Accuracy of marine siltation predictions

N V M Odd

Report SR 550
July 1999

HR Wallingford

Address and Registered Office: HR Wallingford Ltd. Howbery Park, Wallingford, OXON OX10 8BA
Tel: +44 (0) 1491 835381 Fax: +44 (0) 1491 832233

Registered in England No. 2562099. HR Wallingford is a wholly owned subsidiary of HR Wallingford Group Ltd.

Contract

This report describes work funded by the construction Directorate of the Department of the Environment, Transport and the Regions, DETR (previously DoE), under Research Contract PECD 7/6/197, for which the DETR nominated officer was Mr P W Woodhead and the HR Wallingford nominated officer was Dr S W Huntington. The HR Wallingford job number was BDS86. It is published on behalf of DETR, but any opinions expressed in this report are not necessarily those of the funding department. The work was carried out by Nicholas V M Odd FICE, head of the Water and Industry Group.

Prepared by ......N V M Odd...... *(name)*

......Senior Consultant...... *(Title)*

Approved by ......S. V. Huntington...... *(name)*

......Director...... *(Title)*

Date ...20 July 1999...

© HR Wallingford Group Limited 1999

Summary

Accuracy of marine siltation predictions

Nicholas V M Odd FICE

Draft Report SR 550
March 1999

The prediction of the impact of engineering works on marine siltation in estuaries, ports and coastal zones is often a difficult task.

The developer and the relevant national environmental protection agency need to have a reasonable measure of the likely accuracy of the marine siltation predictions proposed by the engineer to check that they are compatible with their needs and to justify the cost.

The expected accuracy of the marine siltation predictions should be compatible with the level of risk as regards the protection of the environment and the economic viability of the development. Otherwise, either the developer or the environmental protection agency will not be able to assess the impact or feasibility of the scheme.

The predictions now usually take the form of a numerical calculation or computational model. There is a wide range of computational models of varying and cost available to the engineer.

The most accurate predictions of marine siltation require a significant quantity of field data collected over a period of years, which may not be compatible with the budget, timescale or location of the engineering works.

The objective of the research described in this report was to audit siltation predictions for projects for which engineering works have been constructed and for which siltation rates have been recorded (prior- and post-construction), and thereby obtain a measure of the accuracy of the original predictions.

The observed rates and patterns of siltation were analysed to determine the most likely reasons for the errors in the predictions. The findings from the research shed light on the factors most affecting the accuracy of marine siltation predictions.

It proved difficult to obtain reliable data because many operators do not maintain accurate records of siltation, as it requires regular bathymetric surveys and detailed logging of sediment transported in dredger hoppers. Instead, they simply arrange to dredge when siltation becomes a nuisance.

There are at least two measures of a model's accuracy.

Firstly, was the model able to hindcast and quantify existing patterns of siltation in terms of processes, timing, spacial distribution and sediment type and density? Were the calibration factors reasonable?

Summary continued

Secondly, how accurately were the model's forecasts compared with the observed changes in siltation patterns following the completion of the engineering works. Both analyses have to be done in the context of natural annual and long-term changes in the marine climate (waves, river discharges etc).

Predictions of incremental changes in marine siltation caused by proposed engineering works – such as capital dredging, reclamations or breakwaters – are usually expressed as a percentage change from the base line conditions. The baseline conditions may be defined as a period between one tidal cycle and 50 years for which there are known external boundary conditions, (tide, river flows, wind and waves) based on historical observations.

The rates of siltation that occur after completion of the engineering works depend on the actual sequence and combinations of the external boundary conditions.

The report consists of two major case studies of post-construction siltation.

The first case study concerns two series of predictions of siltation in the navigation channel in the Tees Estuary made by HR Wallingford since 1964. The engineering works included reclamation of intertidal flats, capital dredging, changes in dredging practices and truncation of the estuary by a tidal barrage. Despite the excellent records on siltation in the estuary maintained by the Tees and Hartlepool Port Authority, it was not easy to unravel the effect of introducing the new engineering works and the natural variation in wave climate in Tees Bay, which is the source of the silting material.

The second case study concerns predictions made in 1977 of siltation in the commercial port of Esmeraldas and a fishing harbour at the mouth of the Rio Esmeraldas. These predictions are compared with 20 years of dredging data.

The main conclusions to be drawn from the two case studies are:-

(i) It is difficult separate and the effect of new engineering works on siltation rates from, year to year variations in wave climate and river flow, the transient effects of construction works and changes in dredging practices.

(ii) A combination of comprehensive field studies and the best available mathematical models can enable an engineer to simulate complex mud sedimentation processes and to predict the effect of significant engineering works on marine siltation to an accuracy better than about 10% of the existing long term average annual siltation rate, in the case of a change to an existing well-documented siltation regime.

(iii) It is not recommended that long term absolute rates of siltation are predicted from a single season, which may be unrepresentative, without some attempt to quantify variations in the driving forces.

(iv) It is safer to predict siltation rates in terms of a percentage of observed rates at a nearby site – with similar driving forces – for which longer term variations are known.

(v) The accuracy of siltation predictions for new developments in virgin sites will be much lower, at about plus or minus a factor of 2 (i.e. –50% or +100%), especially if the necessary long term statistical data on suspended sediment is not available.

Summary continued

(vi) One should distrust the predictions from a model, which is obviously unable to simulate a significant feature of the observed spatial and seasonal patterns of siltation. This usually means that the modeller has neglected to simulate one of the mechanisms governing marine siltation at the site.

(vii) The study highlighted the importance of modelling the mechanisms by which dredgers re-suspend mud into residual currents in a depositional regime, where normal tidal currents are too low to re-suspend mud.

(viii) Volumes of siltation cannot be predicted accurately without allowing for the effect of different grain size fractions and consolidation of the increasing sediment deposit.

(ix) It is usually necessary to predict siltation rates for a range of combinations of tide, wave and river flows to arrive at a representative annual siltation rate.

(x) In situations where maintenance dredging is carried out infrequently, it may be important to simulate the effect of increasing bed levels on the siltation pattern.

(xi) The research did not include an analysis of transient conditions such as wave erosion and the slumping of banks of newly dredged areas.

Contents

Contents continued

1. INTRODUCTION

The prediction of the impact of engineering works on marine siltation in estuaries, ports and coastal zones is often a difficult task.

The developer and the relevant national environmental protection agency need to have a reasonable measure of the likely accuracy of the marine siltation predictions proposed by the engineer to check that they are compatible with their needs and to justify the cost.

The expected accuracy of the marine siltation predictions should be compatible with the level of risk as regards the protection of the environment and the economic viability of the development. Otherwise, either the developer or the environmental protection agency will not be able to assess the impact or feasibility of the scheme.

The predictions now usually take the form of a numerical calculation or computational model. There is a wide range of computational models of varying and cost available to the engineer.

The most accurate predictions of marine siltation require a significant quantity of field data collected over a period of years, which may not be compatible with the budget, timescale or location of the engineering works.

For further information on marine computational models and their data requirements the reader is directed to two earlier DETR reports SR 456 (1996) "Guidelines for the use of computational models in coastal and estuarial studies" and SR 497 (1997) "Development of a unified approach for assessing siltation in harbours."

The objective of the research described in this report was to audit siltation predictions for projects for which engineering works have been constructed and for which siltation rates have been recorded (prior- and post-construction), and thereby obtain a measure of the accuracy of the original predictions.

The observed rates and patterns of siltation were analysed to determine the most likely reasons for the errors in the predictions. The findings from the research shed light on the factors most affecting the accuracy of marine siltation predictions.

It proved difficult to obtain reliable data because many operators do not maintain accurate records of siltation, as it requires regular bathymetric surveys and detailed logging of sediment transported in dredger hoppers. Instead, they simply arrange to dredge when siltation becomes a nuisance.

There are at least two measures of a model's accuracy.

Firstly, was the model able to hindcast and quantify existing patterns of siltation in terms of processes, timing, spacial distribution and sediment type and density? Were the calibration factors reasonable?

Secondly, how accurately were the model's forecasts compared with the observed changes in siltation patterns following the completion of the engineering works. Both analyses have to be done in the context of natural annual and long-term changes in the marine climate (waves, river discharges etc).

Predictions of incremental changes in marine siltation caused by proposed engineering works – such as capital dredging, reclamations or breakwaters – are usually expressed as a percentage change from the base line conditions. The baseline conditions may be defined as a period between one tidal cycle and 50 years for which there are known external boundary conditions, (tide, river flows, wind and waves) based on historical observations.

The rates of siltation that occur after completion of the engineering works depend on the actual sequence and combinations of the external boundary conditions.

The report consists of two major case studies of post-construction siltation. Data from other potentially interesting cases were not complete enough to present in the report.

Chapter 2 describes two series of predictions of siltation in the navigation channel in the Tees Estuary made by HR Wallingford since 1964. The engineering works included reclamation of intertidal flats, capital dredging, changes in dredging practices and truncation of the estuary by a tidal barrage. Despite the excellent records on siltation in the estuary maintained by the Tees and Hartlepool Port Authority, it was not easy to unravel the effect of introducing the new engineering works and the natural variation in wave climate in Tees Bay, which is the source of the silting material.

Chapter 3 describes predictions made in 1977 of siltation in the commercial port of Esmeraldas and a fishing harbour at the mouth of the Rio Esmeraldas. These predictions are compared with 20 years of dredging data.

The conclusions in terms of practical advice to engineers are given in Chapter 4.

2. SILTATION IN THE TEES PORT NAVIGATION CHANNEL

2.1 Background

Before the commissioning of the Tees Barrage in September 1994, the Tees estuary (Figure 1) consisted of a relatively narrow canalised channel extending 44km inland from South Gare, at the entrance in Tees Bay, to Low Moor Weir. The navigation channel of the port, which extends 13km into the estuary, has been dredged continually since at least 1895, with periods of deepening. HR have carried out two series of modelling studies to predict siltation in the navigation channel in the Tees Estuary in the last 40 years.

The first series of studies in 1958-66 were carried out for the Tees Conservancy Commission with the aim of predicting the effect of deepening and widening the navigation channel on siltation rates in the channel. The works were to be carried out in two stages to maximum of –15mOD in Tees Bay, and –13.6mOD in the lower estuary, and –17.5 mOD at a turning circle in Tees Dock and then reclaiming the intertidal flats. The present depth and width of the navigation channel is close to that tested in 1964-66.

In the 1960's, the predictions were made using an undistorted scaled physical model of the approaches to the port in Tees Bays with waves, and a vertically distorted (1:10) model of the estuary with saline intrusion. Both models had mobile sediment beds. (Reference 2.1 and 2.2). At that time, observations were also made of the rate of infill of localised trial dredged pits.

The navigation channel within the estuary, was progressively deepened from about 1968 to 1988 to its present profile, which is maintained as a series of steps with bed levels of about –17.5mOD from Km 0 - 4, - 13.5mOD for Km 6.5 - 10 and -8mOD for Km 10 – 13.

In 1973, the Tees and Hartlepool Port Authority (THPA) started systematic collection and analysis of data to estimate the annual rate and pattern of siltation in the navigation channel covering ten reaches within the estuary (Figure 2.2) and two reaches in the bay and the main berths.

In 1988, the Teeside Development Corporation (TDC) commissioned HR to carry out a field survey (assisted by THPA) and to construct and calibrate a 2D- in-depth, width-averaged mathematical model of stratified tidal flows, mud transport and siltation and water quality in the Tees Estuary. The model was used to help understand the processes of siltation and to predict the effect of the barrage on siltation rates for the purposes of the parliamentary proceedings, and to come to an agreement with THPA as regards liability for siltation arising from the operation of the barrage. The construction of the barrage was completed in September 1994. (Reference 2.3 and 2.4).

In 1991, THPA commissioned HR to develop a 2D-depth-integrated mathematical model of tidal flows, wave bed stress and sand transport in Tees Bay and to use the existing model of mud transport in the Tees Estuary to predict the effect of changing the pattern and method of dredging as part of a dredging review. (Reference 2.5).

2.2 1966 predictions of siltation in a deepened canalised estuary

HR staff (Reference 2.2) who carried out the 1962-66 physical model study concluded from the field data that the null point of the two-layer gravitation circulation and potential shoaling zone for suspended mud was at Km 13.4 in the Billingham reach where the volumetric rate of siltation was greatest. The null point is the position at which the net residual velocity near the bed in the two-layer gravitation circulation is zero (Km 13 in Figure 2.5a). The fluvial sediment load was considered to be small compared to marine sources. It was concluded that sand would only move into the navigation channel on spring tides and that it would not intrude far into the estuary. It was also concluded from past dredging rates that the annual volume of siltation was variable and not obviously related to the depth of the navigation channel.

Two years was spent in calibrating the distorted physical model for tidal levels, velocities, salinities and sand and mud siltations. The sand was represented by 0.55mm granules of white pine ($\gamma = 1.1$) and mud by very fine wood flour. The 1:10 distortion, needed to prevent laminar flow required a very rough bed, which was not generated by the mobile bed of woodgrains. The investigators had no means of quantifying the supply of mud at the entrance to the estuary. The wood grains were injected into the lower layers of the water column 2.4km inside the estuary. It was not possible to simulate the observed high rates of low density mud siltation in the Billingham reach. It was argued that the distorted model did not simulate the flow in the bend in that reach.

The calibrated model was used to test various combinations of channel deepening, widening and reclamations, some very similar to the present day configuration of the estuary.

It was concluded from the model studies that the engineering works (reclamation and deepening) would tend to reduce the tidal velocities and hence further reduce the movement of sediment upstream. As a result the centre of gravity of the siltation would be closer to the entrance with a reduction of siltation rates in the Billingham reach (similar to the patterns shown in Figure 2.4). The average annual dredging commitment in the estuary would remain at about 800,000m^3/year with adjustment depending on changes in the tidal volume. The proportion of muddy siltation would increase.

In the decade 1983 – 1992, before the construction of the new barrage, the annual volume of siltation in the estuary (reaches 1 – 10) averaged 1.1Mm^3/year. Therefore the prediction in 1966, based largely on the analysis of past trends in siltation, and only partially on the model appears to have been about 25% less than actual siltation rates two decates later. This is reasonably good if one considers the difference between the schemes tested and the actual shape of the estuary in 1983-92. However, the 1966 predictions were wrong as regards the forecast reduction in muddy siltation at the landward end of the navigation channel. This indicates that there was a vital process missing in the model, which was evident by the failure of the model to simulate the existing (i.e. before channel widening and deepening) siltation in the Billingham reach.

2.3 Predictions of the effect of truncating the estuary with a barrage

In 1988-89, HR set up and calibrated a 2D in depth, width-averaged mathematical model of flow, saline intrusion and mud transport in the Tees Estuary for the Teeside Development Corporation (TDC), who planned to construct a barrage to truncate the tidal compartment at Km 17. (Reference 2.3 and 2.4).

2.3.1 Calibration of the siltation model

The model was calibrated for tidal velocities and saline intrusion in the usual manner. The vertical mixing was defined by universal mixing length damping functions.

The concentration of suspended mud measured by a silt meter located near the bed at the mouth of the estuary (Figure 2.3), was correlated with observed peak wave bed stress and tidal current in Tees Bay. The peak wave stress was calculated from the wave height, period and depth of water and the tidal current in the approaches to the estuary were assumed to be directly proportional to the rate of change in the tidal level. The mud concentrations in the river water was correlated with the river discharge. The wave climate was used to calculate the duration of periods during which the concentration of mud in the bed waters of Tees Bay would be maintained at a given value. Values were derived for the winter and summer periods of high and low river flows and strong and weaker wave activity, respectively.

The total average annual siltation was computed by weighting the predictions for each combination of river flow and mud concentration in Tees Bay, ignoring rare events. The large fluvial flood and storms in Tees Bay were treated as special events and simulated as such.

An implicit assumption was that the supply of mud in suspension at the mouth of the estuary would vary from year to year depending on the wave climate.

The model reproduced the same exponentially decreasing rate of siltation from the mouth of the estuary (Figure 2.4) as the 1968 physical model with little or no muddy siltation at Billingham at the null point of the two layer gravitation circulation (Figure 2.5). However, it was noted that the two trailing hopper dredgers employed continuously by THPA had a practice of allowing the full hoppers to overflow (weiring) for 10-15 minutes while the fluidised mud consolidated in the hopper. This occurred about 3 times a day in reaches 1-6.

The overflowing mud would tend to settle into the lower layer and be carried upstream by the gravitational circulation (Figure 2.5). It was also considered that the jets from the propellers of heavily laden vessels with a low keel clearance could re-suspend mud into the lower layer.

It was therefore decided to disturb and re-suspend the thin (<10mm) low density (<300kg/m^3) "slack water" mud deposits on the surface of the bed into the lowest layer of the model flow between km0 and km11 at regular intervals throughout the tidal cycle. This was done by increasing the bed stress by an extra 2 N/m^2 for 5 minutes. The model results were not sensitive to the exact frequency of disturbance. At the same time, the rate of vertical mixing between the lowest three layers (≈5m) was also increased to simulate the turbulence caused by the passage of passing vessels and dredgers. The effect of the surface wash caused by passing vessels, which erodes the slack water deposits on the submerged mud banks at the sides of the estuary, was simulated by increasing the bed stresses in the two surface layers.

The introduction of the effect of mechanical disturbance and re-suspension of thin slackwater deposits on the bed surface by dredging and ships propellers greatly improved the simulated distribution of mud siltation in the estuary, with a peak near the null point of the gravitational circulation in Billingham reach (~Km13) (Figure 2.6).

2.3.2 Effect of the barrage

The model was then modified by inserting a barrage into the estuary 17km upstream of South Gare (Figure 2.1. The barrage was set to retain a minimum water level of + 2.5mOD upstream and it was not allowed to be overtopped on the flood tide. The boundary conditions of the fluvial discharge and the concentration of suspended mud in Tees Bay for the various tests were unchanged. The model tests were re-run and the siltation was calculated and summed up over a period of a 15 day neap-spring tidal cycle in an identical fashion to the tests carried out for calibration purposes.

The model predicted that the construction of the barrage would reduce the tidal volume at the mouth by about 10%, and modify the gravitational circulation and decrease tidal currents near the barrage. The model was used to predict siltation for several combinations of river flow and wave conditions in Tees Bay (Figure 2.7).

The breakdown of average annual siltation with the barrage during the winter and summer periods were calculated as follows;-

Table 2.1 Prediction of seasonal siltation with the barrage

%time	Days	Mud conc in Tees Bay (ppm)	Wave condition	Predicted siltation (tonnes)
Winter and equinoctial period: 7 months				
14.3	30	600	Storms	320,000
21.4	45	250	Moderate waves	150,000
14.3	30	125	Small waves	40,000
50	105	Negligible	Calm conditions	Negligible
100	210		Winter Sub Total	510,000
Summer period: 5 months				
14.5	22.5	250	Moderate waves	50,000
14.5	22.5	125	Small waves	20,000
71.0	110	Negligible	Calm Conditions	Negligible
100	155		Summer Sub Total	70,000
Fluvial sediments:				40,000 tonnes
			Total	620,000 (-11%)

An analysis of the above figures compared with the earlier estimates of existing siltation indicated that the construction of the barrage would, in an average year (based on the period 1983-87), tend to reduce siltation in the estuary (excluding Seaton Channel), by up to about 80,000 tonnes (160,000m^3). Most of the reduction from 1,400,000 to 1,240,000m^3/yr, which represents about 11% of the average annual rate of siltation in the main channel and berths, was predicted to occur during stormy periods in the winter months. The same percentage reduction in siltation was predicted to occur in the summer months. The beneficial effect of the barrage, which was assumed to be caused by a reduction in the tidal volume and gravitational circulation at the mouth of the estuary, would vary from year to year depending on the frequency and strength of the winter storms. During calmer periods it was expected that the settled mud would continue to be re-suspended by dredging and the passage of larger vessels and re-distributed along the estuary.

It was not practical to predict the final aggregated distribution of siltation in the estuary with and without the barrage by superposing the various distributions in proportion to their frequency of occurrence, because it was not certain how the effects of dredging would redistribute the large mass of mud which was predicted to settle in the lower estuary during storms in Tees Bay. However, it was expected that the change in the shape of the longitudinal distribution of muddy siltation caused by the construction of the barrage would be likely to be similar to that shown in Figure 2.7, if dredging practices remain unchanged. (i.e. weiring continued). The overall long-term average rate of siltation was predicted to decrease by about 10%. The model predicted that most of the reduction would occur in the vicinity of Redcar (Chart area 9) (Figure 2.2) during relatively infrequent storm events. During calmer weather the model predicted that the barrage would alter the tidal and gravitational flows, and hence the distribution of siltation in the estuary. Assuming the continuation of the present dredging practices, the construction of the barrage will tend to reduce the rate of siltation in Billingham Reach by 10-20%. The actúal rate of siltation in the estuary and in particular reaches would continue to vary widely from year to year depending on the frequency of storms and rough weather in Tees Bay.

The 10% reduction in the tidal currents and the gravitational circulation at the mouth of the estuary should also reduce the influx of fine sand and coarse silt into the Tees mouth from Tees Bay during storms. The actual percentage reduction in sandy siltation in km 0-2 could not be quantified using the model, which was designed to predict mud transport.

The Tees Barrage was constructed between February 1992 and September 1994

An analysis of the actual effect of the construction of the barrage is described in Section 2.5.

2.4 1991 Predictions of effect of changes in dredging practices

In 1991, THPA commissioned Sir William Halcrow and Partners, HR and Environmental Management Ltd to review their dredging practices and to make recommendation for improvements.

HR used the model developed for TDC, to examine the effect of the cessation of dredging upstream of Middlesborough (Km10) combined with a continuation of the existing pattern of over-dredging and agitation and weiring downstream. The model predicted severe shoaling of more than 1.5m/year upstream of Middlesborough. The level of the shoal would ultimately be controlled by scour by large fluvial floods. The shoal might adversely affect water quality downstream of the barrage.

It was predicted that the cessation of regular dredging for periods of between several months and one year would result in concentration of siltation in the lower estuary with little siltation at Billingham. The overall mass of mud trapped in the estuary would increase as a result of less sediment agitation and re-suspension on the ebb tide, but the presence of silt and fine sand in the mud would produce a higher density deposit, which should be fairly evenly distributed across the dredged navigation channel. The depth of siltation after one year without dredging would be accommodated by the depth of over-dredging, which had built up over the past years, except perhaps in Chart 10. There was no need for a specially constructed mud trap. Eighty per cent of the sediment was predicted to be deposited in the 7 month period October-April. Annual dredging would have to be carried out in the summer months and, ideally dredging should be conducted when the current in the bed layer is either stationary or flowing seaward, which occurs between HW and HW + 5 h in the lower estuary.

In late 1991, as a result of the dredging review, THPA stopped the practice of overflowing full hoppers when dredging the most muddy reaches (1-6). (km 6-14).

2.5 1998 follow up study

In May 1998, the author obtained THPA's estimates of actual siltation the Tees Estuary in the years 1987 – 1997, a period during which the depths in the navigation channel were maintained at a nearly constant value. (Table 2.2).

The data (Figure 2.8) showed at continuous decrease in total siltation in Chart zones 1 – 10 from 1.45Mm^3 1988 to 0.62Mm^3 1994, inclusive and then an increase to 1.0Mm^3 in 1995 with equal lowest ever levels of siltation of 0.55Mm^3 1996-97. It should be noted that an error in the estimated siltation in one year is usually reversed by an equal and opposite error in the next year.

The author obtained best estimates of the wave climate in Tees Bay each year from an analysis of the UK Met Office wave data for the years 1987 – 97. The selected variable to measure the severity of the annual wave climate was the percentage of time for each year during which the significant wave height in Tees Bay exceeded 1.5m. From the Institute of Hydrology, the author also obtained the median annual discharge of the River Tees at Low Moor Weir at the head of the estuary for the same period. The median flow was selected because it was not overly biased by large floods or drought flows.

The field data for 1987-97 showed no strong correlation between total annual siltation and the median river discharge, which confirms the model behaviour reported in 1989 (Reference 2.3). The model had showed that the effect of the river discharge, via the gravitational circulation, was small compared to the effect of the mud concentration in the bed layers of Tees Bay. For example, the model had shown that a fourfold reduction in the flow in the River Tees from 32 to 8.5m^3/s only reduced the rate of siltation of marine mud in the estuary by 20%. Furthermore, the distribution of siltation along the estuary was almost unchanged. This relatively small effect is almost wholly explained by the fact that the gravitational circulation had the same pattern as with the lower flows. All available suspended sediment is simply moved landward towards the null point. The gravitational flow in the bed layers at the mouth of the estuary did, however, reduce the influx of mud from the bay.

The THPA data showed nearly a 60% (0.8Mm^3) reduction in annual siltation from 1989 to 1994 before the completion of the new Tees Barrage. The author believes this can be explained as follows:-
The percentage of the year during which waves in Tees Bay exceeded 1.5m decreased from 19% and 14% in 1987 and 1988 to an average of 10% in the 6 years 1989-1994. In 1989, the model had predicted that the rate of siltation in the estuary would increase with approximately the square of the concentration in the bed layers in Tees Bay at the mouth of the estuary. For example, the rate of siltation in the estuary over a 15 day period with a flow of 32 m^3/s in the River Tees increased from 14,000 to 200,000 tonnes with a four fold increase in mud concentration at the entrance to the estuary from 125 to 600 ppm. This is to be expected because the rate of deposition of mud varies with the square of the concentration of suspended mud, which is a function of the wave bed orbital velocity in Tees Bay. It follows that the siltation rate in the estuary will fall in relatively calm years.

The effect of a reduction in the percentage of time when the waves exceed 1.5m in Tees Bay for about 18% to 10% is estimated to have caused a reduction of 0.4Mm^3 of siltation in the estuary (A in Figure 2.8).

At the end of 1991, THPA ceased overspilling (weiring) in reaches 1-6, which appears to have been responsible for a considerable reduction in siltation (B in figure 2.8) from 1992 onwards. This effect was predicted by the model in 1989. The siltation data indicates that this reduction could be as high as 0.3Mm^3 which is the peak rate of siltation in Billingham reach in a bad year (1987). The rate of siltation in Billingham reach (chart 2) fell sharply between 1991/92 and has remained low ever since. (Table 2.2).

THPA data showed that the percentage of dredged siltation (by insitu volume) between Km 6 and Km 14 – including Billingham reach – decreased from 46% to 35% of the total in the estuary upstream of South Gare in the three year periods 1989-91 and 1992-94 before and after the cessation of spilling (weiring) upstream of Km 6. (Figure 2.9).

The wave climate was fairly constant but 50%-ile river flows doubled throughout the period of 1989-94 which also covered the construction of the Tees Barrage.

The total annual volume of siltation in the estuary between 1989-91 and 1992-94 decreased by 20%. This may be explained by the fact that the settled mud has a higher density if it settles and remains in the lower estuary (Figure 2.10).

It is unlikely that the higher 50%-ile river flows in the 1992-94 period caused a significant shift in the null point of the gravitational circulation.

The new Tees barrage was commissioned late in 1994 and siltation rose by 0.4Mm^3 from 1994 to 1995. However, at the same time the percentage of waves exceeding 1.5m in Tees Bay rose from 8 – 18%.

In 1997, the siltation fell to about 0.6 Mm^3/year, 0.2Mm^3/year less than in 1993 before the operation of the barrage when the wave climate was similar (waves exceeded 1.5m for about 10% of the time) and overspill had been stopped. This implies that the operation of the barrage has reduced the annual rate of siltation permanently by about 0.1 - 0.2Mm^3, which was about 10% of the siltation rate in 1988, as predicted by the model (in 1989).

Table 2.2 Volumes of Siltation in Charts 1-10 (1987-1997)

Chart	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
1	174,500	124,108	69,554	23,881	61,019	49,190	55,194	56,899	17,763	4,030	34,189
2	278,000	129,535	111,263	101,000	176,948	82,352	47,331	54,490	41,343	9,612	32,575
3	77,800	72,240	53,688	92,535	74,621	41,858	52,248	39,881	24,583	18,498	21,192
4	88,700	70,049	76,918	240,276	48,861	77,710	62,249	-4,639	72,764	13,676	192
5	110,300	136,313	132,399	107,754	67,572	71,577	67,393	-50,524	247,985	12,139	29,295
6	99,200	67,217	118,894	98,295	81,206	13,929	102,387	77,231	68,283	-8,289	92,528
7	13,000	137,984	103,005	102,231	60,036	65,560	69,176	73,728	42,793	66,324	17,875
8	76,600	167,324	171,513	178,467	73,489	173,372	175,685	136,845	221,040	97,364	69,071
9	239,500	256,754	199,250	228,980	147,211	186,693	280,938	115,688	86,246	236,097	214,710
10	19,400	248,623	63,964	186,775	89,607	185,420	106,989	124,684	166,781	92,124	56,372
Total	**1,177,000**	**1,370,149**	**946,612**	**1,360,194**	**871,277**	**947,661**	**1,019,590**	**642,283**	**989,581**	**541,595**	**567,999**

Notes:

overspilling stopped landward of 6 Km (charts 1-6) start of 1992
(i) relatively calm years 1989-94 and 1997
(ii) barrage under construction 1992-94
(iii) barrage closed start 1995
(iv) an error in siltation in one year is usually compensated the next year
(vi) units are cubic metres on insitu siltation
(vii) the dry density of the deposit increases from charts 1-10

The percentage of siltation by volume settling upstream of Km 6 also averaged 35% in the three year period 1995-97 after the completion of the barrage.

The volume of siltation settling near Billingham (Chart 2) decreased after the construction of the barrage and remained low in the period 1995-97, an effect predicted by the model.

To summarise:-

(i) Natural variations in the wave climate in the Tees Barrage are the biggest cause of changes in the annual rate of siltation. In the past year to years variation of up to 0.8Mm^3/year have been recorded (1982-83). This was equivalent to about 60% of the long term average siltation rate at that time.

(ii) Stopping the practice of allowing overflow of dredge hoppers (weiring) in reaches 1 – 6 appeared to have reduced muddy siltation in Billingham Reach permanently by 0.3Mm^3/year. However, some of this reduction is caused by the barrage. The model (Figure 2.4) predicted a reduction of abut 30% of 1.4Mm^3/year which is about 0.4Mm^{3}year.

(iii) The truncation of the estuary by the Tees Barrage appears to have reduced the rate of siltation in the estuary permanently by about 0.1 - 0.2Mm^3 /year. The model predicted a reduction of 10% of 1.4Mm^3/year, which is 0.14Mm^3/year.

Rates of marine siltation may have also been reduced further by the introduction of differential GPS navigation systems on the 'Heortnesse' and 'Cleveland County' dredgers in 1996 and 1997, respectively, allowing a more surgical removal of shoals with minimum disturbance of the bed.

It is worth noting that cost of dredging 1m^3 of soft mud from Billingham Reach is about twice that for a denser mud in the lower estuary.

It is concluded that the mathematical model used to predict mud transportation in the Tees Estuary was able to predict the effect of changes in river flow, wave climate, capital dredging, barrages and some dredging practices on mud siltation to an accuracy equivalent to about 10% of the average annual volume of muddy siltation in the estuary. (ie about $\pm$ 0.1 million m^3 in this case). However, this can only be achieved if the model is calibrated carefully by comparison to existing patterns of siltation, and provided that the concentration of suspended mud at the mouth of the estuary can be quantified in terms of the frequency and amplitude of the tidal currents and bed orbital velocities in the seaward approaches.

3. SILTATION AT THE PORT OF ESMERALDAS, ECUADOR

3.1 Background

The commercial port of Esmeraldas is situated at the mouth of the estuary of the Rio Esmeraldas (Figure 3.1). The majority of the flow is derived from rainfall at the head of the 2,000km^2 catchment high in the Andes. There are strong seasonal variations in the river discharge, which peaks in the period January to early May.

The breakwaters forming the 36ha port area were built on the edge of a 100m deep 1000m wide submarine canyon leading from the Pacific Ocean, which penetrates into the shallow sandy estuary. The capital dredging of the port was finished in January 1976 giving it an initial bed level of about –11m LAT.

The depth of water in the lower estuary beyond the edge of the canyon varies from 1m at LAT to 5m at HW mean spring tide. Vessels have to make a 90° turn west at the southern landward end of the canyon to enter the port.

Shortly after completion of the commercial port it was decided to construct a separate fishing harbour adjacent to the commercial port, and Livesey and Henderson (now incorporated in Binnie, Black and Veatch) commissioned HR to assist in the field survey and to use mathematical models to obtain a better understanding of the causes of siltation in the port.

HR was also required to use the mathematical models to help optimise the layout of the new fishing harbour, to reduce rather than increase siltation in the commercial harbour and to minimise siltation in the fishing port entrance. An analysis of the most likely mechanism of siltation in the port area is given in Section 3.3. The methods used to predict the effect of the new fishing harbour on siltation in the port area are described in Section 3.5.

In 1977, HR (Reference 3.1) predicted that the construction of the fishing port based on the outline design provided to HR, would reduce siltation by about 30% compared with the situation in 1976/77. The construction of the fishing harbour would probably raise siltation rates in the port temporarily. The actual rate of mud siltation in the commercial port would depend on the amount of mud carried by the river in the wet season, which varies from year to year.

HR also predicted that the rate of siltation in the approach to the new tidal fishing harbour (Figure 3.1) with an area of about 18ha, and a 400m long, 90m wide approach channel with a bed level of –6m LAT would be significant, and about 50% of that occurring in the commercial port under the same 1977 wet season conditions. The report showed tables of annual rates of siltation based on 1977 wet season conditions (15,000 – 25,000m^3/year) – the only year for which mud concentrations were available.

Between January 1976 and March 1977, 270,000m^3 of muddy sediment settled in the port, mainly in the 350m wide entrance (Figure 3.2). The period of siltation nearly covered two wet seasons. The amount of accretion varied from 4-5m on the bar across the entrance to less than 0.5m in the port basin. The siltation between July 1976 and March 1977, including most of the 1977 wet season, was less than 25% of the siltation which occurred in the 1976 wet season. It was considered, at the time, that the 220,000m^3 of siltation in the 1976 wet season was caused in part by dredging activities or engineering works associated with the reclamation of land in the estuary immediately upstream of the entrance to the port.

3.2 History of siltation at Esmeraldas

It is assumed the port was re-dredged to its design depth in 1977, otherwise vessels would not have been able to use the port.

It proved difficult to obtain information on dredging at Esmeraldas directly from the Port of Authority of Esmeraldas (APE) because many of the original records were missing. It took several years to collect the following data. Firstly, evidence from the consultants (Ref 3.2), secondly via Ecuador Navy via contracts in Venezuela (Ref 3.3), and most recently (1999) by private correspondence with an engineer in Ecuador (Ref 3.4). A summary of the estimated rates of siltation in the commercial port and the fishing harbour are given in Tables 3,1 and 3.2 respectively.

At the end of the 1979 wet season, 237,000m^3 were dredged from the commercial port (equivalent to a siltation rate of 120,000m^3/yr). At the same time the fishing harbour was dredged to –8m LAT in the entrance channel and between –7m LAT and + 0.3m LAT in the inner harbour. The inner harbour was not dredged to its design depths of -3.5 to –5.5m LAT.

The average annual rate of siltation in the commercial port in the four years 1976-79 before the fishing port was built is about 130,000m^3/yr.

In October 1981, it was reported (Reference 3.2) that the rate of siltation in the entrance to the commercial port had decreased significantly to 10,000m^3 (over 2 years) and deposition in the entrance to the fishing port was similar.

However, in between May 1984 and July 1985, the Ecuador Navy were reported to have dredged 545,000m^3 from the inner basin and approach channel to the fishing harbour to give depths of –5m and –8m LAT respectively. An estimated 300,000m^3 was capital dredging and 120,000m^3 was un-dredged siltation in the approach channel. The average siltation in the six years 1980-85 was about 60,000m^3/yr.

At the same time about 660,000m^3 was dredged from the commercial port increasing depths to –12.5m giving siltation rate of six years of about 110,000m^3/yr. Between December 1992 and May 1993 the Ecuador Navy dredged 719,000m^3 from the Port, which is equivalent to a siltation rate of 90,000m^3/yr over 8 years. Between July 1996 and January 1997 422,000m^3 was dredged from the commercial port equivalent to a siltation 140,000m^3/yr over 3 years. The silt was removed from the port bar the rate of about 70,000m^3/year in 1997 and 1998. In both cases the pre-dredging depth on the bar was quoted as –6m LAT (6.5m above the declared depth).

Table 3.1 Siltation in the Esmaraldas Commercial Port 1976-98

Year	Siltation rate (m^3/year)
1976	220,000 (measured directly)
1977	50,000 (measured directly)
1978-79	120,000 2 year average
	Capital dredge of the fishing harbour
1980-85	110,000 6 year average
1986-93	90,000 8 year average
1994-96	140,000 3 year average
1997	60,000 bar only
1998	75,000 bar only
1980-1998	100,000 19 year average

The corresponding data from the fishing harbour suggested an average annual rate of siltation of 60,000m^3 in the 6 wet seasons of 1980-85, which is about 60% of the rate of siltation in the commercial port during the same years.

However, in 1996 a bathymetric survey of the fishing harbour was made to quantify maintenance dredging volumes to give bed levels of –7.5m LAT in the channel and –5.5m LAT in the inner harbour. A comparison was made with the 1985 post dredge survey (figure 3.1) and it was estimated that 120,000m^3

of siltation had accumulated in the entrance channel and 35,000m^3 in the inner basin over a period of 10 years, equivalent to an annual rate of siltation of 15,000m^3/yr. The survey showed that the level of the mud bar or plug in the approach channel had risen to –0.6m LAT at a section about 100m into the 350m long channel.

Table 3.2 Siltation in the Esmaraldas Fishing Harbour

Years	Siltation rate (m^3/yr)	
1980-81	7,500	(2 year Average reported by consultant)
1980-85	60,000	(6 years average estimated from dredging volumes)
1986-1995	15,000	(10 year average. Entrance channel heavily silted)

3.3 Analysis of the mechanism of siltation at Esmeraldas

An analysis of the mechanism of siltation at Esmeraldas and data available in 1977 is needed to judge the cause of any errors in the original predictions.

The commercial port of Esmeraldas is situated at the mouth of the estuary of the Rio Esmeraldas. The majority of the flow is derived from rainfall at the head of the 2,000km^2 catchment high in the Andes. There are strong seasonal variations in the river discharge, which peak in the period January to early May.

A stage-discharge section was established at San Mateo, 14km upstream from the mouth of the estuary and operated from February to December 1977. The river discharges varied from low flow of about 400 m^3/s in June in the dry season to a peak of 4000m^3/s in March 1977.

The maximum daily suspended mud load of the river during the survey was about 200,000 tonnes/day. This is equivalent to about three years annual siltation in the commercial port at a dry density of 0.65 tonnes/m^3. The observations at San Mateo showed that a negligible amount of mud was carried into the estuary in the dry season. This showed that the siltation in the port area could be concentrated in the wet season between January and April.

An intensive survey of the Esmeraldas estuary was carried out between February and May in the 1977 wet season.

A salt wedge forms in the estuary. The flow in the estuary in the wet season approximates to a series of quasi-steady states where by the position and shape of the intruding salt wedge is balanced by the forces exerted by the outflowing river water. The position of the nose of the wedge, where the Densimetric Froude Number approaches a value of unity, is usually close to the edge of the canyon at LW in the wet season.

The thickness of the freshwater layer averaged about 2m in the 1977 wet season survey. The saline wedge intruded into the estuary and the commercial port as the tide rose by a maximum of 4m.

The thickness of the surface freshwater layer in the commercial port adjusted itself so that it was in balance with conditions that prevail outside the entrance, thus the upper brackish layer was thinnest at HW. The tidal flow into the port basin from the lower saline layer equalled or exceeded the nominal tidal volume of the port.

The warmer, fresh, mud-laden (100-400ppm) surface layer of fluvial water flowed strongly past the entrance to the port at speeds of up to 1m/s. The much thicker lower layer was almost stagnant except for a slow movement in and out of the port basin. There was also a weak counter flow into the estuary to balance the vertical flux of salt water entrained into the surface layer. The suspended mud in the surface layer was in a de-flocculated state with a settling velocity of less than 0.05mm/s. The suspended mud that had been mixed across the halocline into the lower layer had flocculated and was settling at a velocity of about 2mm/s.

For the purposes of the study, HR constructed and calibrated a steady state 2D in-plan 2-layer model to simulate flows and the transport of suspended mud in the lower estuary (Ref 3.1) . The model covered an area of 10km^2 with a uniform horizontal grid of 70m aligned in a N-S direction. The flow model was calibrated for river flows of 3700m/s and 1425m^3/s using float track data. The model simulated a slow anti-clockwise eddy in the surface layer in the commercial port with circulating velocities in the range 30-50mm/s.

The model was then used to predict mud concentrations in the surface and saline layers in the lower estuary. It was shown that vertical turbulent exchange was the main mechanism for transporting mud from the upper into the lower layer. The simulated mud concentrations in the lower layer outside the entrance to the commercial port varied between 10-30% of the surface layer concentrations, which was in the range of the observed differences..

The approximately calibrated model was then used to predict the effect of the embankments forming the new fishing harbour on surface flows and mud concentrations in the approaches to the commercial port and the proposed fishing harbour.

A second two-dimensional in-vertical analytical model (i.e. an analytical solution to linear differential equations) was developed to describe the curved trajectories and pattern of deposition of mud flocs settling within the port.

The path and point of deposition of each mud floc depends on its initial height as it enters the port on the rising tide, the phase of the horizontal motion, its settling velocity (five fractions) and the amplitude of the tidal excursion, which is the product of the tidal range and surface area of the port divided by the cross-sectional area of the entrance channel. The maximum tidal excursion was about 400m on spring tides, hardly enough to carry mud into the main body of the basin.

The analytical model ignored transport in the relatively thin surface layer and the effects of lateral and vertical turbulent exchange in the lower layer. The model was used to hindcast siltation in the port for the period February to April 1977.

The theory predicted a pattern of siltation decreasing exponentially from a maximum at the entrance to the port. In other words, a bar across the entrance to the port. The best fit for siltation in the port in the 1977 wet season (Figure 3.3) was achieved assuming the mud concentration in the bed layer outside the entrance to the port was 20% of the value observed values at San Mateo 14Km upstream. This fraction agreed with the results from the 2D 2-layered model and fell within the range of the field observations made in the entrance to the port.

The rate of siltation just outside the entrance to the port would be higher because there would be a continuous rain of mud particles settling from the overlying fluvial layer at all stages of the tidal cycle. However, the bed in this area sloped steeply into the canyon. The transport of de-flocculated mud into the port by the anticlockwise eddy in the surface layer probably raised siltation rates on the northern end of the bar across the entrance. (Figure 3.2).

3.4 Prediction of the effect of the fishing harbour on siltation in the commercial port

The design of the fishing harbour was not finalised at the time the siltation predictions for the commercial port were made. However, it was planned to be constructed on very shallow ground inland and adjacent to the port entrance.

The reclamation was positioned as close to the mouth of the commercial port as foundation conditions would permit. The 2D model predicted that the reclamation containing the 18ha fishing harbour and 400m long 100m wide approach channel would reduce the cross flow in the surface layer in the immediate vicinity of the entrance to both the commercial port and the fishing harbour.

The model did not predict an eddy in the lee of the fishing harbour – a forecast apparently confirmed by the current vectors shown on the latest chart (Figure 3.1). The model also predicted hardly any circulation within the commercial port.

The ability of the model to resolve the detailed shape of the reclamation was limited by the 70m North/South grid.

The model also predicted a reduction of the mud concentrations lower saline layer (relative to that in the river water) at HW. The effect was less at LW when the bank, on which the fishing harbour was to be built, would normally be nearly dry. Although, the mud concentrations showed a tendency to be lower than without the fishing harbour, it was not possible to be precise. It was estimated that concentrations of mud entering the commercial port and therefore the rate of siltation would be reduced by "about 30% compared to conditions without the Fishing Harbour". This satisfied the consultant because the minimum objective was not to increase siltation in the commercial port.

Nowadays one would expect be able to make a better prediction using a fine gridded 3D model but only if one carried out a similar amount of field work.

3.5 Prediction of siltation in the Fishing Harbour

The analytical mud floc trajectory model was used to forecast the amount of siltation in the 350m long 100m wide approach channel to the 18ha inner basin of the fishing harbour.

In fact, 27 differing combinations of channel width, depth and harbour surface area were examined. In all cases the tidal excursion was found to be greater than the length of the entrance channel (~ 350m). The model predictions varied linearly with the mud concentration, which was based on observed values in the saline wedge during a 3 month period of the 1977 wet season allowing for a factor of safety of 2 (ie doubling the observed concentrations).

For a design closest to the built design, the model predicted that about 95% of the mass of mud would settle in the 7m deep approach channel. More mud would reach the harbour basin and settle in the channel as it shoaled. However, the predictions were not made for a depth of less than 5.5m.

The volumes of siltation were based on an observed density profile with the dry density increasing to a maximum uniform dry density of 0.7 t/m^3 at a depth of 0.5 m. The model predicted a fairly evenly distributed low density deposit in the inner basin.

The model predicted the development of a bar near the seaward end of the channel with a peak annual shoaling rate of between about 0.8 and 1.3m/year (a factor of 2 in concentration). The predicted annual volume of siltation in the approach channel was between about 10,000 and 16,000m^3/yr with a total siltation volume between 15,000 and 25,000m^3/yr or about 50% of the rate of siltation in the commercial port in 1977.

At the time the predictions were made it was pointed out that the suspended mud concentrations in the lower saline layer and hence the amount of siltation in any one year would depend on the magnitude of the fluvial flows in each wet season (an unknown random factor), erosion in the lower estuary at peak flows and the suspension of sediments by construction or dredging works.

3.6 Comparison between model prediction and actual siltation between 1979-98

After extensive investigations and assistance from Captain Garcia of the Laboratorio Nacional de Hidraulica in Caracas, the Ecuador Navy who dredged the port, Mr N Bruinsma who helped design the fishing harbour and Port Authority of Esmeraldas, it has been possible to obtain a fairly complete picture of the siltation rate in both the commercial harbour (1976-98) and the fishing harbour (1980-95).

3.6.1 Commercial port

Siltation in the commercial port averaged about 130,000m^3/yr in the 4 year period 1976-79 before the fishing harbour was completed. However siltation varied from 220,000m^3/yr in 1976 to 50,000m^3/yr in 1977. Siltation rates in 1976 and 1979 could have been increased by engineering work upstream.

In the 18 years since 1979, the commercial port has silted up at an average rate of about 100,000m^3/yr – varying from about 60,000m^3/yr to 140,000m^3/yr (3 year average in 1986-93). It is concluded that the annual rate of siltation in the commercial port reduced by 23% compared to the period before the construction of the fishing harbour and almost certainly had not increased as a result of the construction of the fishing harbour. This compares with a 30% reduction predicted in 1977. The local rates of siltation on the bar across the entrance to the port is still up to 5m/yr.

3.6.2 The fishing harbour

The evidence from the fishing harbour is more uncertain except in the period 1986-95. In 1981, Livesey and Henderson (Reference 3.2), reported rather low rates of siltation of 7500m^3/yr in the approach channel to the fishing harbour.

Yet in 1985 it was reported (Reference 3.3) by the Ecuador Navy that a total of 540,000m^3 was dredged from the inner basin and approach channel to the fishing harbour. It is certain that a considerable part of this dredging was deepening parts of the inner basin, which were not dredged to its full design depth of 5m in 1979. However, the rate of siltation was probably as high as 60,000m^3/yr for in the period 1980-85 (55% of the rate of siltation in the commercial port). The model predicted that the siltation in the fishing harbour could be 50% of the commercial port under the same wet season conditions.

Apparently the fishing harbour has not been dredged since 1985 and a survey made before or early in the 1996 wet season showed that the rate of siltation had averaged only 15,000m^3 over the 10 years (1985-95), 75% of which settled in the approach channel.

By 1996, it appears (Reference 3.4) a mud bar had formed in the channel with a peak bed level of – 0.6m LAT compared to a post dredged depth of –5.5m LAT. Such a shallow bar would raise the speed of the current across the bar from about 70mm/s to 0.3m/s, which is enough to erode soft mud deposits and limit further siltation, a condition not simulated in the model.

The field and modelling exercise did forecast the location of the shoal correctly and warned of a rate of siltation of 1.3m/yr on the bar, but assumed the harbour would be dredged at frequent intervals.

The main uncertainties appear to be the variation in the concentration of mud carried by the river in flood in the wet season from year to year, scour of bed deposits near the port area and the effect of dredging works in the port entrance by raising mud concentrations in the lower layer.

The study took no accountof the effect of occasional stormwaves in the wet season breaking near the edge of the canyon and perhaps increasing the mixing of river mud into the lower saline layer.

In retrospect, the predicted absolute rate of siltation in the newly dredged fishing harbour based on the 1977 wet season (25,000m^3/yr) was 60% less than the recorded rate of 60,000m^3/yr for the period 1980-85.

The exercise shows the weaknesses of relying on observations from a single intensive survey of one wet season, in particular, because the 1977 wet season appears in retrospect to be unusually mild.

The follow up study also showed the importance of predicting the final compacted density of a thick mud deposit when predicting volumes of siltation accumulating over a period of years without regular maintenance dredging and the effect of large amounts of siltation on the flow and siltation regime.

The exercise shows that it is much easier to predict the effect of a small change in conditions as a percentage of an existing rate and pattern of siltation (ie in the commercial port) than to predict siltation in a new situation such as a yet un-built fishing harbour based on observations on a single and possibly unusual seasonal condition.

4. CONCLUSIONS

The research covers two case histories concerning mud siltation, but both have been analysed in considerable detail.

The main conclusions to be drawn from the two case studies are:-

(i) It is difficult separate and the effect of new engineering works on siltation rates from, year to year variations in wave climate and river flow, the transient effects of construction works and changes in dredging practices.

(ii) A combination of comprehensive field studies and the best available mathematical models can enable an engineer to simulate complex mud sedimentation processes and to predict the effect of significant engineering works on marine siltation to an accuracy better than about 10% of the existing long term average annual siltation rate, in the case of a change to an existing well-documented siltation regime.

(iii) It is not recommended that long term absolute rates of siltation are predicted from a single season, which may be unrepresentative, without some attempt to quantify variations in the driving forces.

(iv) It is safer to predict siltation rates in terms of a percentage of observed rates at a nearby site – with similar driving forces – for which longer term variations are known.

(v) The accuracy of siltation predictions for new developments in virgin sites will be much lower, at about plus or minus a factor of 2 (i.e. –50% or +100%), especially if the necessary long term statistical data on suspended sediment is not available.

(vi) One should distrust the predictions from a model, which is obviously unable to simulate a significant feature of the observed spatial and seasonal patterns of siltation. This usually means that the modeller has neglected to simulate one of the mechanisms governing marine siltation at the site (see Table 4.1).

(vii) The study highlighted the importance of modelling the mechanisms by which dredgers re-suspend mud into residual currents in a depositional regime, where normal tidal currents are too low to re-suspend mud.

(viii) Volumes of siltation cannot be predicted accurately without allowing for the effect of different grain size fractions and consolidation of the increasing sediment deposit.

(ix) It is usually necessary to predict siltation rates for a range of combinations of tide, wave and river flows to arrive at a representative annual siltation rate.

(x) In situations where maintenance dredging is carried out infrequently, it may be important to simulate the effect of increasing bed levels on the siltation pattern.

(xi) The research did not include an analysis of transient conditions such as wave erosion (total internal reflection) and the slumping of banks of newly dredged areas.

Table 4.1 Mechanisms governing marine siltation

Driving forces	Sediment mobilisation /source	Transport mechanisms	Mechanisms causing increased sedimentation
Wind action Wave action Tidal motion Gravity/density Mechanical Ecological Climate change	Wave stirring/breaking Formation of fluid mud Bed erosion and resuspension Bank instability Fluvial inputs Wind blown sediment Dredging Shipping Bioturbation	in suspension by: Tidal currents Wave driven currents Wind driven currents Current/wave interaction Density currents Turbulent mixing Settling Bed load	Reduced bed stress/near bed currents Increased flocculation Increased sediment concentrations Interception of fluid mud or bed load Bank slumping and wind transport Ecological stabilisation of sediments

Based on Table 1 M P Dearnaley et al, Reference 4.2.

5. REFERENCES

2.1 Hydraulics Reseach Station. The Tees Estuary. Report EX 166. November 1961.

2.2 Hydraulics Research Station. The Tees Estuary. Report EX 336. August 1966.

2.3 Hydraulics Research. Tees Barrage. Effect of the barrage on marine mud siltation in the estuary. Report EX 1975. November 1989.

2.4 Hall, J, Frith S J, and Odd N V M. Tees Barrage Part 1. Planning. Proc. Inst. Civ. Engrs. Mun. Engr. 1995. 109 Sept 137-152.

2.5 Tees and Hartlepool Port Authority. Dredging Review 1991. Final Report. Oct 1991.

3.1 Hydraulics Research Station. Port of Esmeraldas, Ecuador, siltation study. Report EX788 September 1977.

3.2 Discussion on papers 5 and 6. Conference on Hydraulic Modelling in Maritime Engineering. ICE. London. October 1981.

3.3 Private correspondence. Captain Norberto Diaz-Garcia, Director Laboratorio Nacional de Hidraulica, Caracas, Venezuela.

3.4 Private correspondence. Mr N Bruinsma.

3.5 Admiralty chart 2799. Ports on the coast of Colombia and Ecuador, Esmeraldas.

4.1 Cooper, A J and Dearnaley M. P. Guidelines for the use of computational models in coastal and estuarine studies. Flow and sediment transport models. HR Wallingford. Report SR 456. July 1996.

4.2 Dearnaley M P et al. Development of a unified approach for assessing sedimentation in harbours. HR Wallingford. Report SR 497. March 1997.

Figures

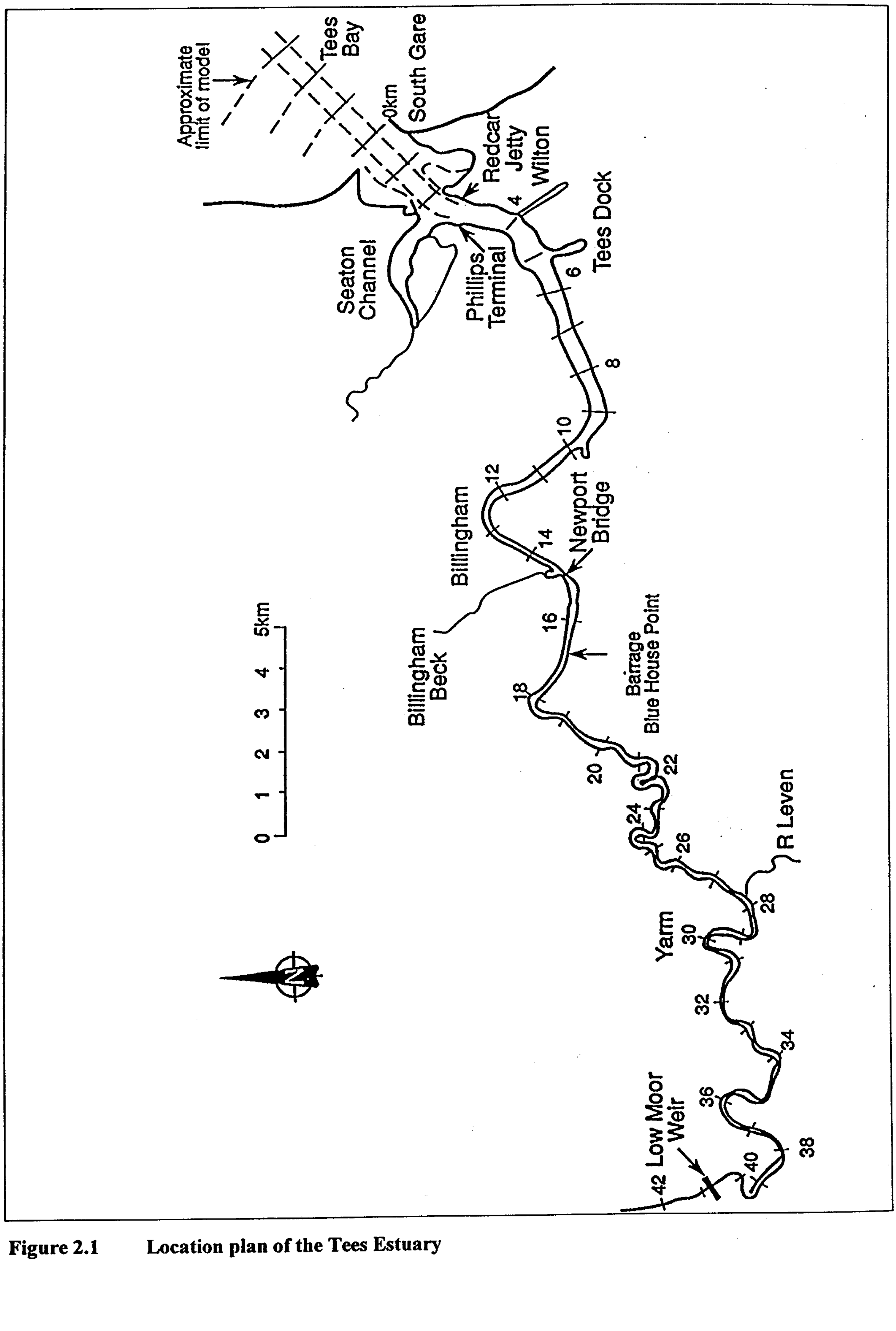

Figure 2.1 Location plan of the Tees Estuary

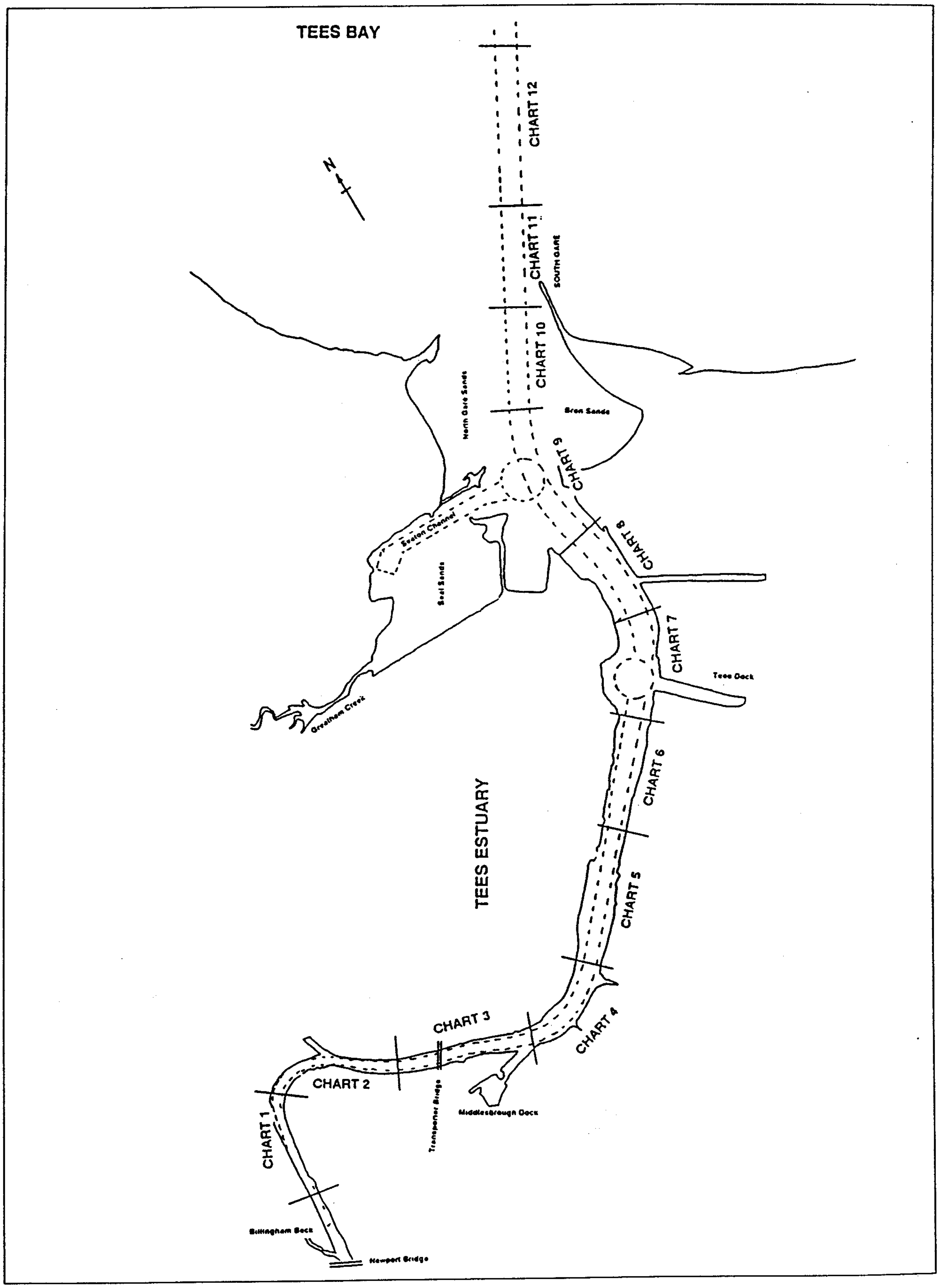

Figure 2.2 Limits of charts used to measure siltation in the Tees Estuary

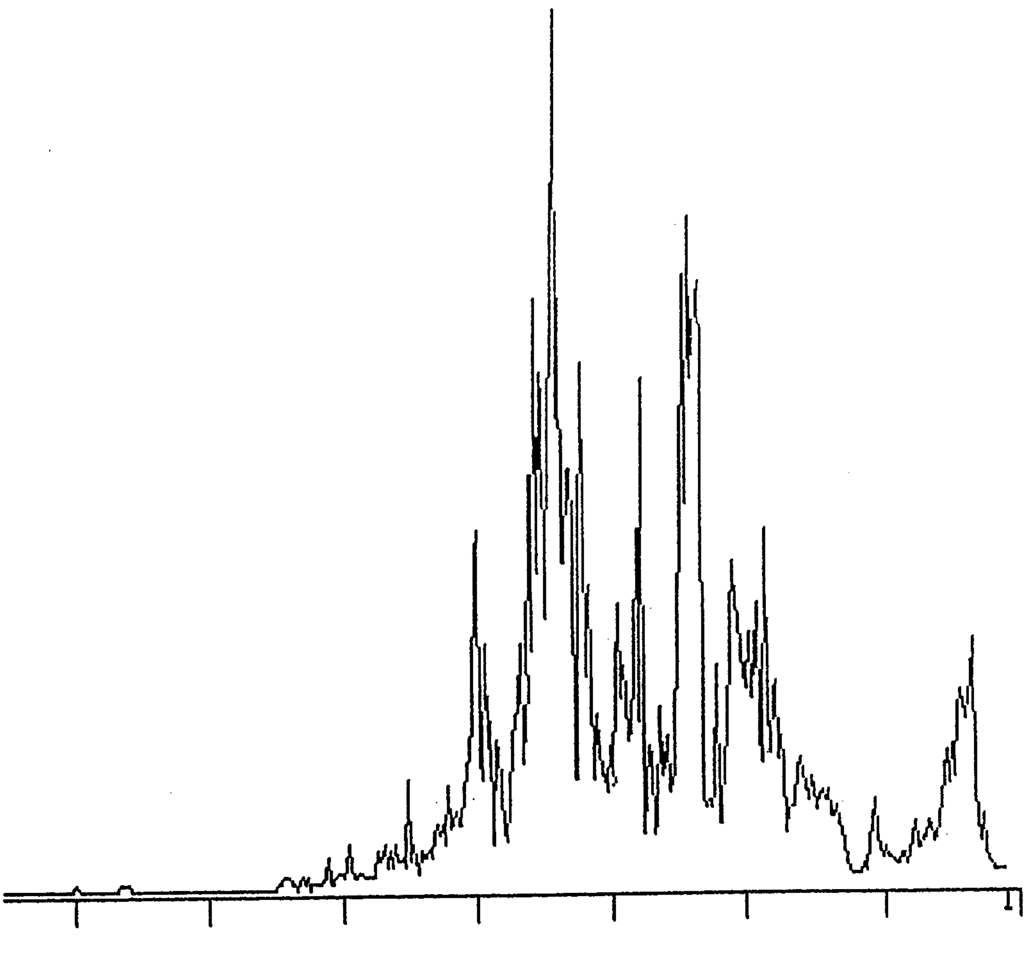

Figure 2.3 **Observed mud concentrations in the bed layer of Tees Bay November 1988**

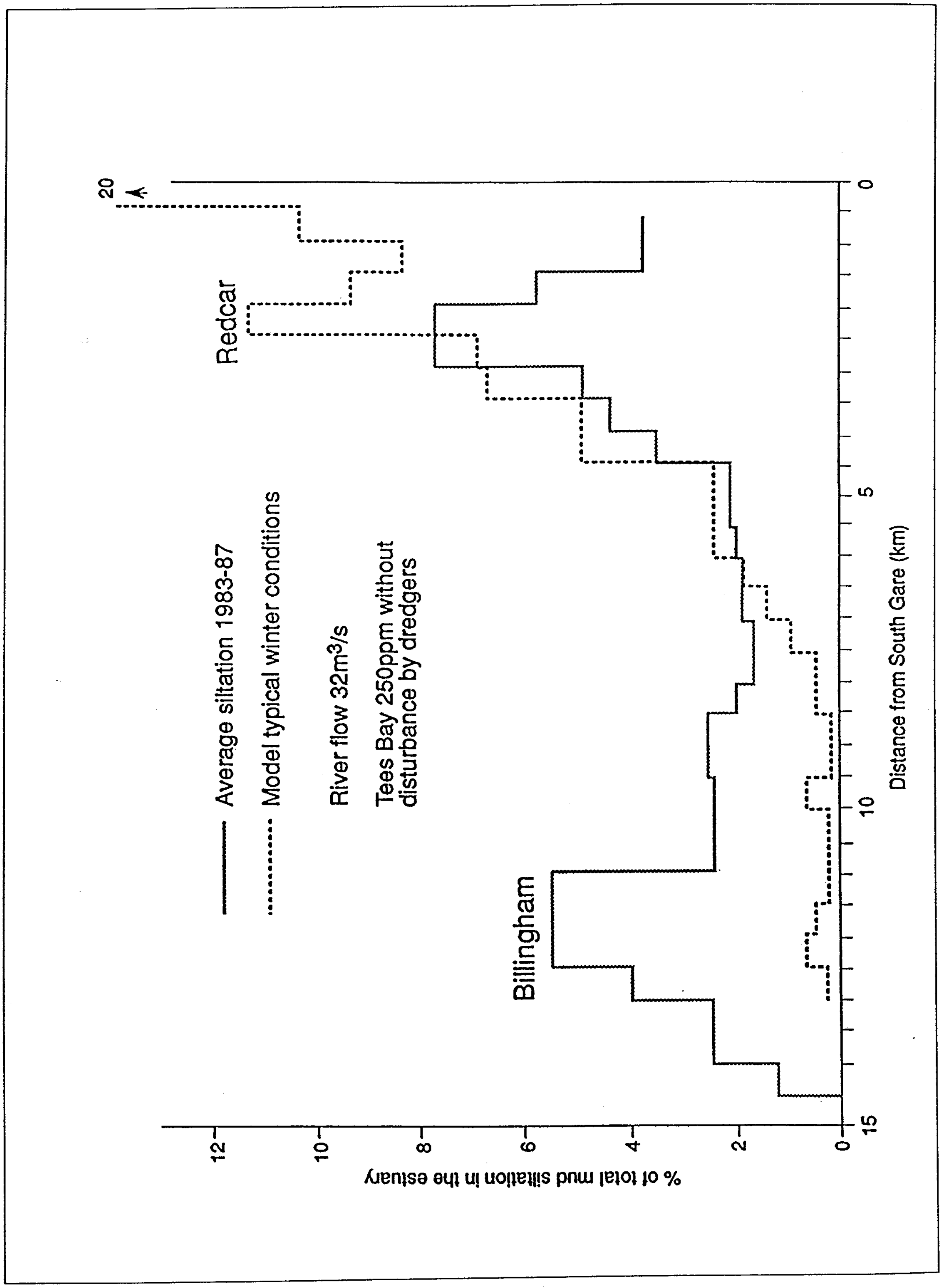

Figure 2.4 **Comparison of recorded and simulated distribution of siltation in the Tees Estuary without disturbance of the bed by dredgers**

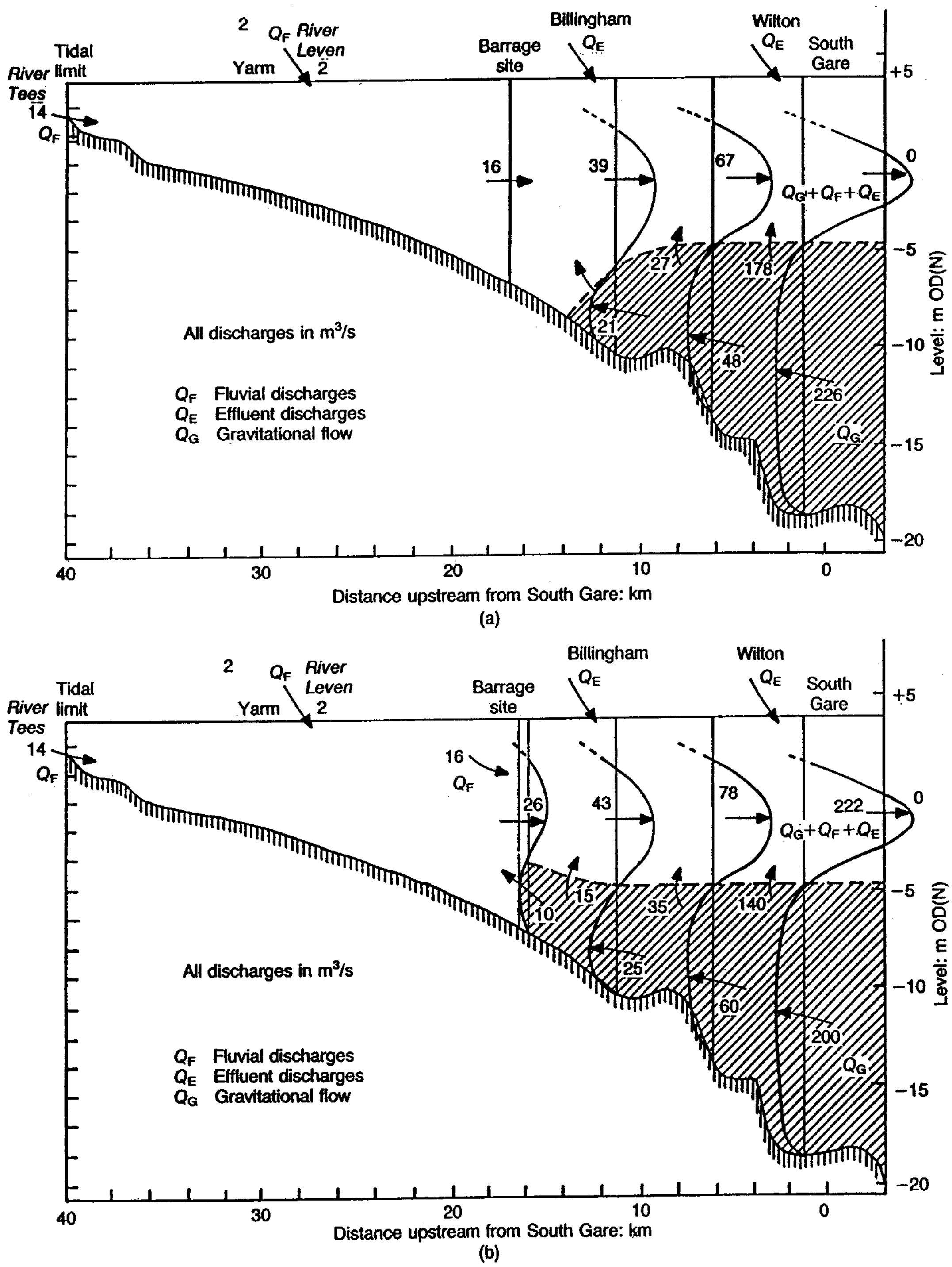

Figure 2.5 **Simulated gravitational circulation in the Tees Estuary (a) without and (b) with the barrage**

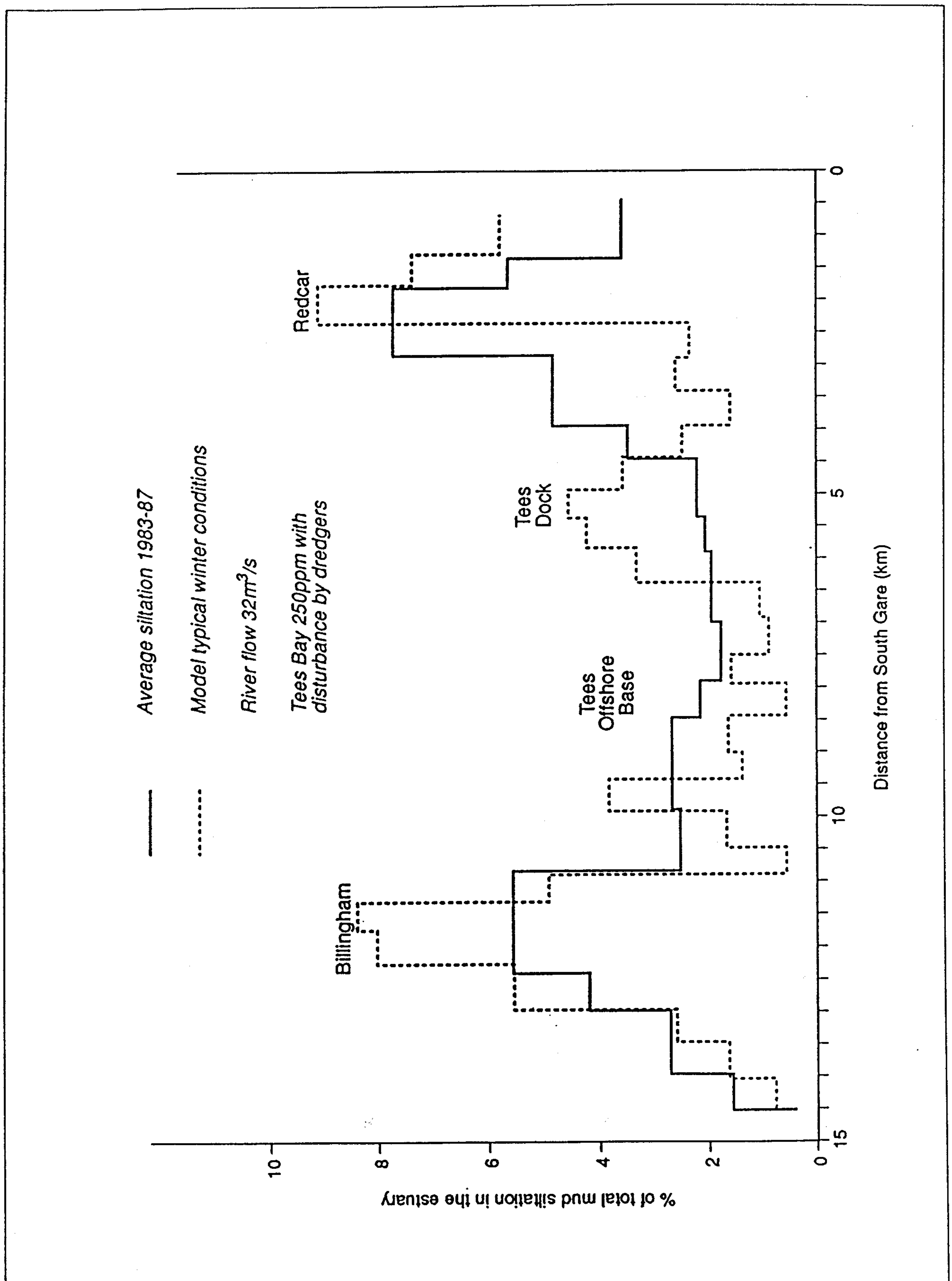

Figure 2.6 **Concentrations of recorded and simulated distribution of siltation in the Tees Estuary with disturbance by dredgers**

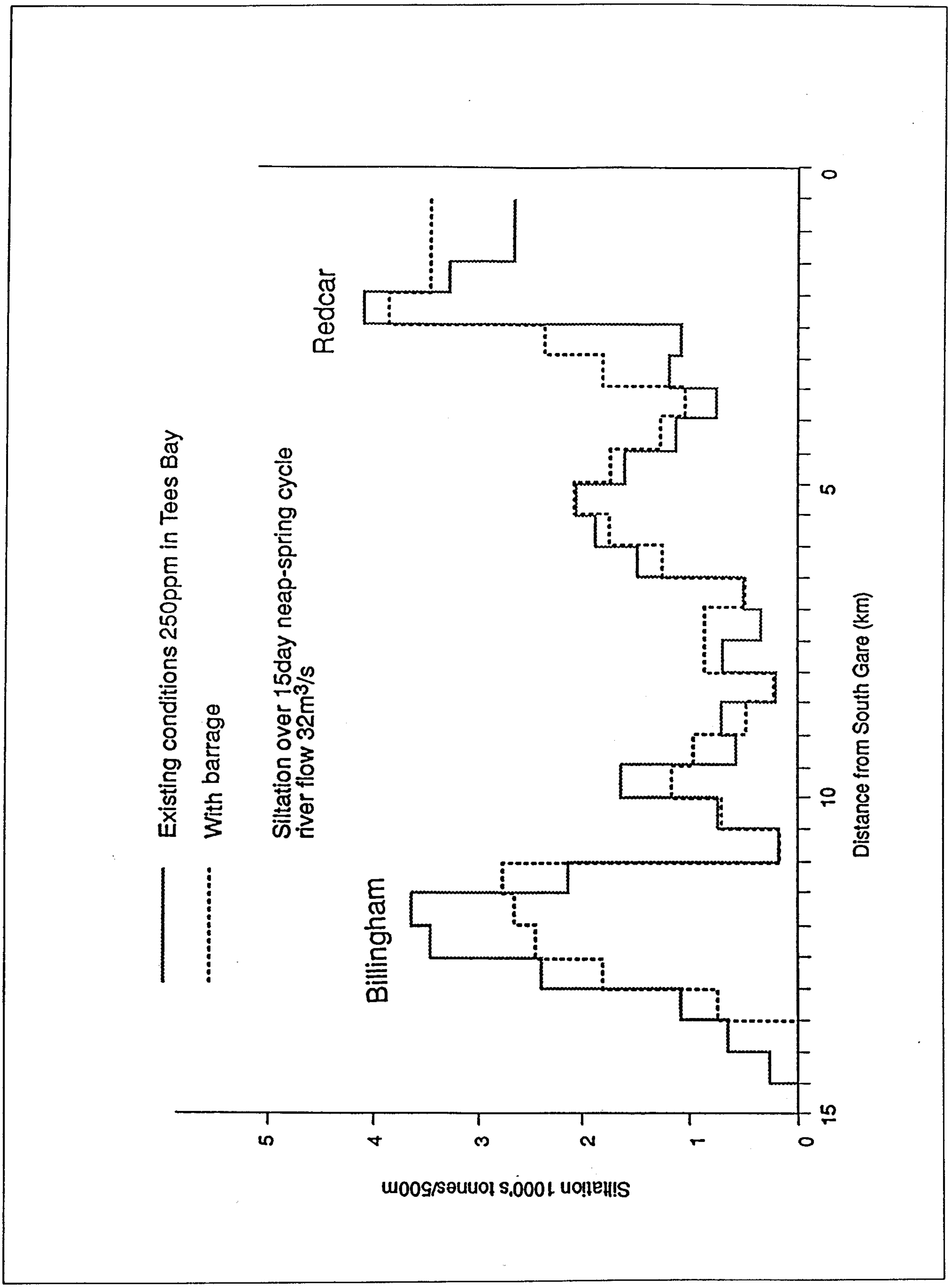

Figure 2.7 **Predicted effect of barrage on siltation during moderate wave action in Tees Bay with typical winter river flows (45 days/yr)**

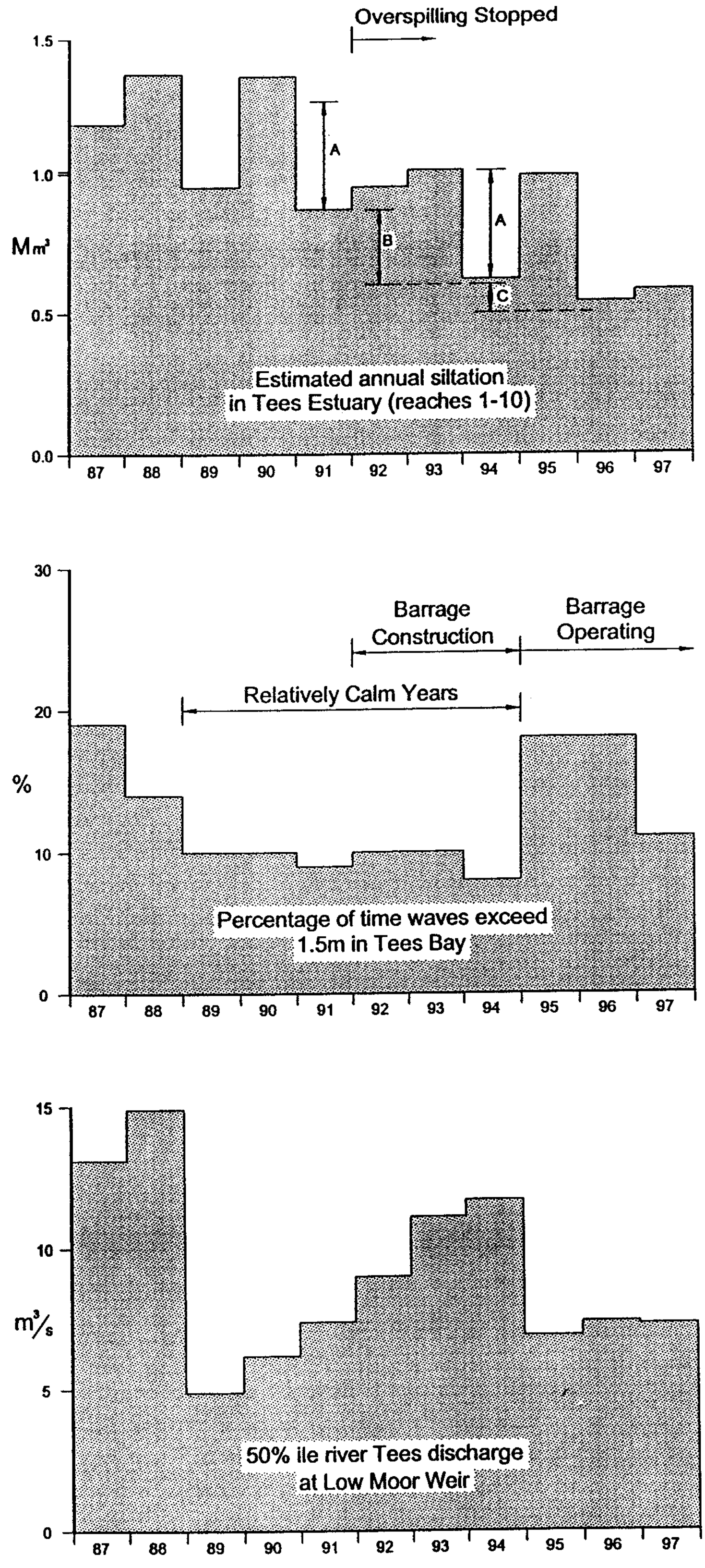

Figure 2.8 **Recorded variation in siltation in Chart 1-10, wave action in Tees Bay and 50%ile river flows 1987-1997**

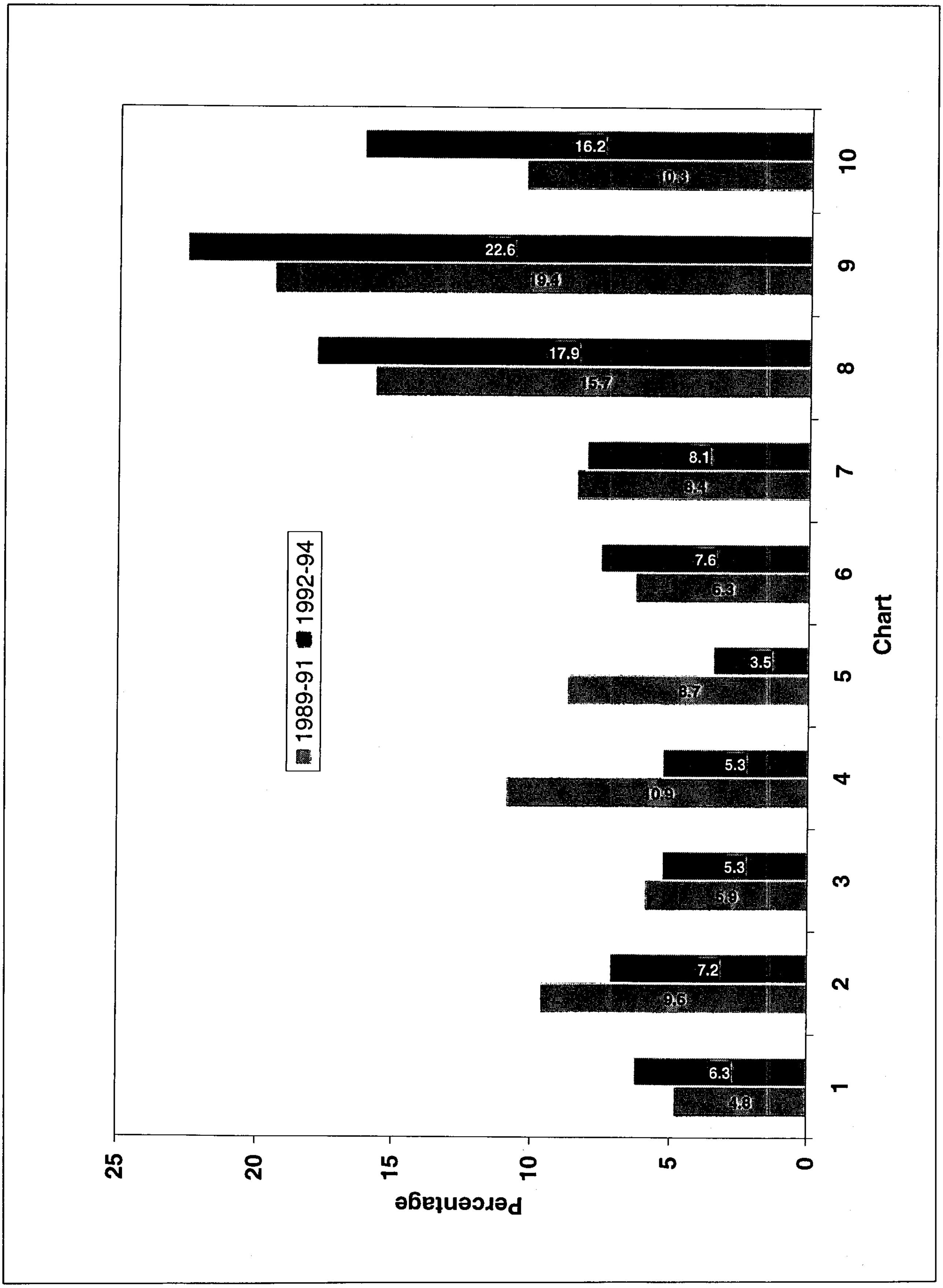

Figure 2.9 **3 year average siltation rates in charts 1-10 before and after the cessation of weiring upstream of Km 6**

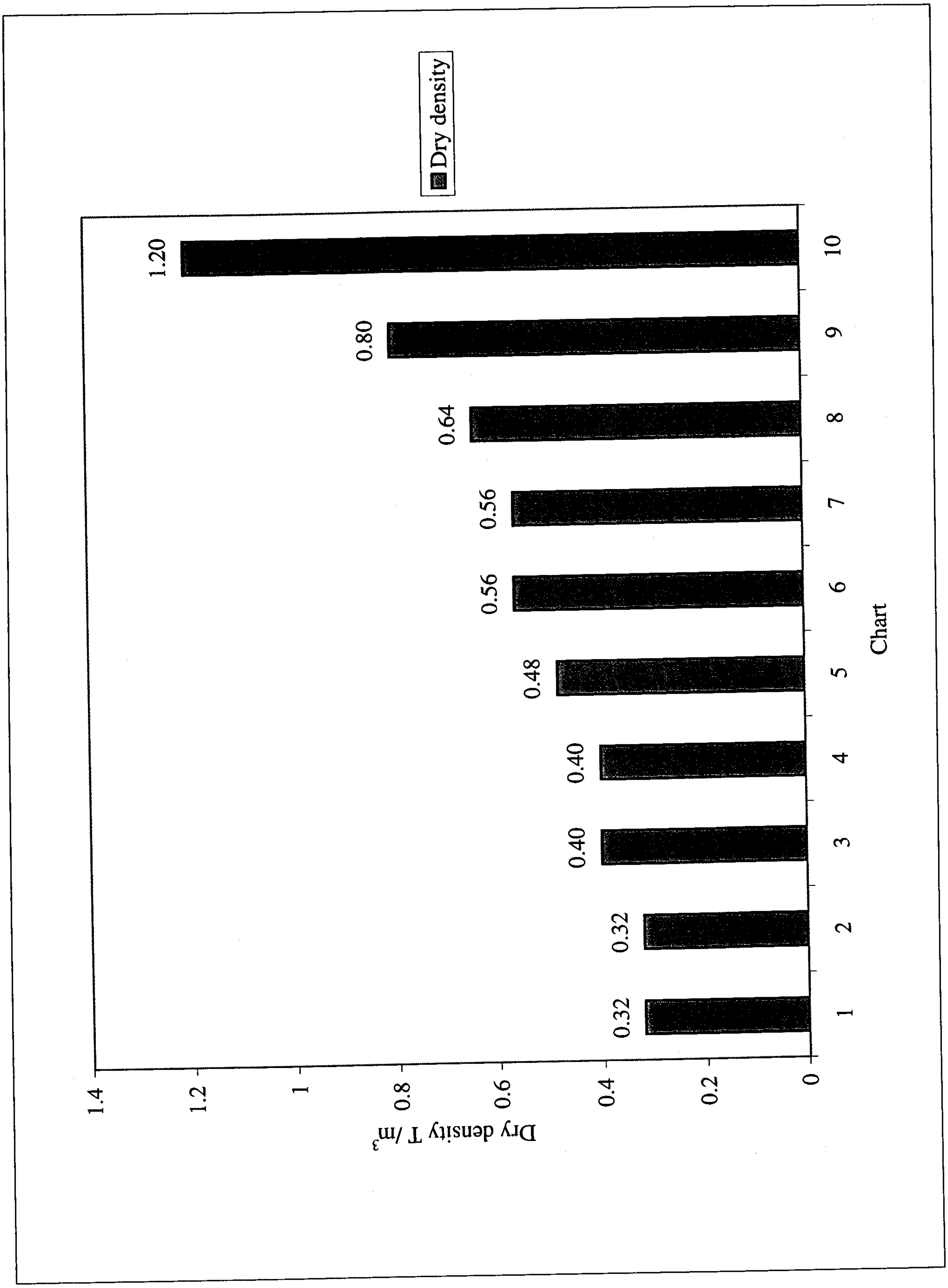

Figure 2.10 **Variation in the dry density of the sediment deposits along the estuary.**

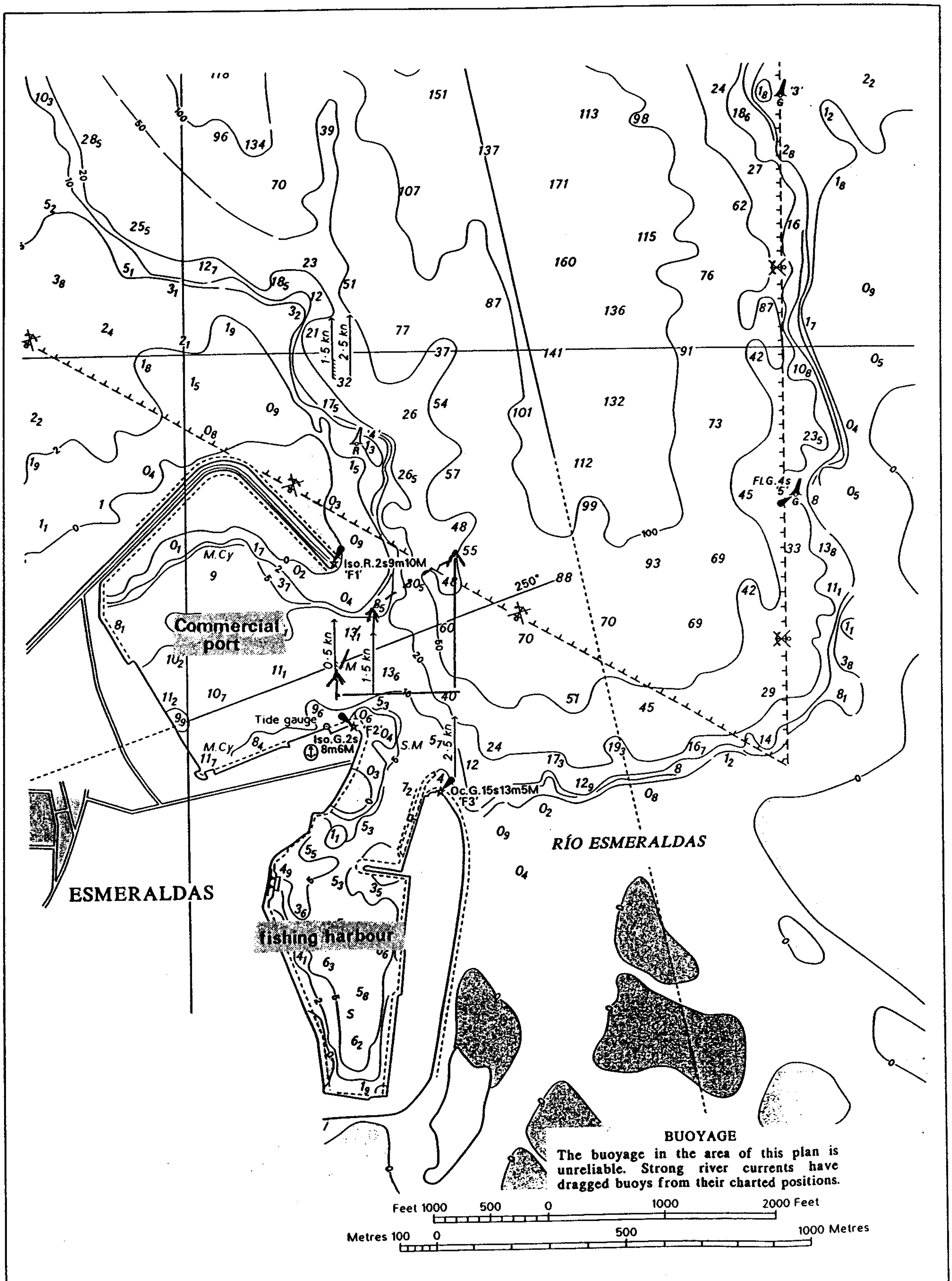

Figure 3.1 Chart of Port of Esmeraldas based on 1985 post dredge survey

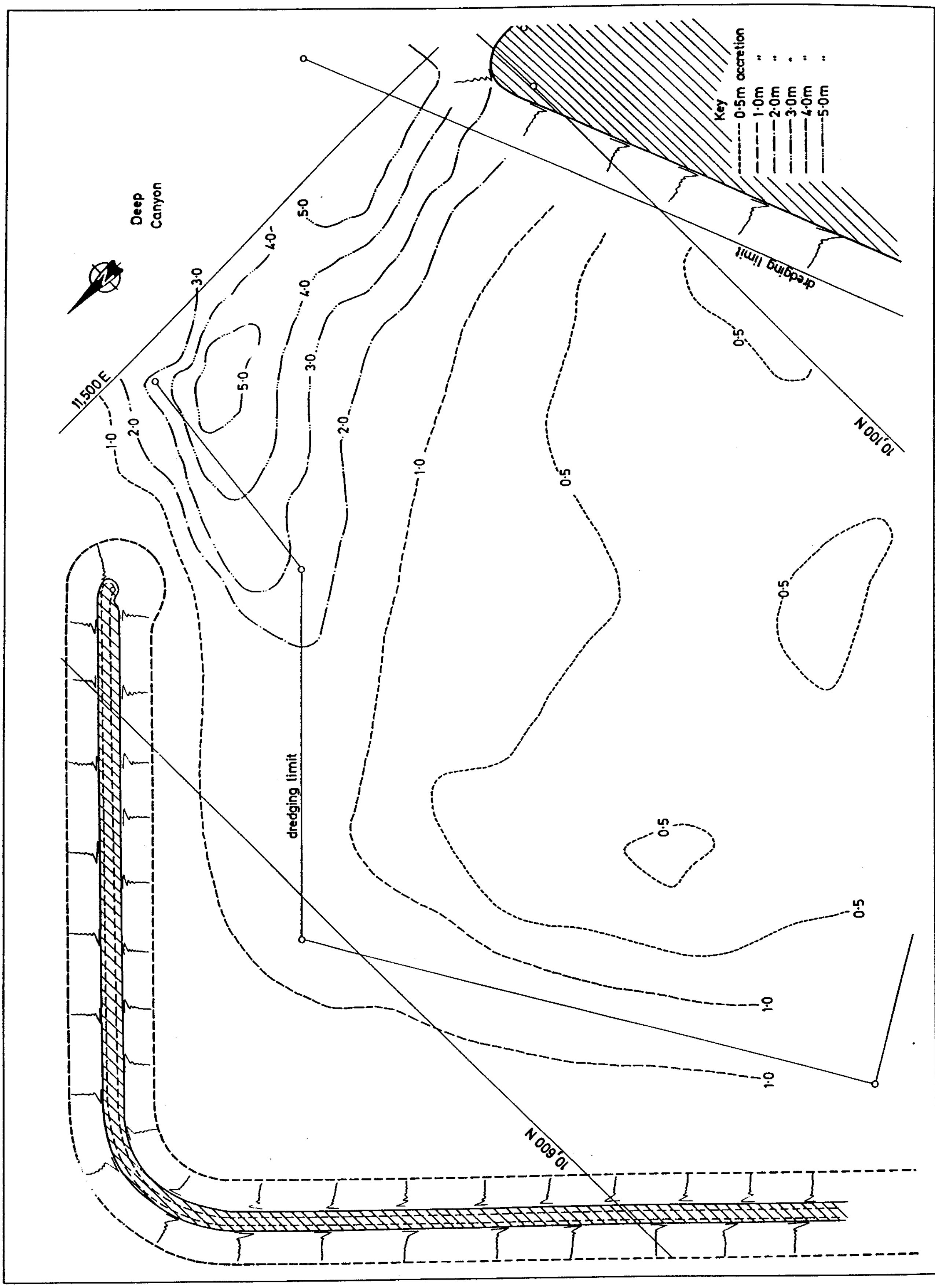

Figure 3.2 Net accretion in the Commercial Port of Esmeraldas January 1976-March 1977

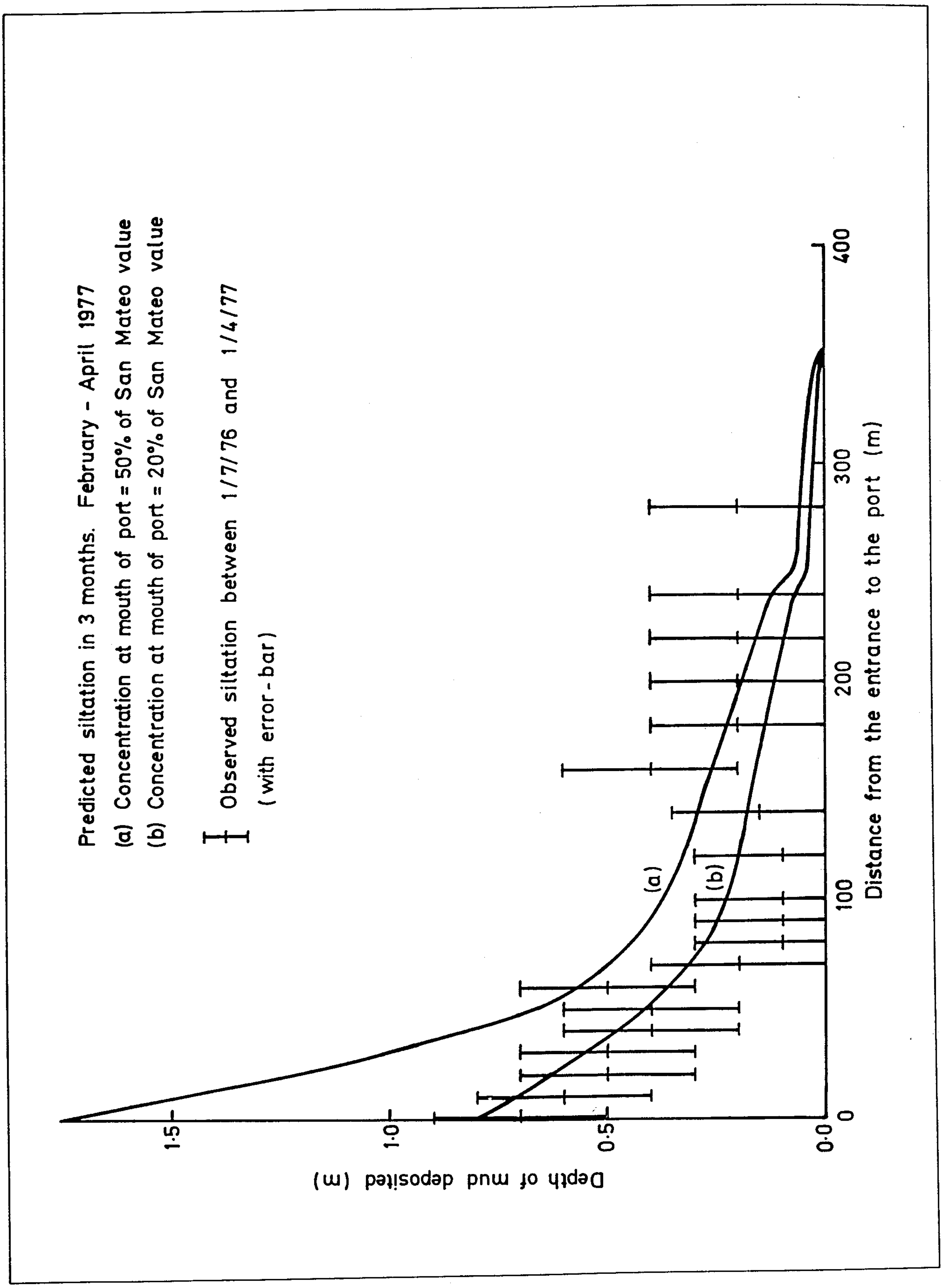

Figure 3.3 **Calibration of model of siltation in entrance to the Commercial Port of Esmeraldas**