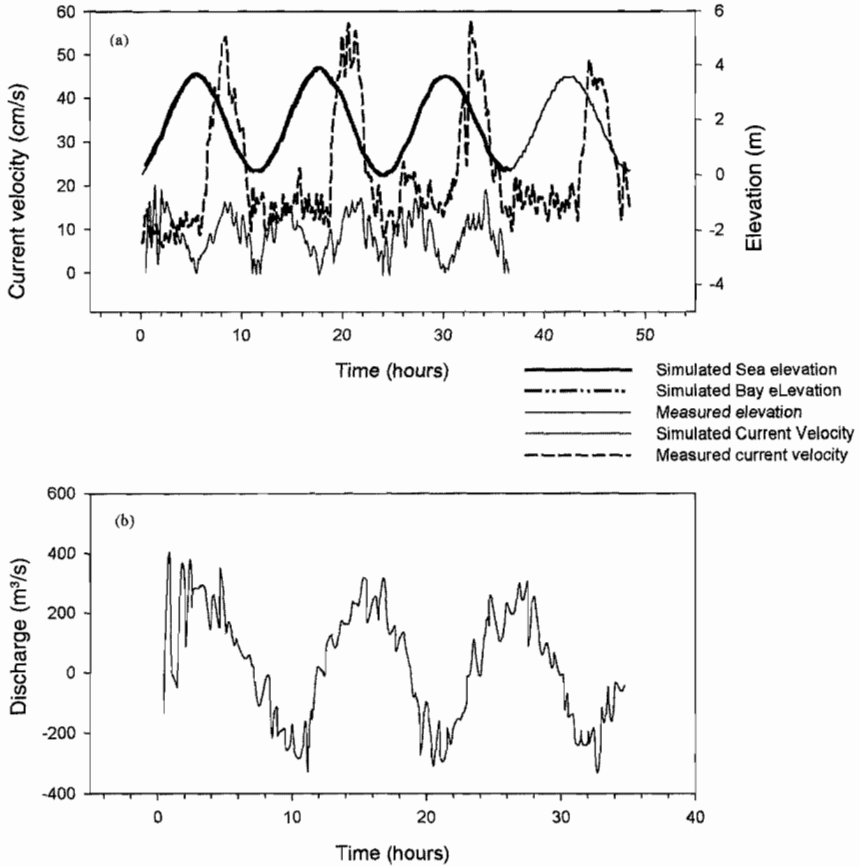
Fig. 2 (a) Comparison between measured current velocity and water elevation and simulated current velocity and water elevation in the Dar es Salaam Harbour; (b) Simulated discharged volume of water in and out of the Harbour

passes through the entrance channel during NE monsoon season at spring tide for flood was 7.154 x 10^7 m^3 and for ebb it was 7.199 x 10^7 m^3. During SE monsoon season water discharge was estimated to be 7.246 x 10^7 m^3 and 7.044 x 10^7 m^3 for the flood tide and ebb tide respectively. Thereafter, the sediment load into the harbour (spring tide) during the NE monsoon season is about 8.6 tonnes per day and about 13.1 tons per day during the SE monsoon season.

DISCUSSION AND CONCLUSION

A bathymetric survey carried out in 2002 along the berth basins after improvement of the entrance channel (within 4 years) showed that there is a very significant sediment deposition in the harbour, especially on berth 8. The rates of sediment deposition are between 13 and 43 cm/year.

According to SLI Consultants, (1994), a sounding survey carried out in 1993 (before improvement of the entrance channel) estimated the sedimentation rate to be between 7 and 25 cm/year. The observed higher sedimentation after improvement of the entrance channel could be attributed to: (1) dredging activities in the harbour basin and in the entrance channel agitated bottom sediments, which could have been carried by tidal flow into the harbour basin; (2) the change of channel alignment and subsequent erosion on Ras Makabe could be a source of sediments that were being carried by the tidal flow and later deposited in the harbour basin. Assuming the sedimentation rate will remain constant, the implication is that the harbour basin will need more frequent dredging than was necessary before improvement of the entrance channel. It took 20 years for the harbour basin to require dredging when the sedimentation
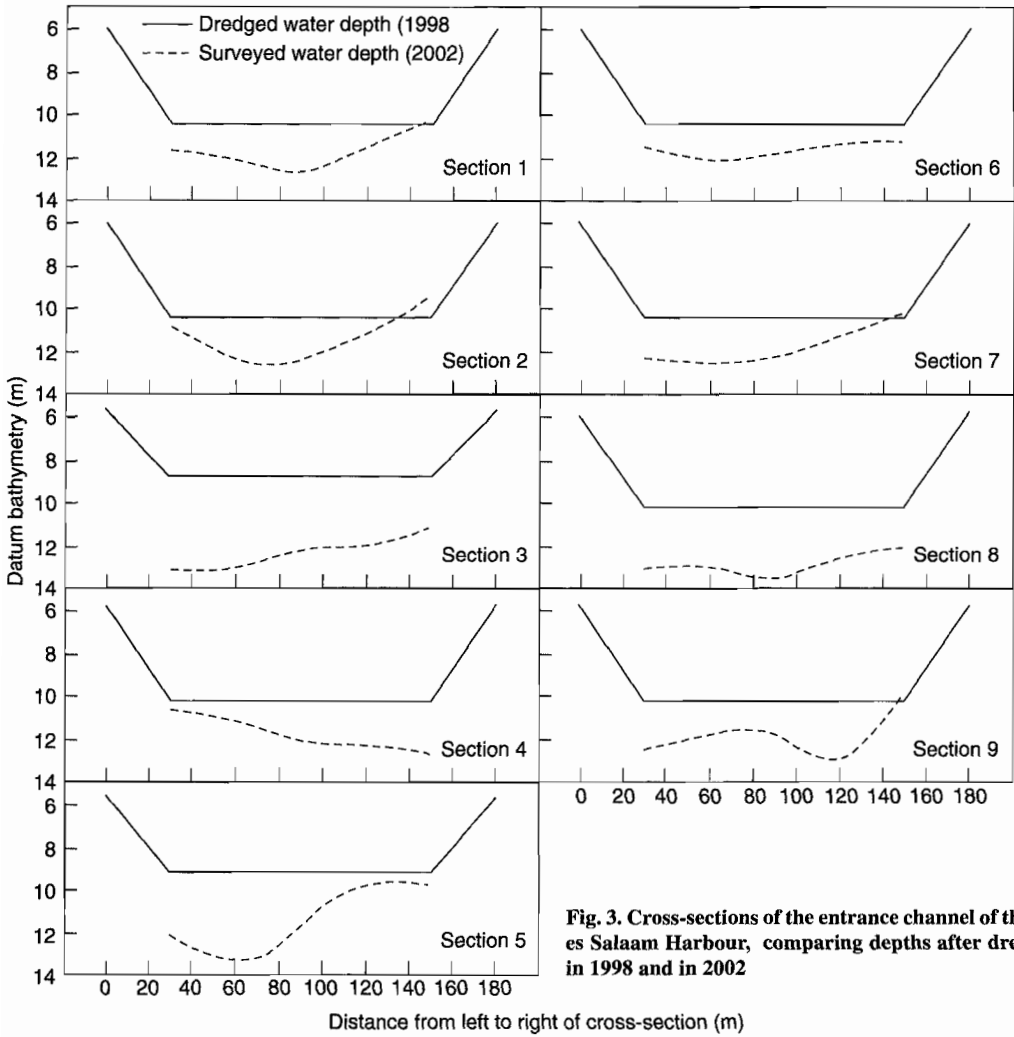
Fig. 3. Cross-sections of the entrance channel of the Dar es Salaam Harbour, comparing depths after dredging in 1998 and in 2002
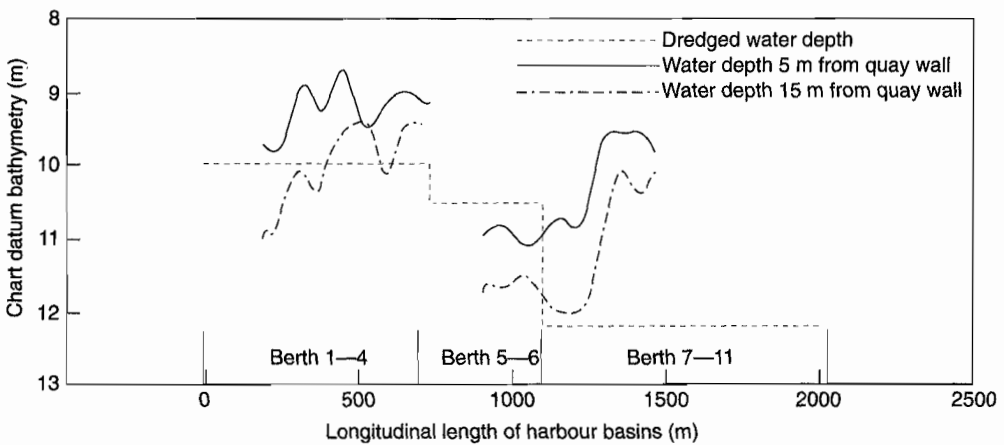
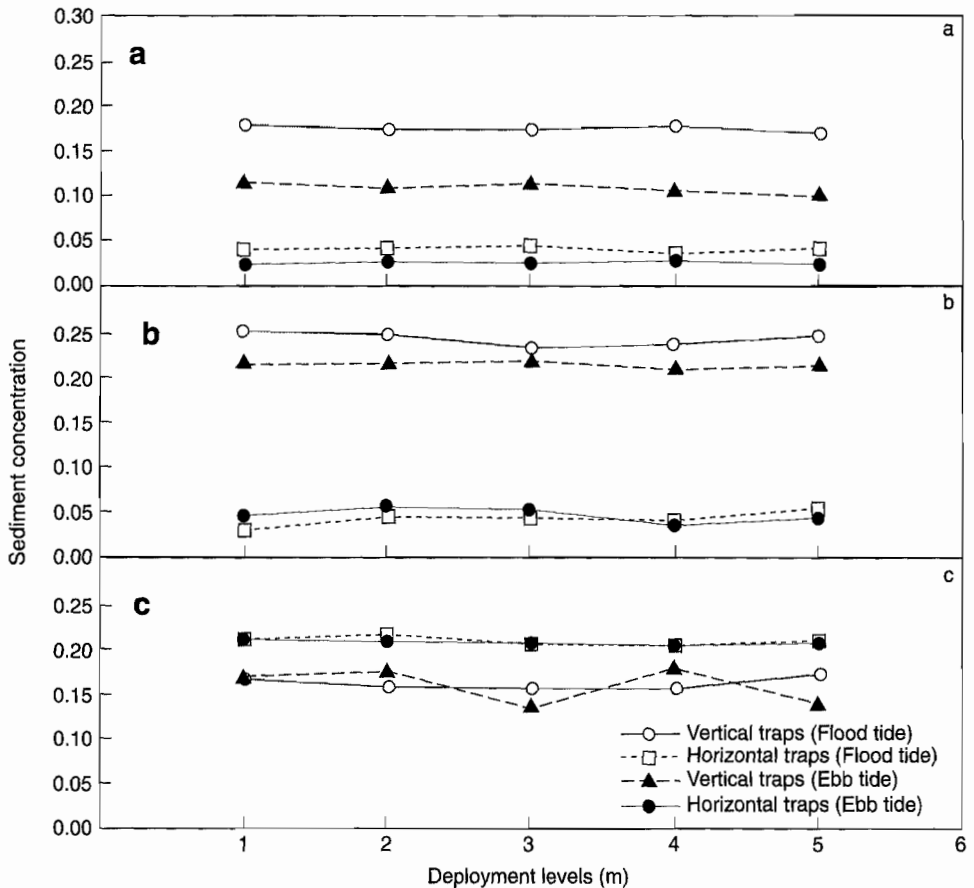Fig. 4. Reduced water depth in the Harbour basins surveyed on August 2002

Fig. 5. Sediment concentration at different levels in the entrance channel collected during (a) NE monsoon season on February 2001; (b) SE monsoon season on August 2001; (c) SE monsoon season on August 2002

rate was 25 cm/year. With the present rate of 43 cm/year it will only take 11 years.

It is recommended that a thorough study be carried out on the impact of the improvements to the entrance channel, and especially on the ongoing erosion on the Ras Makabe. Further studies should also be conducted so as to establish the pattern of sedimentation along the berth basin and to investigate why sedimentation on berth 8 is high, while at berth 6 and probably berth 5 there is scouring. Also of interest is whether the trend of sedimentation in berth 8 extends to berth 11.

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