Overstrand to Walcott

Littoral Sediment Processes

Part II: Technical Support Information

Report EX 4692
March 2003

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HR Wallingford

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Summary

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The littoral sediment processes in the region between Overstrand and Walcott on the North Norfolk coast have been investigated through observations and modelling. The potential net longshore sediment transport has been modelled, and beach volume changes have been derived from repeated surveys of set profiles. The evolution of high and low water and the changes in beach steepness have been derived from historical maps, while cliff recession and sediment yields have been derived from observations of recession and sediment type. The cross-shore sediment transport due to storms has been modelled, and some sediment samples have been analysed.

The sources of information have been combined to give a conceptual sediment transport map, and the interactions with adjacent coastal management units have been discussed. Furthermore, results of previous studies, to include regional and national level research as well as adjacent Coastal Strategy Studies, have been reviewed and incorporated into the analysis where appropriate.

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1. INTRODUCTION

This report is concerned with the littoral sediment processes that change the shoreline, namely the interaction between the cliffs, beaches, and seabed with the hydrodynamic 'loadings' as described in the hydrodynamics interim report. The principal aim of the study of these 'littoral processes' is to explain and then later quantify the potential recession of the cliffs in response to natural forces and to possible changes in the coastal defences. The following simplified flowchart sets out the main littoral processes and their interrelationship.

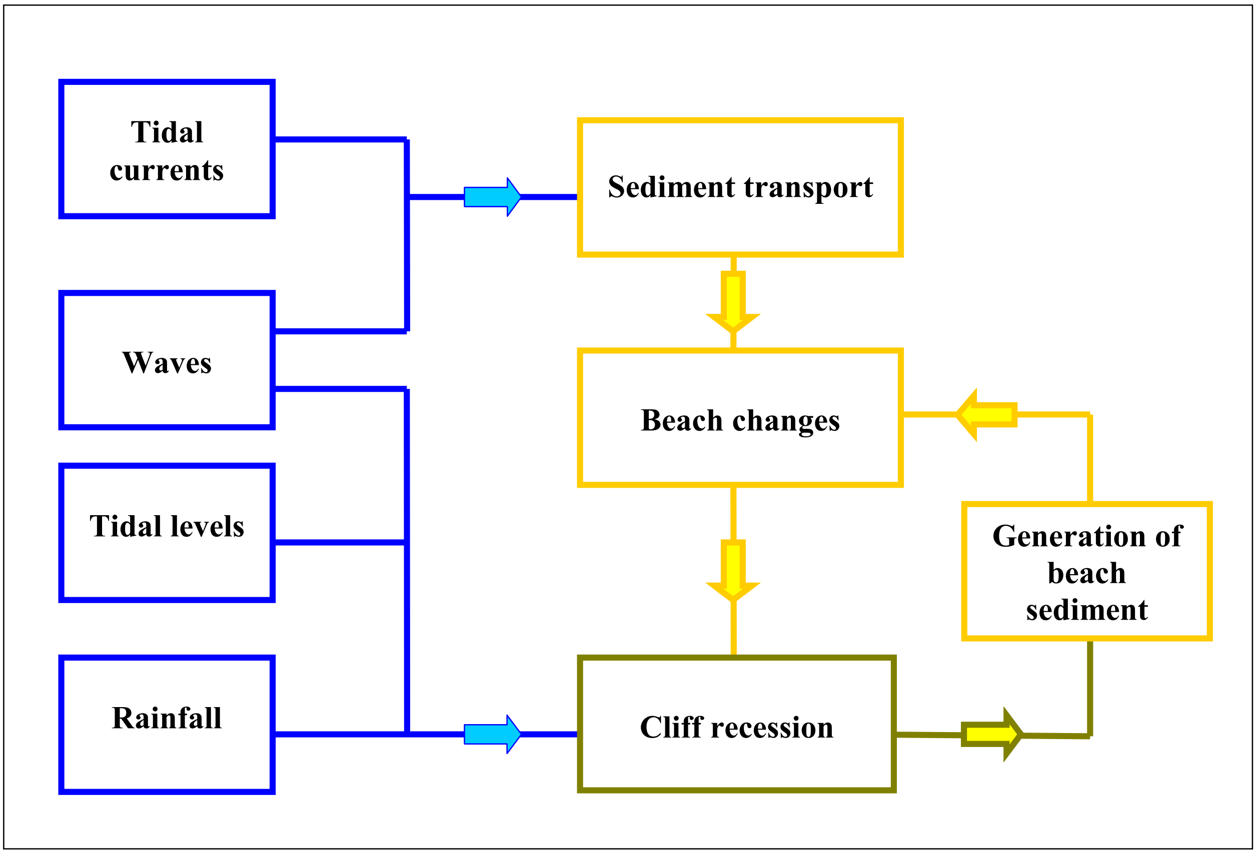

Figure 1.1 Simplified flowchart of littoral processes

This Norfolk coastline has been subject to erosion and retreat since the end of the last Ice Age when the North Sea basin filled (again) with water. The main processes causing the coastal changes can be summarised as follows:

- Variations along the coast in the rate of beach sediment transport (longshore drift);
- Erosion of the nearshore seabed, which is of similar soft rock to the cliffs;
- Landwards migration of the beach profile in response to sea level rise;
- Loss of sand from the beaches to the nearshore seabed;
- Wave attack on the cliff face at and above the high water mark;
- Cliff weathering and erosion, e.g. by winds, rainfall, freeze-thaw etc; and
- Landslides of the cliff faces due to saturation caused by groundwater flows.

Prior to the construction of coastal defences in the study area, the rate of cliff recession due to all these causes was approximately 0.65m to 0.75m/year (Cambers 1976). However, there have been substantial variations in this rate along the coast and in response to varying weather conditions, variations in the glacigenic sediments in the cliff material and the frequency of wave attack on the cliff base. Clayton and

Coventry (1986) investigated the recession rate between Overstrand and Trimingham between 1885 and 1985 and found that it reached a maximum rate of 1.75m/year

The construction of coastal defences, especially seawalls, altered these natural processes. While a reduction in natural cliff recession rates was achieved in some areas (typically at the sites of greatest human development of the cliff-top land), this generated increased recession on undefended sections. This increased recession occurred on the downdrift (eastern or southern) side of the coastal defences for the following reasons:

- The coastal defences reduced the erosion of the cliffs behind them, thus reducing the supply of sediment to the beaches locally.
- The defences, particularly the groynes, tended to trap beach sand travelling along the coast, typically from the west to the east.

Both of these effects reduced the amount of sand arriving on the beaches in front of the cliffs immediately east of the defences, a phenomenon known as ‘drift starvation.’ Because the sediment drift on the unprotected coast was now not supplied by sufficient sand from the defended frontage, the beaches (and shortly afterwards the cliffs) eroded to make up the deficit in the sediment budget. Such problems often resulted in the construction of more coastal defences, typically groynes and sometimes seawalls or revetments, further down the coast. Such construction reduced the direct wave attack on the cliff faces and reduced the changes in the plan shape of beaches caused by variations in the longshore drift.

In contrast to this, a positive effect on beaches updrift (i.e. to the west of defended frontages) was observed, in which beach material tended to accumulate since it could only travel past the groynes and seawalls more slowly. Even this effect, however, can have disadvantages since it may reduce cliff erosion and hence the supply of extra beach material.

Other littoral processes, however, have continued including the erosion of the nearshore seabed and the increase in mean sea level. Previous studies have commented on the significant quantities of beach sediment that are lost offshore from the North Norfolk coastline, although without explaining the mechanisms involved in detail.

Other causes of beach loss have also been mentioned in connection with the continuing problems of coastal erosion in the study area. Of these the most frequent concern is the effect of offshore dredging for aggregates. The nearest area of seabed where any such dredging has taken place in recent years is offshore from Caister, about 50km distant to the SE. This dredging is too far away and in water too deep to affect waves, tidal currents or sediment transport processes in the Overstrand/Mundesley area.

The principal concern of this study is to predict the future changes in the beaches, of the coastal defences and subsequent recession of the cliffs along the frontage between Overstrand and Mundesley. This prediction exercise has assumed that the process that is most influential in causing beach changes will be the variation in longshore drift rates along the study frontage. The assessment of longshore drift rates is therefore described in some detail in Section 2 of this report.

2. WAVE-DRIVEN LONGSHORE SEDIMENT TRANSPORT

2.1 Introduction

Long-term beach changes are usually dominated by changes in the beach plan shape. These types of change are related to the transport of sediment along a coastline, the 'longshore drift'. Where this volumetric rate of transport varies along a stretch of shoreline, then the beach plan shape alters in response. The importance of this mechanism to beach evolution, and hence to coastal defences, is emphasised by the following quotation from an eminent coastal engineer in the USA, C J Galvin (1990) who wrote:

'... all examples of shore erosion on non-subsiding sandy coasts are traceable to man-made or natural interruptions of longshore sediment transport'.

While this somewhat overstates the case, in many situations (including this study frontage) the cause of rapid beach erosion (or accretion) is similar to that described by Galvin.

Along most coastlines of the world, longshore sediment transport (or longshore drift) is predominantly caused by waves that break obliquely to the shoreline. This is also the situation along the North Norfolk coast, where the prevalence of waves from the north-west creates a net drift, i.e. from Sheringham towards Great Yarmouth. Unusually, strong nearshore tidal currents also affect the longshore drift on this coastline. Further discussion of the modifying effects of tides on the longshore drift is presented in Section 3.

Researchers at the University of East Anglia made early estimates of the net annual longshore drift rate along the coastline of Norfolk in the 1970s. As normal in such studies, the longshore drift rate was calculated by a simple formula that estimates the instantaneous rate of sediment transport caused by any wave condition. By repeated use of this formula for the whole wave climate, as predicted for a chosen location at the coast, the total volume of longshore drift at that location was estimated. While this approach is still widely used, it is important to realise that the longshore drift rates calculated by this numerical method are subject to a considerable degree of uncertainty unless a site-specific validation can be carried out. In addition, estimates made using information on waves over one period can vary dramatically from subsequent estimates made using wave information for a different period.

Despite many studies estimating drift rates along the North Norfolk coast having been carried out, there is no way of physically measuring the rates of sand transport along the coastline. Any drift rates quoted must therefore be treated as rather uncertain estimates rather than absolute values.

The early work by the University of East Anglia, however, served to emphasise two main points, namely:

(i) Estimated longshore drift rates along some parts of the Norfolk coast are very large (indeed as high or higher than anywhere else in the UK); and

(ii) The longshore drift rate increases eastwards along the coastline from the Sheringham area, where the rate is very low, to the Happisburgh area, where the rate has a maximum value. Further east and south, the drift rate decreases until it is nearly zero again south of Great Yarmouth.

The latter point is fundamentally important in understanding the evolution of the coastline in the study area. It implies the drift rate out of the eastern end of the frontage (towards Bacton) is likely to be higher than the rate of sediment arriving at the western end (i.e. from Cromer). This difference in volume leads to beach erosion, and then cliff recession. This is therefore a purely natural phenomenon, caused by the gradual changes in orientation of the Norfolk coastline and the character of the waves generated in the North Sea. The distinct change in beach orientation in the vicinity of Overstrand can be expected to locally emphasise the increase in drift rates from west to east along this part of the coast.

The seawalls along the frontages at Overstrand, Trimingham, Mundesley, and Bacton now effectively prevent any additional sediment being added to the beaches to compensate for this deficit in volume, leading to an underlying trend for erosion. The traditional solution to this underlying problem has been to interfere with the longshore drift by installing groynes. Over the past two centuries, the beaches from Cromer to Overstrand and from west of Mundesley to Happisburgh have been largely maintained by this practice, with the length and spacing of the groynes being determined by rules-of-thumb and experience based on observing their effects. Given the likelihood of the drift rates being higher along the eastern part of the study area, it is not surprising that the groynes to the east of the study area tend to be longer and more substantial structures than those to the west. Along much of the Cromer to Happisburgh frontage, a variety of cliff toe protection measures have been used. Where the cliffs are susceptible to landslides at Overstrand, timber revetments and gabion retaining walls have been constructed to protect the cliff toe from wave attack, thereby slowing the rate of natural cliff recession.

The net longshore drift rates in the study area have been estimated several times in the past, with a wide range of predictions. Much of the work has been focused on Cromer to the west and on Happisburgh to the east. One of the earliest studies by Vincent (1979) estimated a potential net sand transport rate of 148,000m^3/year at Happisburgh. This was revised by a subsequent study by Vincent, McCave, and Clayton (1983) establishing a drift rate at Happisburgh of 260,000m^3/year. Vincent, McCave, and Clayton (1983) also estimated a rate of 100,000m^3/year passing Overstrand, and Clayton (pers. comm.) estimated a southerly drift of 180,000m^3/year passing the cliffs at Trimingham, decreasing to 160,000m^3/year at Happisburgh. This reduction was thought to be a function of sand being lost offshore. All these estimates have been made assuming that the coastline was still in a natural state, i.e. with no groynes or other coastal defences that affect the transport of beach sediment.

2.2 Modelling of longshore drift rates

In order to study the future (and recent past) evolution of the coastline between Overstrand and Mundesley in this study, a further calculation of net longshore drift rates along the ‘natural’ coastline was made. These calculations used the long-term wave conditions summarised in the hydrodynamics report. 23 years of offshore wave data (from 1st January 1978 to 31st March 2001) were used to predict wave conditions for nine nearshore wave prediction points. These points (a to i) were located on the -3.25m contour along the frontage between Cromer and Happisburgh (shown in Section 4 of the hydrodynamics report which illustrates four of these nearshore wave prediction points). Estimates of drift were made based on the wave conditions using the standard CERC formula, a simple empirical method that relates the total longshore sediment transport at any time to the height and the direction (relative to the beach normal) of waves at breaking. This is the same technique as used by previous researchers, and therefore allows a straightforward comparison with the results of the earlier studies mentioned above.

The beaches along the coastline between Overstrand and Mundesley are largely comprised of 45% muds, 54% sand, and 1% gravel (BGS 1996). This mixture of beach sediments complicates the calculation of drift rates, especially in the absence of any possibility of measurements of the sediment transport.

However, calculations have been carried out that ignore the shingle component of the beach sediment as its contribution to the overall sediment ‘budget’ is negligible. These calculations also ignore the mud component as it is removed from the system by suspension. This procedure produced the results shown in Figure 2.1, which plots the mean annual potential drift rate averaged over 23 years. Figure 2.1 shows an upper and a lower limit for the mean potential longshore drift rate, as the calculation of drift rates is extremely sensitive to beach angle. As expected, these results indicate that the open-beach drift rate generally increases from west to east along the study area, thus implying the likelihood of beach erosion along the frontage.

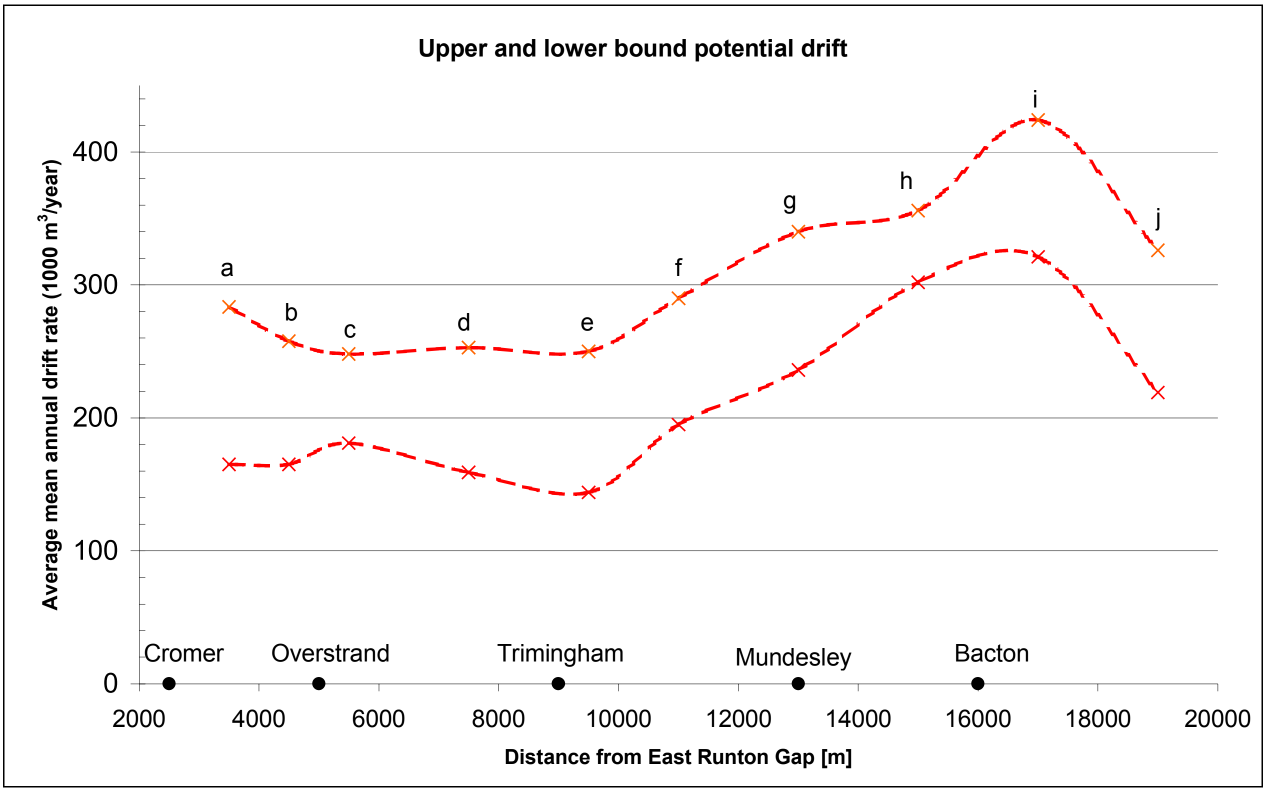

Figure 2.1 **Average mean annual potential drift along the study area**

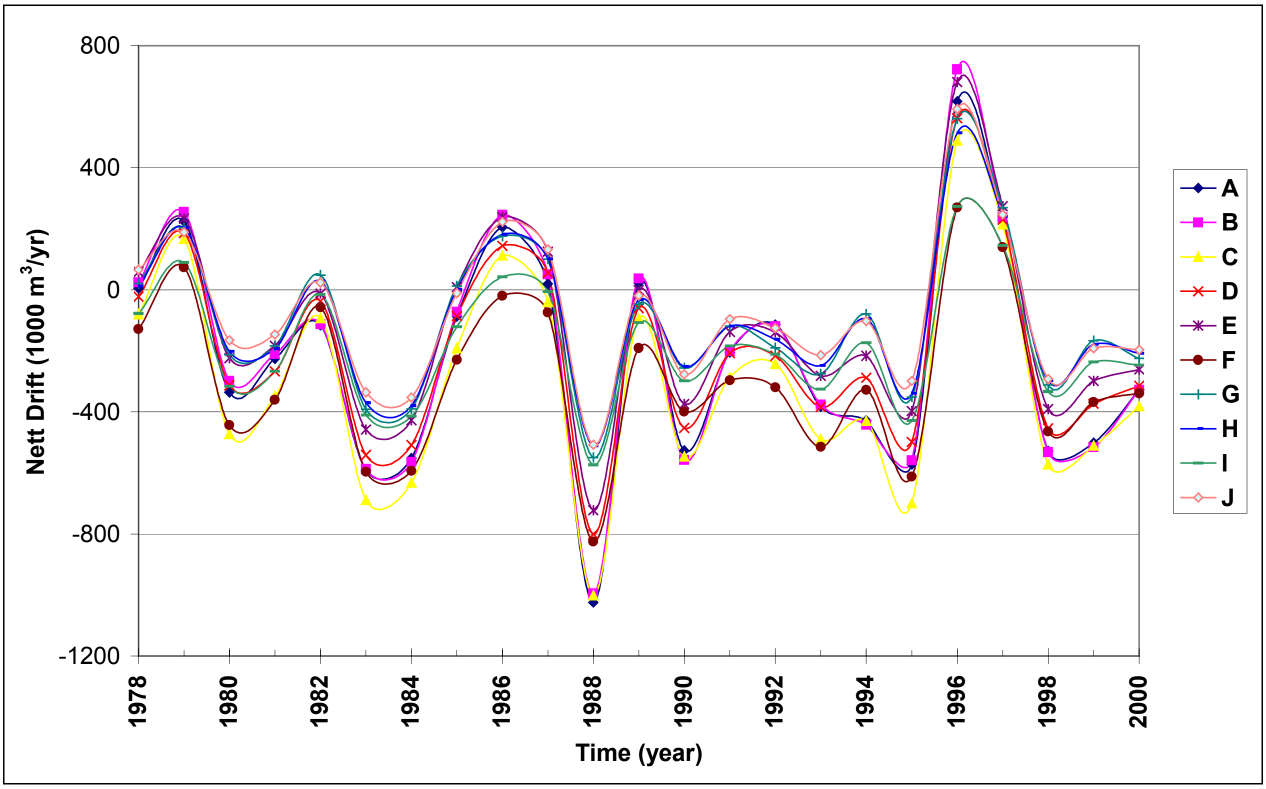

Figure 2.2 **Estimated annual net potential longshore drift rates 1978 to 2001**

The estimated net drift rates from the calculations are summarised in Figure 2.2, which illustrates the predicted net longshore transport rate for each year between 1978 and 2001 at each location. It is noticeable that during the 23 years, the annual drift varies with an eastward transport in some years, westwards in others. Although there is a predominant eastward transport, in 1979, 1982, 1986-87, 1989, 1996, and 1997, the average annual longshore transport is in a westerly direction at some or all locations. Figure 2.2 also illustrates the difficulty in comparing results from different periods as averaging the results over different periods yields different net potential transport rates.

As mentioned previously, there are substantial uncertainties in these theoretical calculations. One of the most important of these potential sources of error is whether there is sufficient sediment to satisfy this calculated drift rate. The source of sand on the beaches of this coastline is largely from the eroding cliffs west of Cromer and from the cliffs between Cromer and Mundesley. Further inaccuracies will result from the numerical modelling of the waves and the neglect of tidal currents (see next section). However, based on the evidence from site appraisals, drift calculations and beach sediment morphology, the net longshore drift rate along this coastline is eastwards. The installation of groynes, even if they are only partly effective at altering the natural drift rates, will provoke changes in the beach plan shape. Such plan shape changes typically result in accretion on the western faces, with a comparable danger of erosion to the east. However, if the existing groynes along the frontages at Overstrand and Mundesley were to be removed (or allowed to fall into disrepair), the spatial variation in the longshore drift would rapidly remove the beaches along these frontages.

2.3 Cross-shore distribution of longshore drift

The drift rates calculated using the CERC formula cover the whole surf zone and are potential transport rates, calculated in the assumption that there will be sufficient sand available over the cross-shore profile. Therefore they reveal no information about the cross-shore distribution of longshore drift. This can be important when there are groynes on a beach or when there are areas without sand offshore. Comparing the cross-shore distribution of longshore drift to the length of a groyne enables an estimate to be made of the effectiveness of the groyne in slowing or preventing longshore drift. If it is known that there is no sand cover over the underlying bedrock beyond a certain chainage, then a potential drift rate can be reduced to a more appropriate level, if the cross-shore distribution of longshore drift is known.

The cross-shore distribution of longshore drift at the three modelling points at Overstrand, Trimingham and Mundesley were modelled using COSMOS, HR Wallingford's cross-shore profile model, described by Southgate and Nairn (1993) and Nairn and Southgate (1993). The model was run using the wave height versus direction distributions at the nearest inshore wave points (described in the Hydrodynamics Report). It was also run at a constant water level of 0mODN. The cross-shore distribution of longshore drift at the three modelling points at Overstrand, Trimingham and Mundesley are shown in Figures 2.3, 2.4, and 2.5 respectively.

It can be seen that the large transport rates all occur at bed elevations above –6m. At Overstrand there are two peaks in the transport rates. The first peak is at the base of the cliff at approximately chainage 135m and elevation -0.9m. In contrast, the second peak is at the change in slope (which could be considered as the junction between the upper beach and the lower beach) at chainage 300m and bed elevation -3.5m). The small variations in transport rate that have a length scale of a few metres would be smoothed out by using a variable water level so should not be considered significant. At Trimingham there is a large peak at the change of slope at approximate chainage 165m and bed elevation -1.3m. While this is the dominant region of long-shore transport, there is a second peak in the transport rate located at the other change of slope (chainage 300m). At Mundesley the highest longshore transport rate is at chainage 150m, but there is significant transport out to about chainage 400m.

The percentage of the total longshore drift that occurred at bed elevations above -4m varied from 57% at Overstrand to 69% at Trimingham to 51% at Mundesley. Therefore COSMOS predicts that between 30% and 50% of the longshore drift occurs at depths greater than 4m.

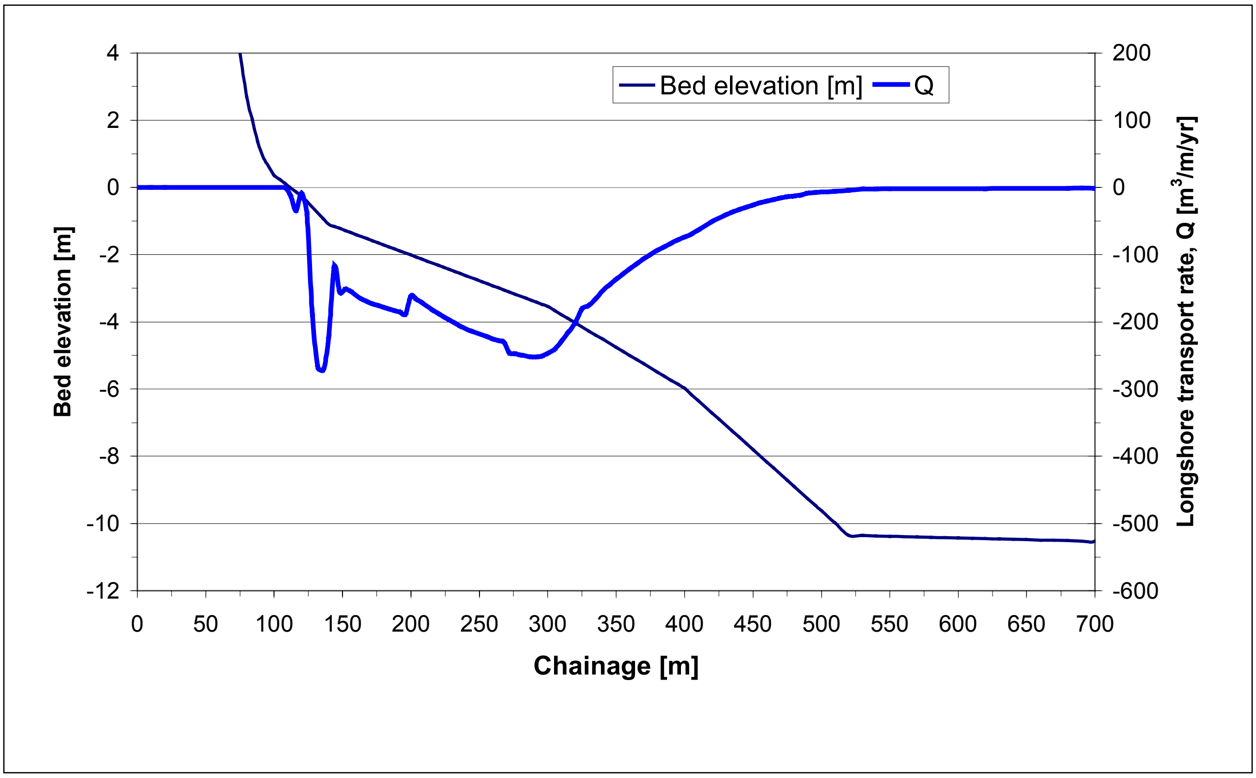

Figure 2.3 Cross-shore distribution of longshore drift at Overstrand

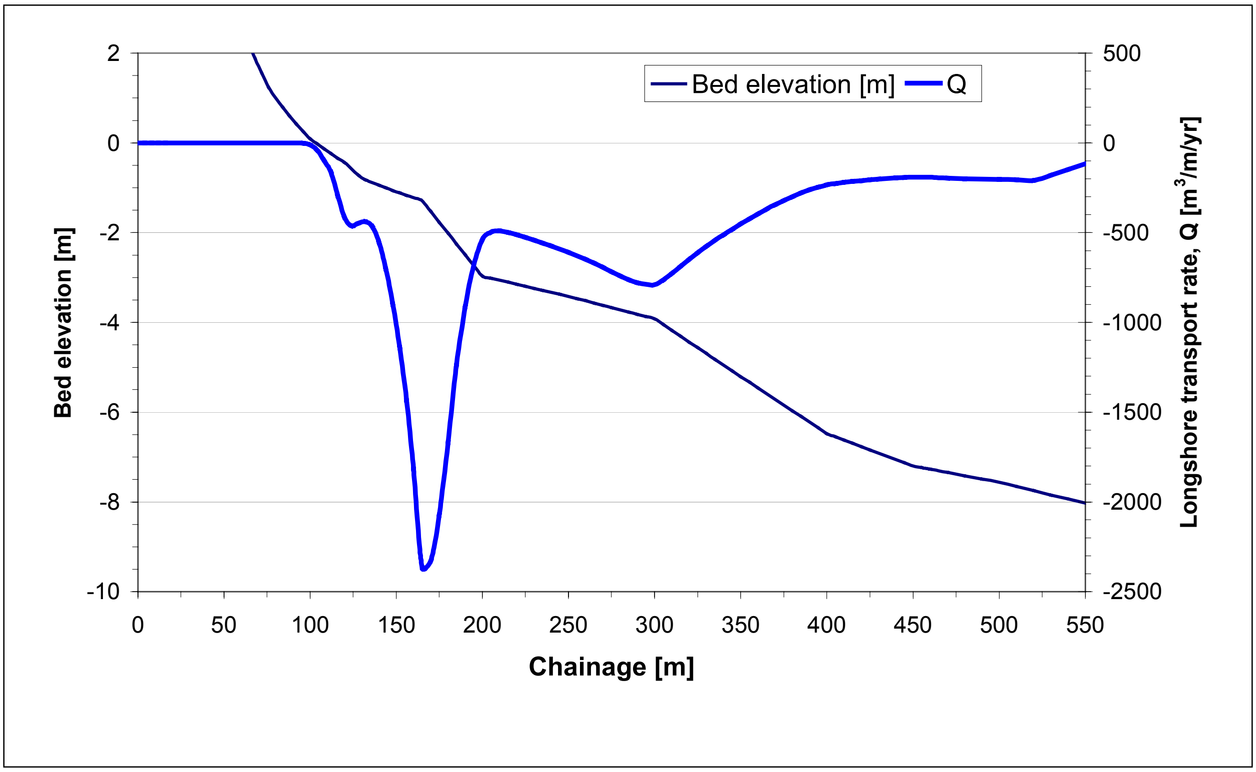

Figure 2.4 Cross-shore distribution of longshore drift at Trimingham

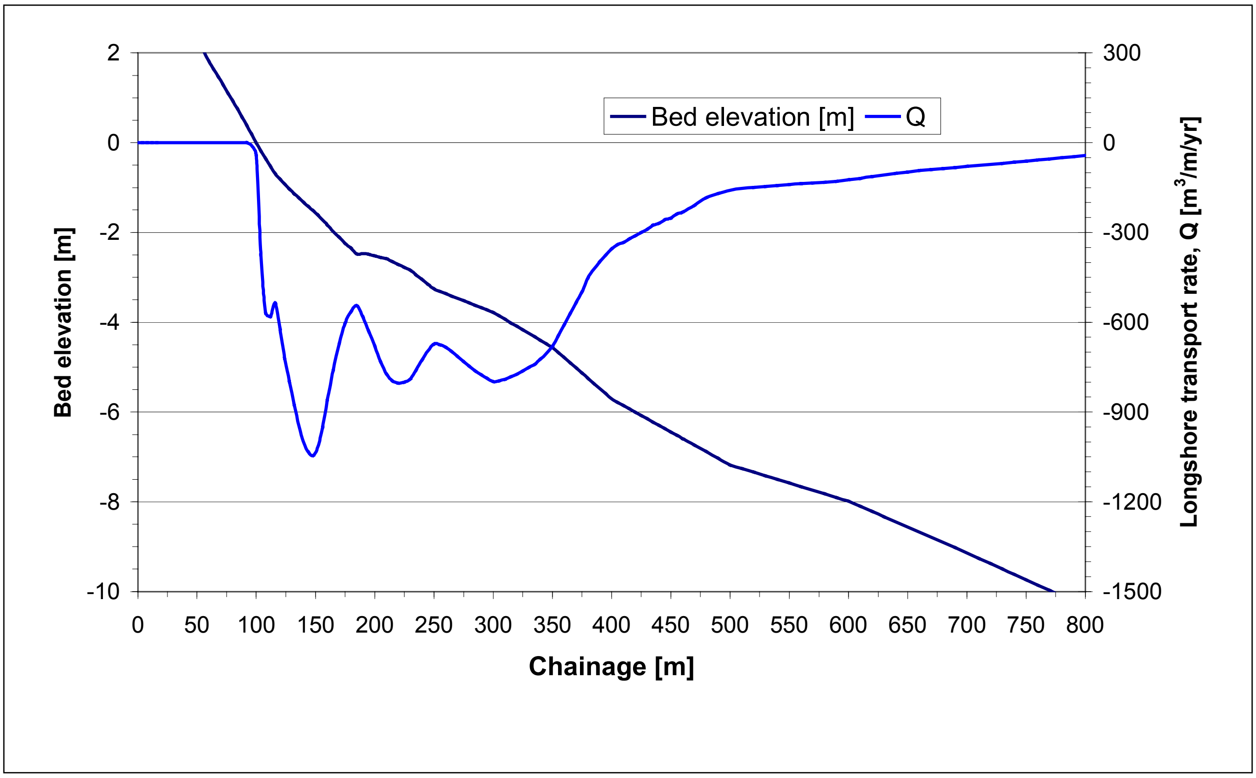

Figure 2.5 Cross-shore distribution of longshore drift at Mundesley

3. EFFECT OF TIDAL CURRENTS ON LONGSHORE DRIFT

It is not usual to consider the effects of tidal currents on the transport of beach sediments, except perhaps near the mouth of an estuary or tidal inlet. This is partly due to the fact that much of the research into longshore drift has been carried out on coastlines with virtually no tidal currents (e.g. in the western USA). In the UK, where tidal ranges are much larger and tidal currents stronger, it might be thought that a different approach would be needed. However, on most coasts, the times of high (or low) water and slack water (i.e. no tidal current) are close to one another. As a result, tidal currents on the upper part of a beach (close to the high water mark) are small, and at lower levels the effects of the tidal currents are similar and opposite during the flood and ebb. Under these circumstances, the net effect of tidal currents on the longshore drift is very small compared to the effect of waves.

In the study area, the tidal currents can be seen to be generally parallel to the coastline with some directional changes caused by the offshore sandbanks. Current speeds are lower closer inshore because of the increased frictional resistance of the seabed. However, they are predicted to be about 0.8m/s (1.5kt) at high water and slightly slower at about 0.6m/s (1.2kt) at low tide (when water depths close to the shore are less than at high tide, further increasing the frictional resistance). These current speeds, on their own, are capable of mobilising and transporting large quantities of seabed sediments up to the size of small gravel. The added effects of breaking waves, which disturb and agitate much larger gravel and shingle particles, means that tidal currents along this coast strongly affect beach sediment transport.

As discussed in the accompanying report on hydrodynamics, a particular feature of this part of the Norfolk coastline is that the strongest tidal currents will occur at about the time of high water during an exceptionally large tide. While this occurs regularly during Spring tides, it will also occur during storm surges, which will increase the total water level and add to the eastward flowing currents. On such occasions, winds are normally from the north or north-west, and will therefore create large waves along the study frontage as well as affecting the tides.

Such a combination of events will occur several times during a winter, and will have a strong effect on beaches, producing sediment transport both along the shore and offshore, with a flattening of the beach profile. Such events are referred to by local fishermen as 'scouring tides', and this is an appropriate if unusual terminology. Such strong currents close to the shoreline will interact strongly with groynes or breakwaters, and this issue needs to be borne in mind when considering the design of such structures.

However, with reference to the aspects of the tidal currents mentioned above, sediment on the upper portion of the inter-tidal zone will only experience tidal currents flowing to the east and south. This is because, at low water (when the ebb tide current is in the opposite direction), the upper part of the inter-tidal zone will be dry. Therefore, the tidal flows may have a significant impact on the transport of beach sediments, particularly through alteration of the behaviour of groynes or other coastal defences.

Using the BEACHPLAN numerical model of longshore drift, the previous Cromer Coastal Strategy Study (HR Wallingford 2002a) demonstrated that, without tidal currents, there would be a southward (negative) transport of sand over the whole beach profile. This study also noted that the volume of sediment transported is low at the top of the beach because this area is only affected by waves around the time of high water. Furthermore, the water depth and wave heights at the top of the beach are relatively small even at the time of high water. Thus, the drift rate is highest at a point where the beach level is about 0.5m below Ordnance Datum (i.e. just below the mean tidal level).

By modelling the additional effect of the tidal currents it was clear that these currents have had two effects. Firstly, on the lower part of the beach profile, the predicted sediment transport for this wave condition is reduced or reversed (i.e. with a net transport to the north-west). This is an expression of the ebb tidal flow around the time of low water. At this time, waves are agitating the sand and although they also try to produce a south-east flowing current it is shown that this is countered by the stronger tidal flows.

The second effect was that the peak south-east drift on the upper part of the beach profile is increased (in the order of 7.5%) by the effects of the flood tide near the time of high water. An inaccuracy in the longshore drift calculations of this magnitude, through the neglecting of tidal currents, could be considered acceptable in the light of the general accuracy of sediment transport calculations. However, a possible implication of this is that the downdrift effects of a groyne system may be greater than anticipated at design stage.

4. BEACH VOLUME CHANGES

A beach may be defined as ‘a deposit of non-cohesive material (e.g. sand, gravel) situated on the interface between dry land and the sea … and actively “worked” by present-day hydrodynamic processes (i.e. waves, tides and currents) and sometimes by winds’ (CIRIA 1996). The upper and lower limits of the beach can be taken as the beach crest (at the normal limit of wave induced run-up) and the seaward limit of sediment motion respectively. The beach volume thus includes all the potentially mobile material between the beach crest and the lower limit of wave action. Beach morphology is influenced not only by wave energy, but also by:

- Material added to the beach from slumping and mud flows from cliffs
- Aeolian processes
- The reworking of beach sediments by anthropogenic factors, such as vehicular disruption/digging

Beach profile changes occur over a variety of timescales, which vary from a single tide or storm through to seasonal variations and long term trends lasting thousands of years. Most beaches exhibit a seasonal variation in profile variability and volume in response to changing wave energies. During the summer months most beaches build up to produce a high beach with a berm above the high tide mark, and in the winter, higher waves comb down the beach moving sand down to, and below the low water mark. The higher rainfall and increased wave attack at the base of the cliffs experienced during the winter months are likely to result in a higher incidence of slumping and mudflows from the cliffs, thus in the short term increasing the beach volume.

The volume of the true beach material is very difficult to obtain and therefore, a measure of beach volume is found by calculating the volume of a geometrically developed beach prism, including all material (whether true beach sediment or not). The volume is calculated as volume per unit width (cross sectional area) of a shore-normal beach profile. This profile is constrained by horizontal planes at the lower limit of wave action, a vertical plane at the landward limit of the beach system (such as the beach crest, cliff toe, or seawall), and the beach surface.

North Norfolk District Council has surveyed the beach surface along 18 shore normal profiles, from Cromer to Ostend, see Figure 4.1 below. The surveys were carried out in the summer and winter months from January 1992 to January 2000 so that the seasonal variations in beach morphology can be examined. Furthermore, offshore bathymetric surveys have been carried out at five year intervals, and calculations presented here are based on the 1991 and 1996 surveys. The beach profiles and bathymetric survey data are illustrated in Appendix A.

In some cases it is difficult to determine the volume of beach material accurately due to the erratic nature of the boundary between slumped material at the cliff toe and the beach sediments. This boundary is taken as the upper limit of the beach. The lower limit of the beach sediments is defined as the location where there is an apparent break of slope in the extended beach profile that includes the bathymetric data.

The surveyed beach slope on the upper beach and foreshore was assumed to be representative of the entire beach slope. Thus, the mean slope (represented by a linear trend line defining the slope of the beach identified by the surveys) was extended to cover the entire active beach, down to the lower limit of wave action (with the break of slope defining the lower limit of the active beach).

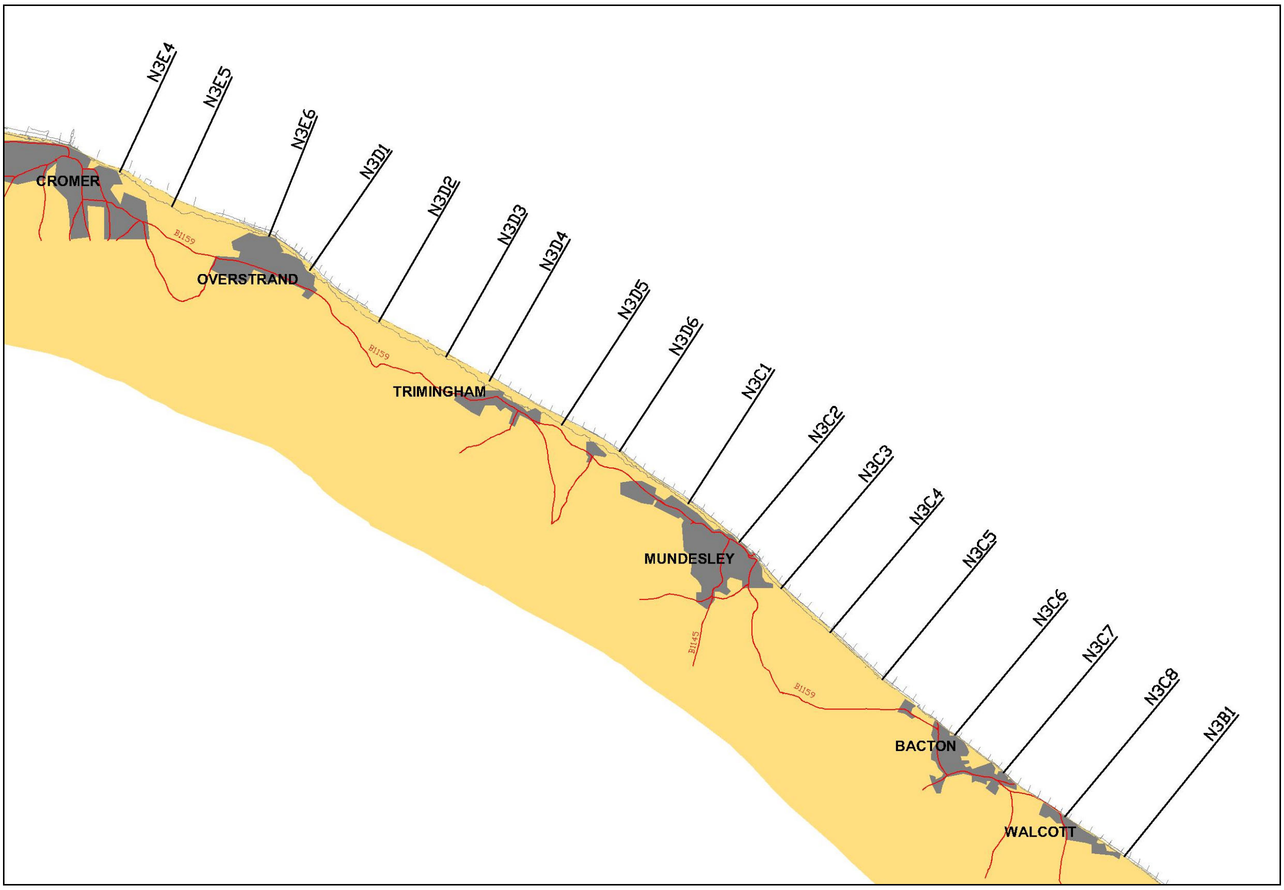

Figure 4.1 Beach profile locations

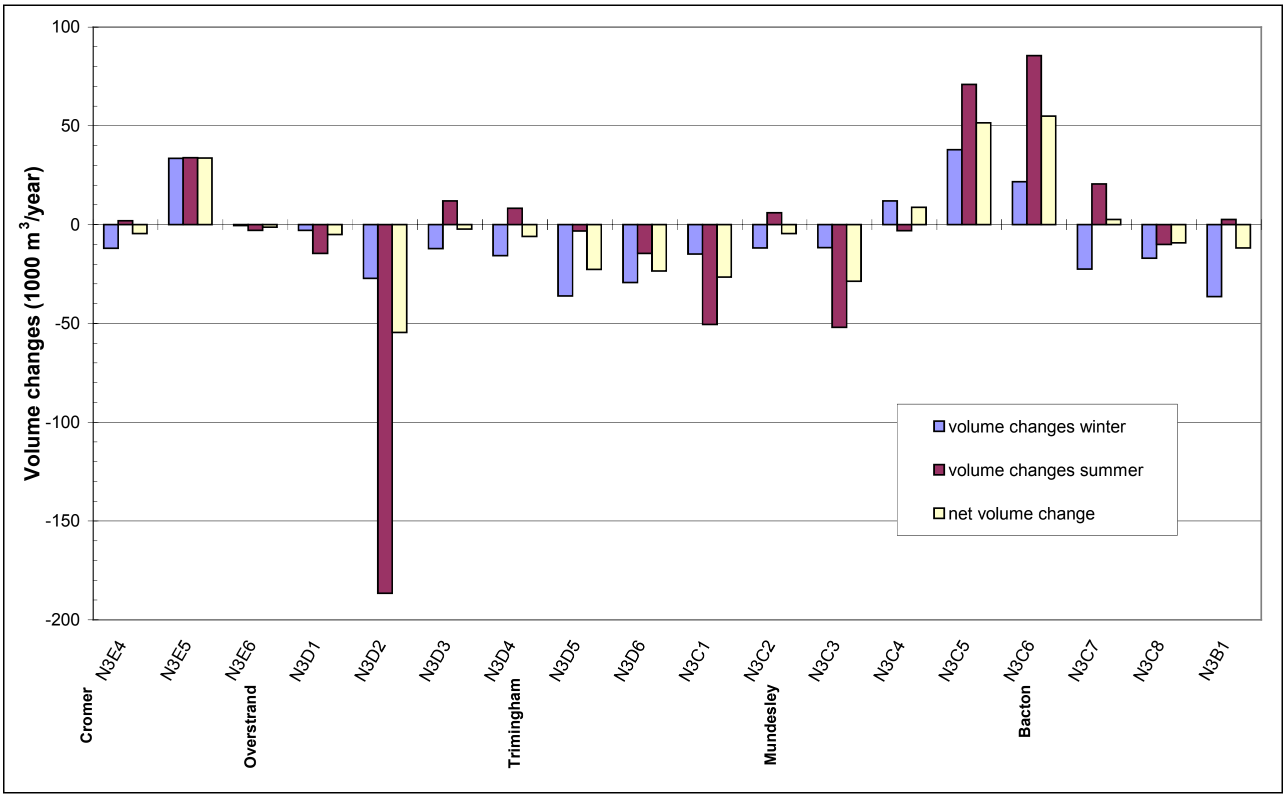

Figure 4.2 Beach volume changes in the study area

BDAS (Beach Data Analysis System, described in Appendix B) was used to calculate the confidence limits and the change in levels over the monitoring period, thereby providing an indication of the direction and magnitude of beach movement, as shown in Appendix A. The area under this trend line down to a constant lower limit, and between the landward and seaward boundary is representative of the beach prism. This area was extracted in BDAS and then multiplied by the length of coastline to provide a volume in cubic metres. It is assumed that each profile is representative of a length of coastline extending half the way to the adjacent profiles to the east and west. In other words, the profile is multiplied by the sum of half the distance between the two stations immediately to the east and west. The volume changes in thousands of cubic metres per year are illustrated in Figure 4.2.

It is difficult to identify seasonal trends within this data set since the surveys were completed once in the summer and once in the winter on an annual basis. Changes to the beach profile may therefore not be indicative of long-term changes, but may reflect short-term changes following a single storm event, or be exaggerated due to a severe episode of cliff landsliding. Therefore it is not possible to identify a long-term seasonal trend with any degree of confidence.

Figure 4.2 indicates a general pattern of beach volume losses between Cromer and Walcott, with an average annual loss of 48,000m^3/year along the entire frontage. The East Anglian Coastal Research Programme carried out a continuous time series of beach profiling between 1974 and 1980 (Onyett and Simmonds 1983; Clayton et al 1983), and the Anglian Region NRA study in the early 1990s also completed similar beach profile measurements. Both studies revealed a widespread decrease in beach volume over the period 1974 to 1980. Furthermore, erosion of the glacial till sediments beneath the beach was found to result in erosion of the base of the beach. The results in this study indicate that this trend is continuing.

Exceptional losses of the order of 190,000m^3/year are evident at N3D2, just to the east of Sidestrand. Although the locations are not directly comparable, losses of 95,000m^3/year were evident between Overstrand and Happisburgh from work carried out for the East Anglian Coastal Research Programme between 1974 and 1976 (Clayton 1977). The graph also indicates overall volume gains at Paston (N3C4 and N3C5) and at one location to the west of Overstrand (N3E5). These trends are not reflected in earlier work where a local accumulation was observed at Mundesley which was thought to be due to a local reduction in wave energies associated with the form of offshore topography (Clayton 1977).

The change in beach slope and width along the coastline was investigated by examining the low water and high water recession rates. The low and high water marks were digitised from Ordnance Survey Maps published in 1885, 1930, and 1969. Figure 4.3 below illustrates the recession of the high and low water marks between 1885 and 1969. A detailed breakdown of the rate of movement between 1885, 1930, and 1969 is given in Appendix C.

Figure 4.3 indicates a high recession rate of both the low and high water mark between Overstrand and Trimingham of up to 2.3m/year between 1885 to 1969. These recession rates compare well with those calculated by Clayton (2002), as shown in Appendix C. As expected, the recession rates along defended frontages are minimal. (As shown in Figure 4.3, the high water mark remains fairly static along the Overstrand and Mundesley seafronts, and in the largely undefended sections of the coastline the rate of change greatly increases, most distinctly around Trimingham.)

The beach slope has been calculated using the high and low water mark measurements, and Figure 4.4 below shows that although there is some degree of scatter, the beach is generally becoming steeper in a west to east direction over the period 1885 to 1969.

The increasing beach steepness from west to east is likely to be a reflection of the decreasing tidal range around the coastline (from west to east). McCave (1979) suggests that the sediment coarsens moving away from the sediment divide (i.e. west of Cromer), and therefore the sediment size will increase to the east.

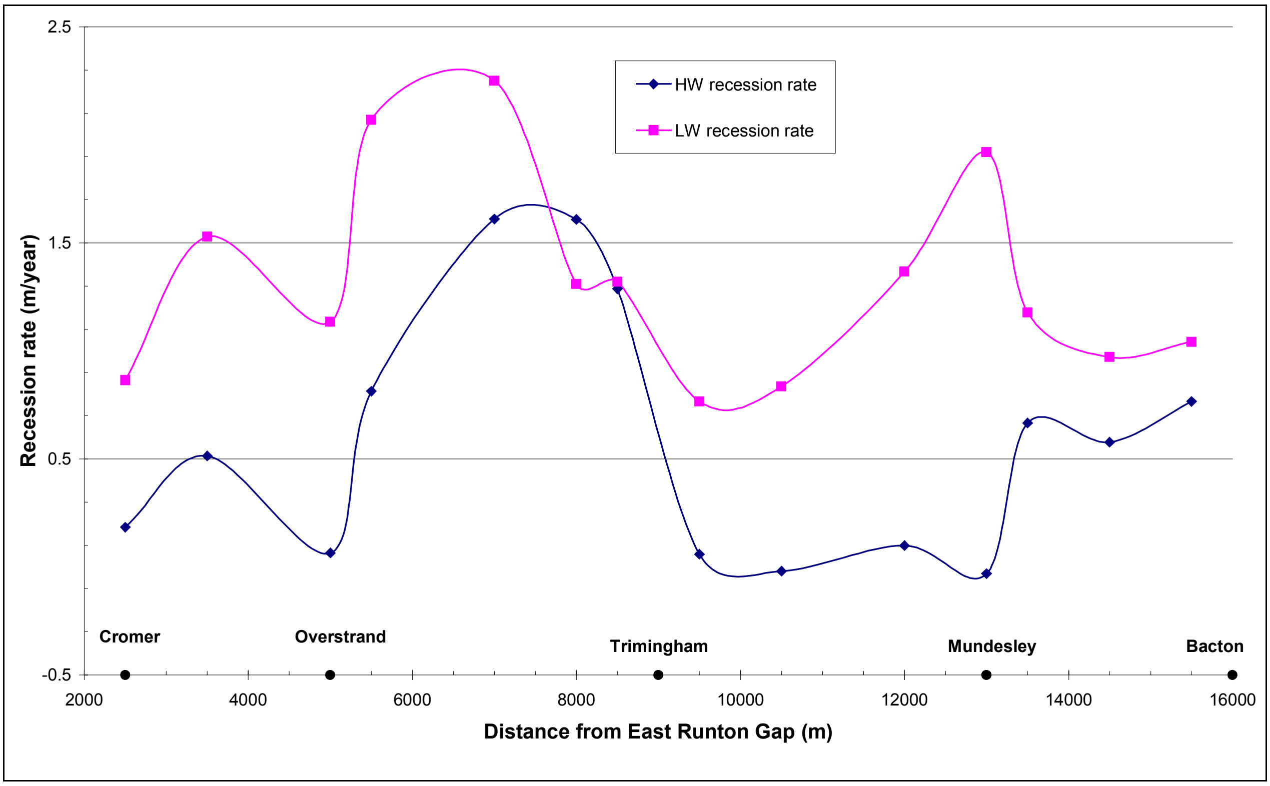

Figure 4.3 High and low water recession rates between 1885 and 1969

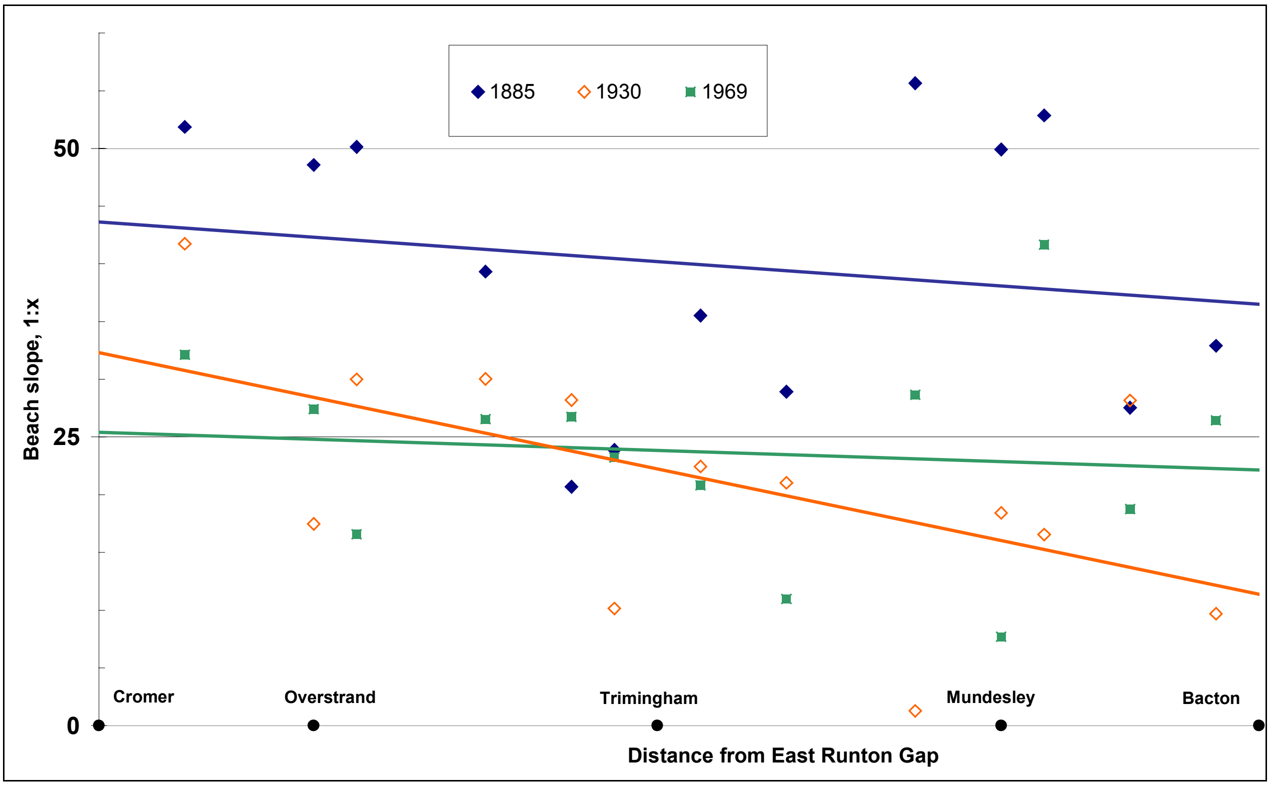

Figure 4.4 Evolution of beach slope between 1885 and 1969

5. CLIFF RECESSION MECHANISMS AND POTENTIAL SEDIMENT YIELDS

The littoral processes discussed above, and particularly the effects of longshore drift, are fundamentally important to the evolution of the beaches in the study area. While the recession of the cliff is of greatest concern to the residents and property owners, these two processes are closely linked. Where beach levels are low, or the beach has disappeared entirely, waves and tides can act directly on the seawalls and, by overtopping, on the cliff face as well. Should the seawalls deteriorate and fail (e.g. as a result of undermining following removal of the beaches at its toe and lowering of the shore platform) then the rate of cliff top recession will increase. Conversely, a high healthy beach will prevent direct wave attack on the seawalls and the cliff face and hence greatly reduce the rate of recession of the cliff top edge. However, even the complete protection of the base of the cliffs will not completely halt cliff top recession because of erosion and weathering of the cliff face as well as the dangers of slumping or land-sliding caused by ground water flows from the land as shown in Figure 5.1.

Figure 5.1 Landsliding on the coast, west of Trimingham (view westward)

The consideration of the possible reactivation of cliff recession following the deterioration and failure of coastal defences is a complex issue. This is considered in greater detail in the accompanying reports on cliff processes and cliff modelling.

Between Cromer and Happisburgh, the cliffs are composed of unconsolidated mid-Pleistocene deposits of clays, sands, and gravels. These deposits are highly susceptible to wave attack and provide an important contemporary source of new sediments to the beaches. The mud and possibly fine sand component from the eroded cliff is reworked by waves and transported away from the beach in suspension to leave only the coarser sand and gravel. The long term average values of cliff retreat rates are very useful in quantifying the potential sediment yield that can contribute to the sediment budget. Using Ordnance Survey large scale maps, Cambers (1976) and Clayton (1989) calculated the retreat rates and found that the highest retreat rates (between 1.4 and 1.7m/year) occur near Trimingham.

The long-term recession rates in the study area over the last century have been calculated in a recent study as shown in Appendix D (Clayton, pers. comm.) and plotted in Figure 5.2. As expected, there is no retreat along the defended sections of the coastline at Cromer, Overstrand, Mundesley, Bacton, and Walcott. Figure 5.2 also indicates a pattern of decreasing erosion rates immediately updrift of areas where groynes have been constructed and a trend of increasing erosion rates immediately downdrift (e.g. at Overstrand and Mundesley). Acting as barriers to the longshore movement of sediment, groynes trap sediment on their updrift side to create a higher, more stable beach and thereby offer a higher degree of natural protection to the cliffs from wave attack. This could account for the lower rates of erosion to the west of Overstrand and Mundesley. Conversely, on the downdrift side of the groynes, sediment supply may be starved, and therefore the beaches will not offer protection to the cliff toe. A description of the location and condition of the groynes in the study area is provided in the defence condition survey report.

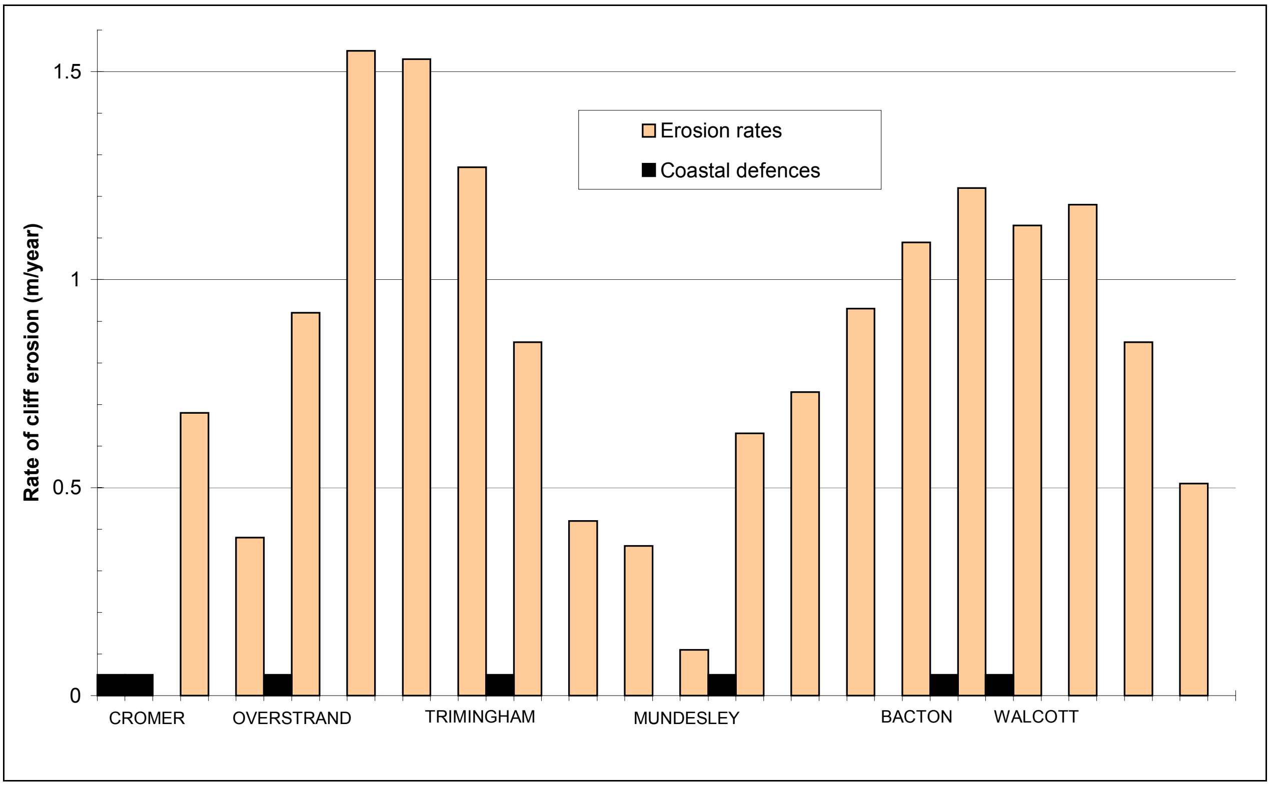

Figure 5.2 Cliff erosion rates from Cromer to the east of Walcott (Clayton, pers. comm.)

Knowledge of the retreat rate, cliff height, and sediment forming the cliff allows the sediment input to the beach to be calculated. The potential sediment yield from the cliffs between Overstrand and Mundesley has been calculated (BGS 1996), as discussed the cliff processes report. Potential sediment yields from the cliffs have also been calculated between Cromer and Overstrand based on the sediment forming the cliff and cliff height as described in the Cromer Coastal Strategy Study (HR Wallingford 2002a).

The potential input of sediment from Cromer to Happisburgh into the regional sediment budget has been estimated using the observed long-term retreat rate and the estimated sediment yields based on sediment yield per metre of cliff recession (see Appendix D). Table 5.1 summarises the potential inputs of cliff material between Cromer and Happisburgh.

Table 5.1 Potential sediment yields from cliffs between Cromer and Happisburgh

Location	Average retreat rate (m/year)	Potential sediment yield (m^3 / m recession)	Potential sand yield (m^3 / year)	Length of frontage (m)
Cromer to Overstrand	0.53	52,000	42,000	3,200
Overstrand to Trimingham	1.30	120,000	43,000	4,000
Trimingham to Mundesley	0.44	96,000	57,000	3,900
Mundesley to Happisburgh*	0.92	110,000	62,000	8,800

Note: All values are averaged over individual length of coastline
* Long-term cliff retreat rates at Happisburgh are known; however, potential sediment yield is estimated based on frontages near Mundesley (assuming sand comprises 54% of cliff material).

As discussed above, the potential sediment yield is comprised of sands, muds, and gravels. The muds will not contribute to the overall 'sediment budget' for the region since they are sorted and removed from the beach system and enter the North Sea mud budget (McCave 1973). Furthermore, the gravel component has been disregarded, as gravels comprise only 1% of the cliff material.

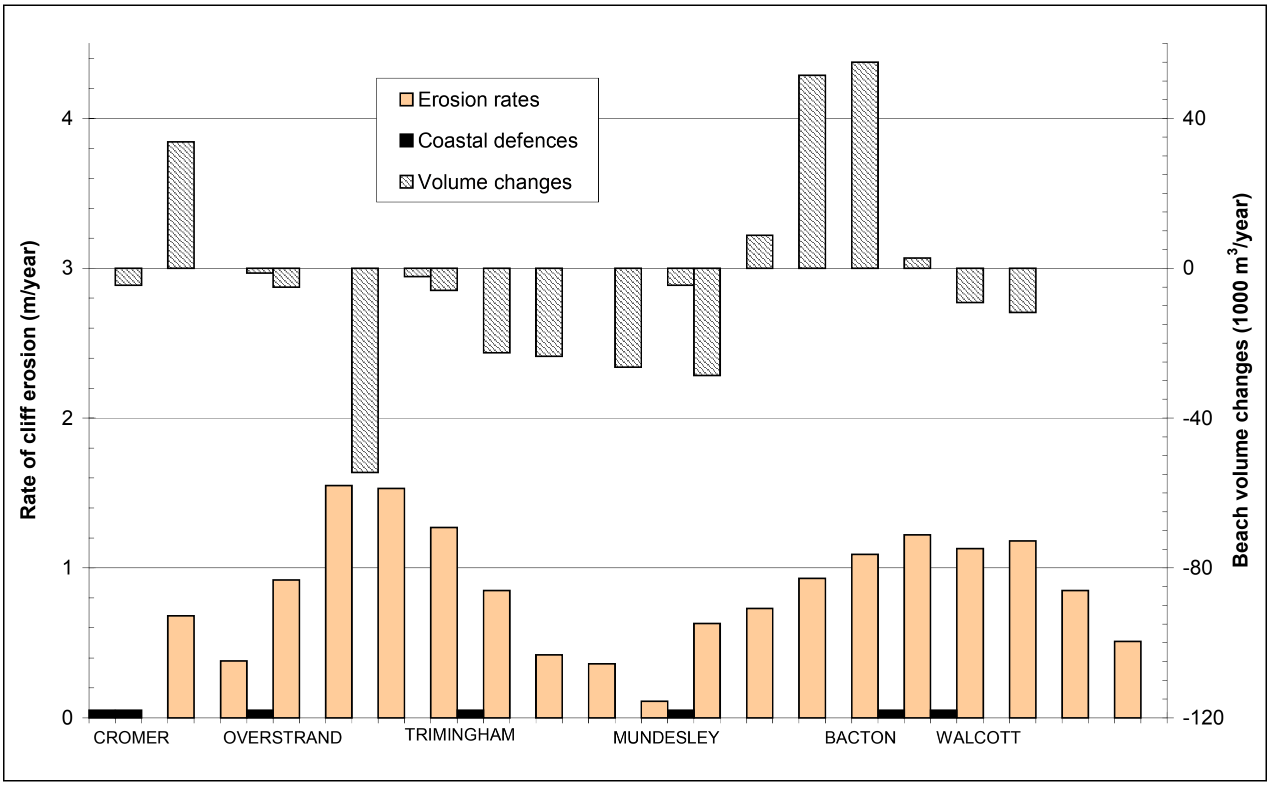

Figure 5.3 Comparison of beach volume changes (Figure 4.2) and erosion rates (Figure 5.2)

Examining the relationship between beach volume changes and cliff erosion, Figure 5.3 illustrates that the cliffs between Overstrand and Mundesley (i.e. near Sidestrand and Trimingham) are retreating at the fastest rate, accompanied by the greatest loss in beach volumes. The cliffs along this frontage are unprotected, and the high rate of recession is likely to be due to:

- Lack of consistency and strength in the cliff material (characterised by contorted drift deposits);
- Action of the waves removing the slumped material at the cliff toe; and
- Groundwater movement where seepage can be seen to be propagating seawards.

Furthermore, the higher beach volume losses in this area are likely to exacerbate the rate of cliff recession.

The successful protection of lower cliffs by seawalls and groynes has reduced local sediment inputs in the defended areas. Where defences have been constructed during the period after the publication of the second edition of large scale OS maps (1905), it has been possible to quantify these reductions. From this, it is estimated that sea defences along the Anglian coastline have caused a decline in natural sediment input of no greater than 100,000m^3/year (Vincent, McCave, & Clayton 1983). Long sections of drift aligned coasts, such as those further to the south east, are totally dependent on large natural feeds from eroding cliffs to remain stable, so Vincent, McCave, & Clayton (1983) recommended that erosion be allowed to continue unhindered. However, this recommendation ignored the possibility of the flooding of large low-lying areas of land, with the consequent costs and risk to human life. Due to the strong possibility of such flooding around Sea Palling, a system of detached offshore breakwaters has been constructed.

6. SEDIMENT ANALYSIS AND TRENDS

To determine longshore drift directions along the coast, McCave (1978) relied primarily on analyses of particle grain sizes in beach sediments. McCave found the mean grain size increases downdrift as the finer sand is winnowed away and lost offshore. In the early 1990s, the Anglian Region NRA study measured beach profiles and characterised the results in terms of their morphology (Halcrow 1991).

As part of this study, sediment samples were taken from trial pits and window samples, and the sample locations and analyses results are presented here in Appendix E. A summary of the mean diameters from the near surface samples is given in Table 6.1 (note that no near-surface samples were taken at Mundesley). Indicating a clear increase in grain diameter from west to east (i.e. away from the drift divide at Sheringham), this analysis confirms McCave's conclusions. However, there are no definitive trends in skewness, kurtosis, or mixing (d_{90}/d_{10}); and the sediment analyses indicated presence of coarse gravel being present at Overstrand, Trimingham, and Mundesley (all containing some samples with d_{90} greater than 10mm).

Lastly, McCave's hypothesis would also suggest that steeper beach faces would tend to occur at the eastern end of the frontage (Mundesley to Walcott) than at the west (Cromer to Overstrand), as beaches made of coarser material tend to be steeper. This trend in beach steepness has been observed in the historical record and is shown in Figure 4.4, further confirming the trend in Table 6.1.

Table 6.1 Mean diameter for near surface sediment samples along the frontage

Location	Overstrand	Trimingham	Bacton	Walcott
d_{50} (mm)	0.41	0.42	0.52	0.55

7. CROSS-SHORE BEACH SEDIMENT EXCHANGE

Cross-shore sediment transport affects the beach volume, sometimes causing beach drawdown during storms. This leads to increased water depth and hence greater wave heights at the top of the beach (or at the structure toe). This can lead to greater erosion of a cliff or the overtopping and possible undermining of a seawall. Moreover, information about the cross-shore sediment gains and losses could inform the numerical cliff and beach recession model, cliffSCAPE, as discussed in the accompanying cliff modelling report.

The short-term cross-shore response of the beach to a storm was modelled using HR Wallingford's coastal profile model COSMOS, which is a 2DV model of nearshore hydrodynamics and sediment transport. The model is described as 2DV as it models variations in both the cross-shore and the vertical directions. The model includes:

- Linear wave transformation by refraction, shoaling, Doppler shifting, bottom friction, and wave breaking;
- Wave set-up from the radiation stress gradient;
- Driving forces for longshore wave-induced currents from the spatial distribution of wave energy dissipation;
- Longshore currents from pressure-driven tidal forces and wave-induced forces;
- A three-layer model for cross-shore undertow;
- Cross-shore and longshore sediment transport rates using Baillard's energetics approach; and
- Seabed level changes due to cross-shore sediment transport.

The model assumes a straight coastline (which in principle is well suited to the study area) with parallel depth contours. Southgate and Nairn (1993) provided a detailed description of the hydrodynamic components of COSMOS, while Nairn and Southgate (1993) described the sediment transport model used by COSMOS.

COSMOS was designed to model the short-term cross-shore response to a storm, and results from the recent EU-funded COAST3D project (van Rijn et al 2002) have shown that COSMOS models the bed level changes due to cross-shore sediment transport during a storm quite accurately. However, as it was designed and calibrated to be a storm-response model, the model's performance reduces as wave height reduces. Therefore, COSMOS can be used to derive cross-shore sediment transport rates during storms but not during relatively calm periods.

While an annual distribution of onshore and offshore sediment transport cannot be accurately calculated using COSMOS, in this study the onshore gains during calm conditions are assumed to balance the offshore losses during storms. This assumption of no net cross-shore drift is based on the results of both the Southern North Sea Sediment Transport Study (HR Wallingford 2002b) and the Futurecoast project (Halcrow 2002).

The following input assumptions were made for COSMOS calculation purposes:

- 0.24mm median sand grain diameter;
- Cross-shore bed depth profile based on the average of the inshore profiles coupled to an offshore profile;
- Wave conditions obtained from the nearest inshore wave point to the bathymetric line surveyed; and
- Wave height versus period scatter plots were used to obtain the incident wave height and period and the probability of occurrence of the condition.

The probability of occurrence mentioned above was converted into an average number of hours of occurrence per year and subsequently used to convert the cross-shore transport rate into an annual average gross offshore transport rate due to storms (in cubic metres per metre per year). This calculation was done for all wave conditions, although only the results for storm wave conditions (in this case incident significant wave height greater than 2m) were used. This 2m cut-off was based on the results from the COAST3D project, when measurements were made on a double-barred beach at Egmond-aan-Zee (NL) (HR Wallingford 2001a). While the cut-off may not be entirely appropriate for the present study (due to differences in beach profile), in the absence of site-specific calibration there is no reason to alter the value. However, as this cut-off may be regarded as somewhat arbitrary, sediment transport rates are provided for all conditions.

The cross-shore distributions of cross-shore sediment transport rates are shown in Figures 7.1 to 7.3. Negative transport rates denote the offshore transport of sand. The distributions show local maxima where the beach slopes most rapidly, causing the most intense wave breaking. Values for the annual cross-shore sediment transport rate were output at points identified as the toe of the beach (where there is commonly a change in the beach gradient). The calculated mean annual gross offshore sediment transport rate due to storms are given below:

- Mundesley – 63m^3/m/year at chainage 800m
- Trimingham – 128m^3/m/year at chainage 550m
- Overstrand – 58m^3/m/year at chainage 500m

The mean annual gross offshore potential transport rates for each wave condition are shown in Table 7.1, calculated at the chainages above. The total transport rate (without the cut-off) and the transport rate using the 2m Hs cut-off is also given. The values with and without the cut-off differ by less than 15%.

Table 7.1 Offshore shore potential sediment transport rates

Hs range (m)	T range (s)	Cross-shore potential transport rates		
		Overstrand (m^3/m/year)	Trimingham (m^3/m/year)	Mundesley (m^3/m/year)
5 to 6	6 to 7	-0.6	-0.2	0.0
5 to 6	5 to 6	-0.1	0.0	0.0
4 to 5	6 to 7	-3.6	-9.5	-9.0
4 to 5	5 to 6	0.0	-0.9	-0.3
3 to 4	6 to 7	-21.2	-51.0	-31.5
3 to 4	5 to 6	-2.0	-10.0	-1.6
2 to 3	6 to 7	-1.3	-1.8	-1.9
2 to 3	5 to 6	-29.0	-54.2	-18.6
2 to 3	4 to 5	-0.4	-0.5	-0.1
1 to 2	6 to 7	0.0	0.0	0.0
1 to 2	5 to 6	-4.3	-9.1	-2.7
1 to 2	4 to 5	-5.5	-8.3	-2.2
1 to 2	3 to 4	0.0	0.0	0.0
0 to 1	6 to 7	0.0	0.0	0.0
0 to 1	5 to 6	0.0	0.0	0.0
0 to 1	4 to 5	-0.1	0.0	0.0
0 to 1	3 to 4	0.0	0.0	0.0
0 to 1	2 to 3	0.0	0.0	0.0
0 to 1	1 to 2	0.0	0.0	0.0
Total rate		-68	-145	-68
Rate with cut-off		-58	-128	-63

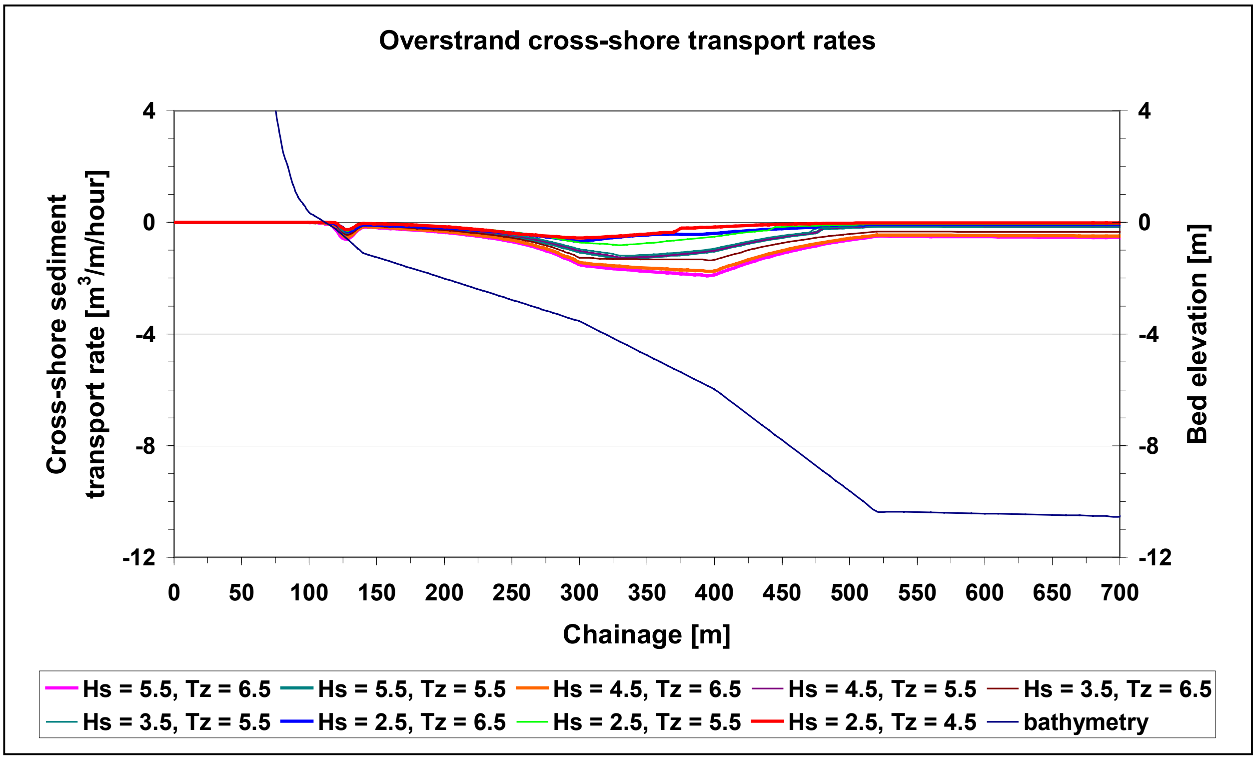

Figure 7.1 Cross-shore sediment transport rates at Overstrand

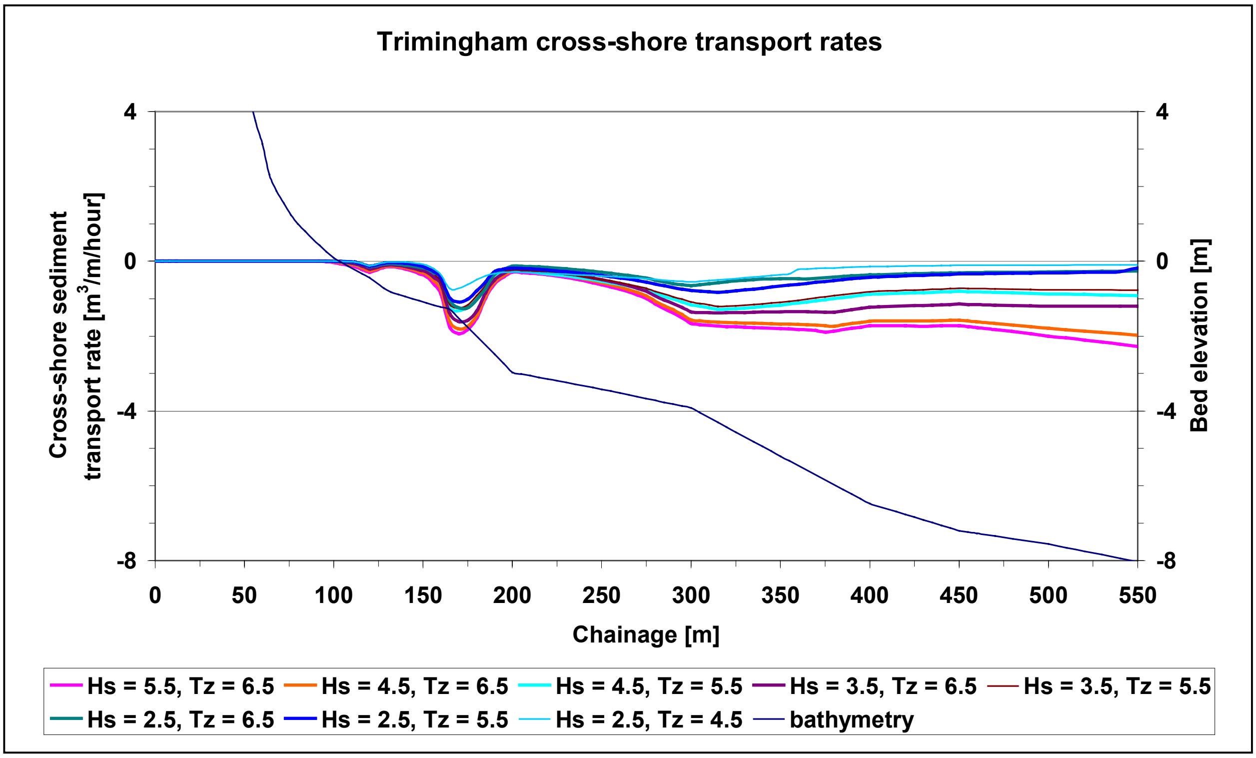

Figure 7.2 Cross-shore sediment transport rates at Trimingham

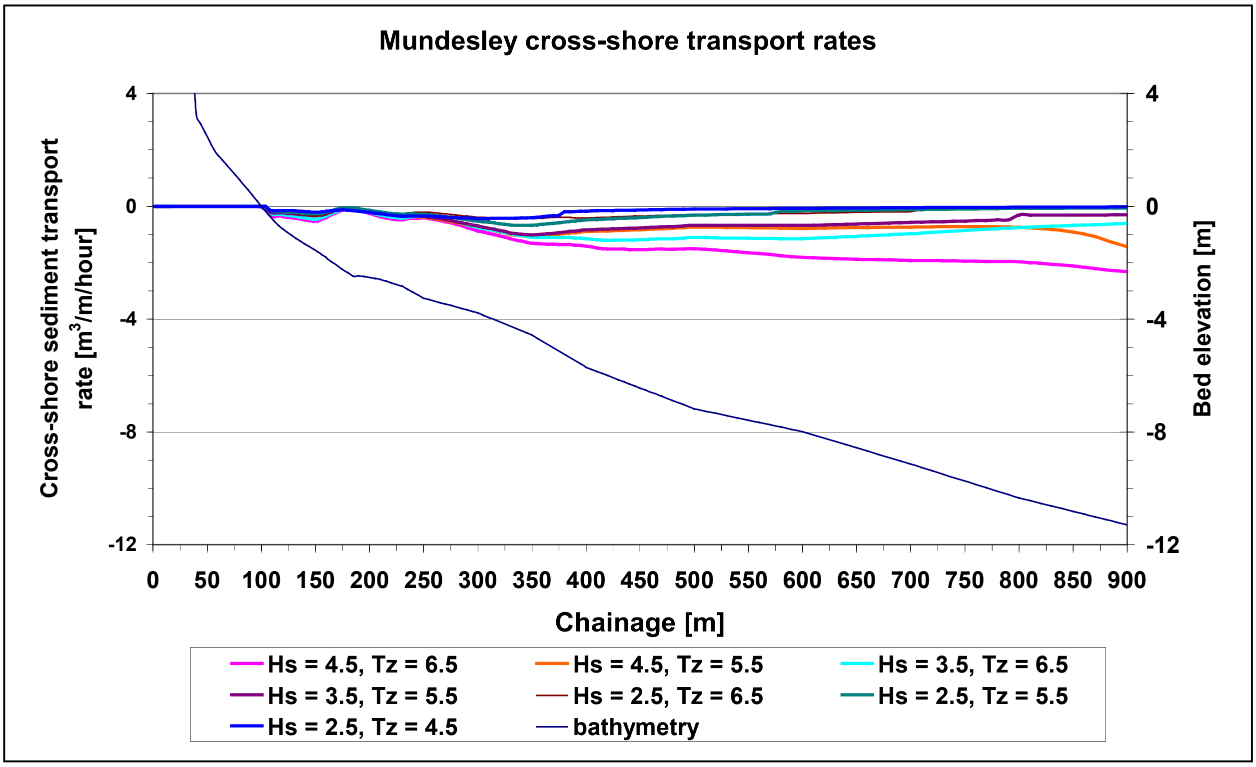

Figure 7.3 Cross-shore sediment transport rates at Mundesley

As discussed previously, the offshore transport rates during storms cannot be converted into an annual volume sediment loss (per metre of coast), as the onshore sediment transport during calm periods was not modelled. However, given the gross offshore transport rate due to storms along the frontage in addition to the lengths of the frontages, an estimate can be made of the average volume of sediment transported offshore. Assuming that the offshore transport rate varies linearly with distance, the gross annual volume of sediment transport offshore for Overstrand to Trimingham and Trimingham to Mundesley during storms was approximately 370,000m^3/year. Thus, as discussed previously, it was assumed that the mean gross annual volume of sediment transport onshore during calm periods balanced this as per the results of previous research (HR Wallingford 2002b and Halcrow 2002).

8. CONCEPTUAL SEDIMENT BUDGET

The fundamental components of the sediment budget have been examined in the preceding sections of this report, which provide values for on-offshore sediment transport rates, sediment inputs from the cliffs, and beach volume changes. A sediment budget was developed using a range of data, which include:

- Input of beach-forming sediment from the retreating cliffs (Cambers 1976 and 1989);
- Changes in beach volume (Onyett and Simmonds 1983; Vincent, McCave, & Clayton 1983);
- An appreciation of the longshore transport rates along the beach and offshore based on numerical and tidal wave modelling (Vincent 1979); and
- Volume of cross-shore exchange between the beach and offshore.

To present a conceptual sediment budget for any coastal frontage, boundary need to be ascertained conditions (i.e. sediment transport rates across the region boundaries must be set). For this study, the input into the western boundary of the study area has been taken from the neighbouring Cromer Coastal Strategy Study (HW Wallingford 2002a). The longshore transport rate to the west of Cromer Pier was calculated to be 54,000m^3/year in the Cromer Coastal Strategy Study on the basis of numerical modelling and 22 years of wave data (1979 to 2000). Similarly, the longshore drift rate calculated on the eastern boundary may be taken from the Ostend to Cart Gap Coastal Strategy Study (HR Wallingford 2001b), wherein average annual drift was estimated to be 430,000m^3/year as based on 7 years of wave data (1979 to 1986). As the CERC formula used in these previous studies is the same as that used here, the values derived are directly comparable with drift rates calculated in this study (and also with previous research carried out since the 1970's).

Figure 8.1 provides a conceptual model, quantitatively depicting the sediment movement in the study area based upon the findings in this report. As sediment transport on either the western or eastern boundary may be fixed on the basis of the previous strategy studies, two sets of results may be calculated. Thus, the net longshore sediment transport rates (in red) are given in terms of upper and lower bound results. While the upper bound values are derived by fixing the eastern boundary to the value from the Ostend to Cart Gap Coastal Strategy Study, the lower bound values are calculated based on the results of the Cromer Coastal Strategy Study (HW Wallingford 2001b and 2002a). Intermediate values of longshore sediment transport are calculated from the previously determined inputs (i.e. the addition or subtraction of the beach volume data, cliff data, and on-offshore transport rates). Again, there was assumed to be no net cross-shore sediment transport, as discussed previously in Section 7.

Figure 8.2 compares these determined values of net drift from the conceptual model with the numerically modelled potential drift as discussed in Section 2. The net sediment transport rates are thought to lie within a range reflected by the upper and lower bands in Figure 8.2. The potential drift at Cromer (calculated by numerical modelling) is much higher than the net drift as calculations of net drift take into consideration mixed sediments on the beach. (The standard CERC equation was adjusted to account for this by setting the time scale coefficient, K_1, to a value intermediate to those used for uniformly sand and uniformly shingle beaches.) Approaching Trimingham, both the potential and net drift follow similar increasing trends. The local maxima (net drift of the order of 345,000m^3/year) downdrift of Mundesley is caused by accretion of the beach in excess of sediment input from the cliffs. However, while such accretion is observed in the short-term beach profile analyses, it is not thought that this will continue over the long-term.

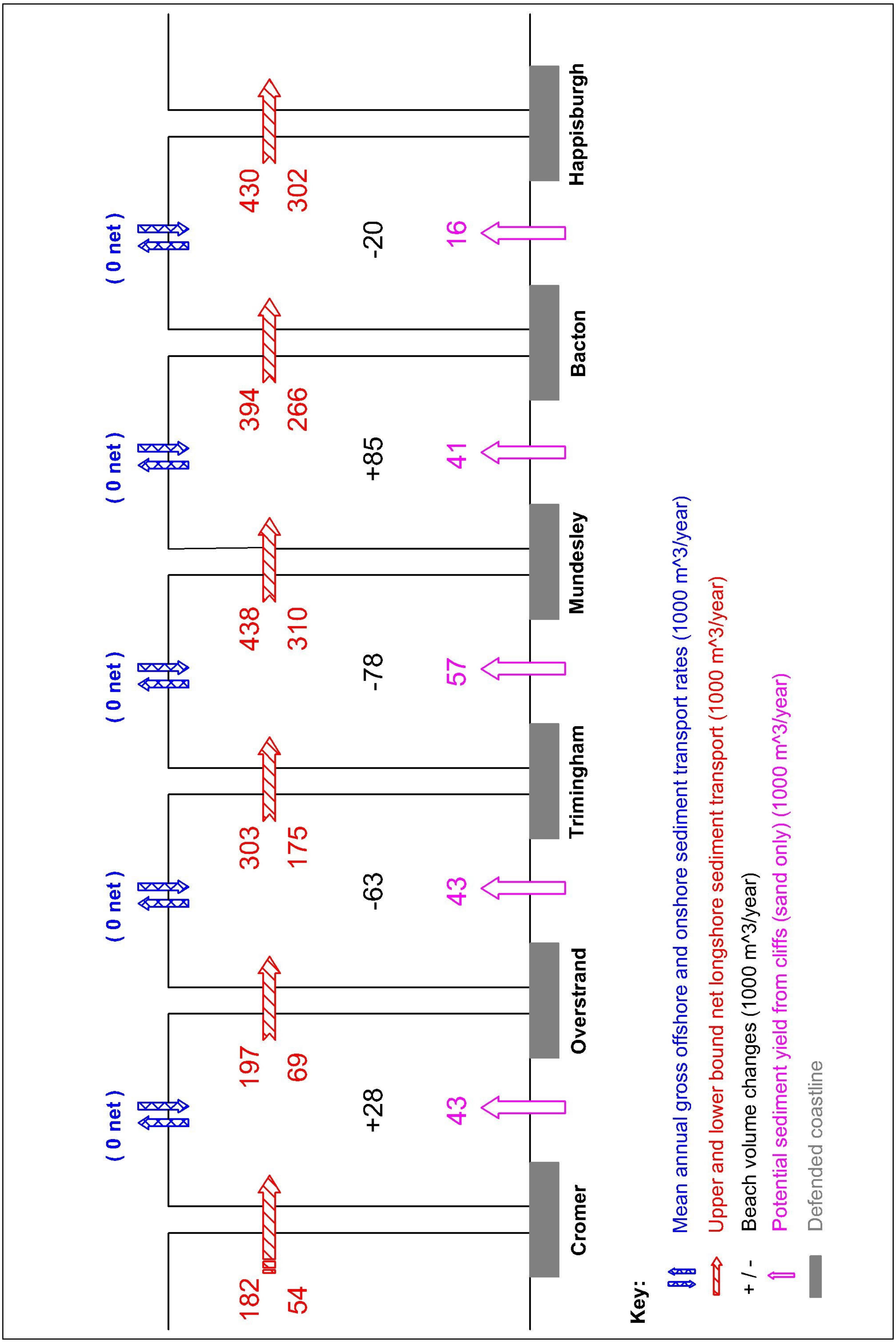

Figure 8.1 A conceptual model for sediment transport

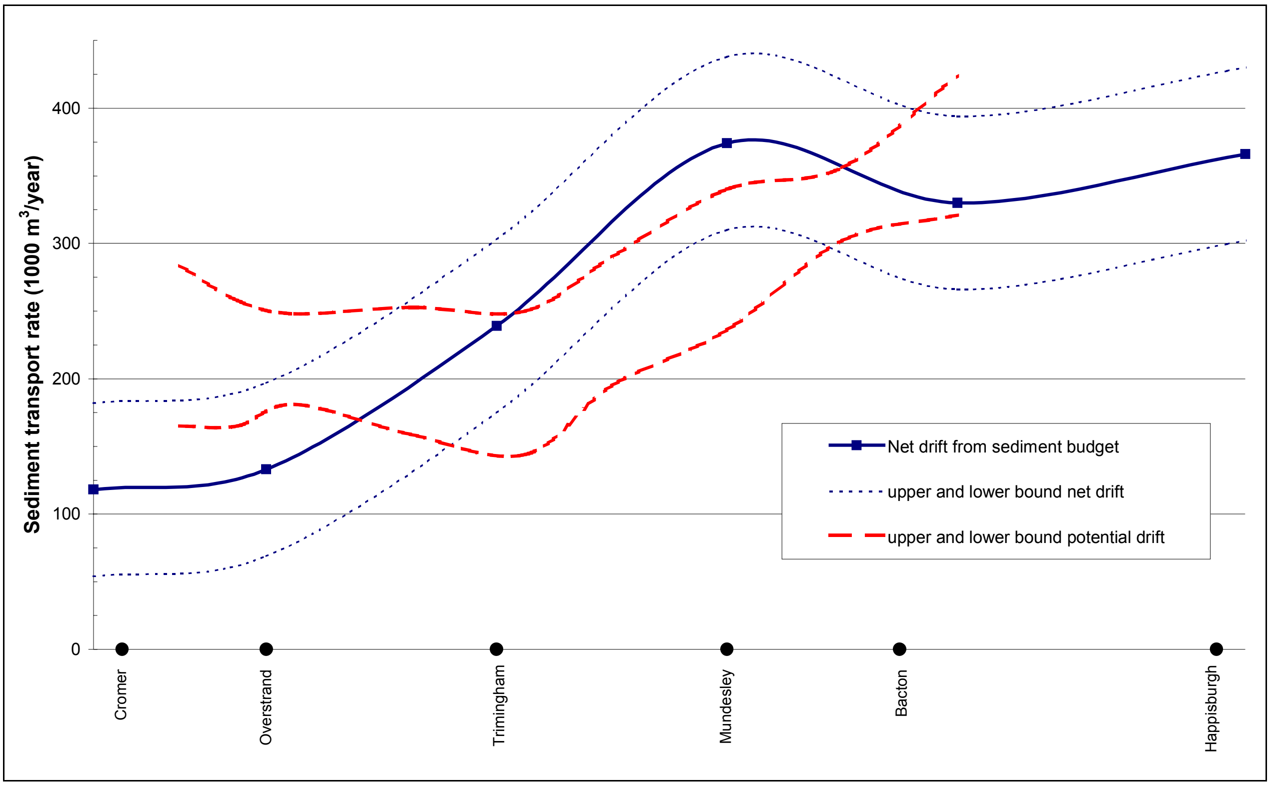

Figure 8.2 Comparison of the potential net drift (Figure 2.1) and the net drift rate from the conceptual model sediment transport (Figure 8.1)

This increasing drift rate along the coastline from west to east confirms earlier work carried out by the University of East Anglia in the 1970's. Vincent, McCave, and Clayton (1983) estimated a drift rate of 100,000m^3/year passing Overstrand, which is reasonable in comparison to the present estimation of 127,000m^3/year (the average of the two values in Figure 8.1). Furthermore, Figure 8.1 shows a mean drift rate of 239,000m^3/year passing Trimingham, and this compares well with Clayton's (pers. comm.) estimate of a southerly drift rate of 180,000m^3/year at Trimingham.

Clayton estimated that the drift rate decreased to 160,000m^3/year from Trimingham towards Happisburgh, as a result of material being lost offshore. However, the estimates from this and the previous Ostend to Cart Gap Strategy Study (HR Wallingford 2001b) suggest that this transport rate would increase to the south east due to the increasing sediment input from the eroding cliffs between Trimingham and Happisburgh. Cliff recession and hence a continued sediment supply is likely since the Shoreline Management Plan (Halcrow 1996) stipulates a preferred policy of 'Managed Retreat' between Trimingham and Mundesley (TRI 5) and between Walcott and Happisburgh (SEA 1), and a preferred option of 'Do-Nothing' between Mundesley and Bacton (BAC 1).

9. INTERACTION WITH ADJACENT COASTAL MANAGEMENT UNITS

A summary of the geographic boundaries of the study area and the preferred policy options identified in the Shoreline Management Plan (Halcrow 1996) is provided in Figure 9.1. West of the study frontage at Cromer, there is a stated policy to 'Hold the Line' (i.e. to continue to hold the line of the existing defences), and this strategy is also the preferred option along the Overstrand, Trimingham, Mundesley, and Bacton frontages. Between Cromer and Overstrand, Overstrand and Trimingham, and Mundesley and Bacton, the policy is not to further intervene in the protection of the coastline (i.e. 'Do Nothing') due to the environmental importance of this stretch of the coastline. Similarly, between Trimingham and Mundesley the stated policy in the Shoreline Management Plan is of 'Managed Retreat' (i.e. setting the present coastal defences further landwards and accepting some cliff recession).

Along this coastline, the 'Do Nothing' and 'Managed Retreat' policies adopted between the protected sections of coastline will result in continued cliff retreat along these sections, the rate of which is likely to increase. These policies will maintain natural processes and continue sediment supply from the cliffs, meeting geological and environmental interests. In addition, these policies will generate more beach sediment, which will tend to propagate eastwards to the downdrift frontages in the study area.

Conversely, the 'Hold the Line' policies, retaining the present line of defences through maintaining cliff toe protection (seawalls) and beach control structures (groynes), will tend to encourage the formation of wider beaches on the defended frontages. In particular, the preservation of groynes will reduce the rate of sediment transport out of these management units.

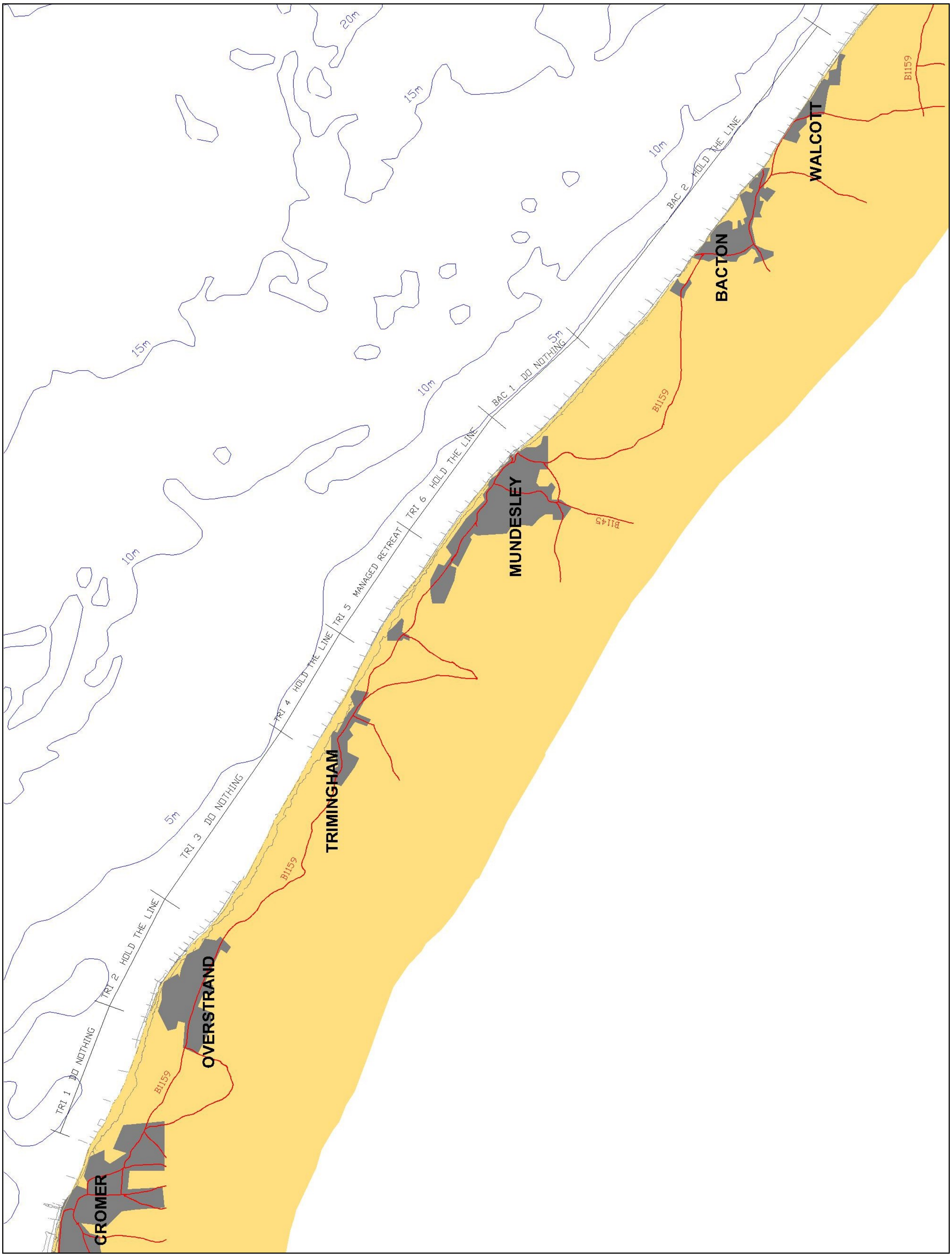

Figure 9.1 SMP policy options for the study area

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Appendices

Appendix A

Beach volume changes – Overstrand, Mundesley, and Bacton

Beach Analysis Results

Overstrand, Mundesley, Bacton.

November 2002

Overstrand

Stations N3D4, N3D3, N3D2, N3D1, N3E6, N3E5, N3E4.
Wave points A, B, C, D.

Overstrand

Station 1: N3D4
Chainages for calculation of the mean profile:
0-20-40-60-65-70-75-80-85-90-95-100-105-110-120-125-130-140-150
Values for the area calculation: 72 / 104 / -5
Height changes per year: -0.025 m/yr
Length of active beach and width of present section: 240/933
Volume changes in m^3/year: -5,930

Station 2: N3D3
Chainages for calculation of the mean profile:
0-40-45-50-55-60-65-70-75-80-85-90-95-100-110-120-130-140-150-160
Values for the area calculation: 64 / 113 / -5
Height changes per year: -0.006 m/yr
Length of active beach and width of present section: 480/837
Volume changes in m^3/year: -2,250

Station 3: N3D2
Chainages for calculation of the mean profile:
0-25-50-75-80-90-100-105-110-115-120-125-130-140-150-160-170-180-190-200
Values for the area calculation: 80 / 156 / -5
Height changes per year: -0.101 m/yr
Length of active beach and width of present section: 500/1076
Volume changes in m^3/year: -54,510

Station 4: N3D1
Chainages for calculation of the mean profile:
0-50-96-100-103-106-110-113-116-120-123-126-130-135-140-145-150-155-160-165
Values for the area calculation: 97 / 132 / -5
Height changes per year: -0.014 m/yr
Length of active beach and width of present section: 390/956
Volume changes in m^3/year: -5,020

Station 5: N3E6
Chainages for calculation of the mean profile:
0-40-45-50-55-60-65-70-75-80-85-90-95-100-105-110-120-130-140-150
Values for the area calculation: 43 / 104 / -5
Height changes per year: -0.031 m/yr
Length of active beach and width of present section: 360/1100
Volume changes in m^3/year: -1,250

Station 6: N3E5
Chainages for calculation of the mean profile:
0-120-130-140-145-150-155-160-165-170-180-190-200-210-220-230-240-250-260-270
Values for the area calculation: 125 / 237 / -5
Height changes per year: 0.060 m/yr
Length of active beach and width of present section: 490/1148
Volume changes in m^3/year: 33,720

Station 7: N3E4
Chainages for calculation of the mean profile:
0-45-50-55-60-65-70-75-80-85-90-95-100-110-120-130-140-150-160-175
Values for the area calculation: 52 / 137 / -5
Height changes per year: -0.008 m/yr
Length of active beach and width of present section: 560/933
Volume changes in m^3/year: -4,560

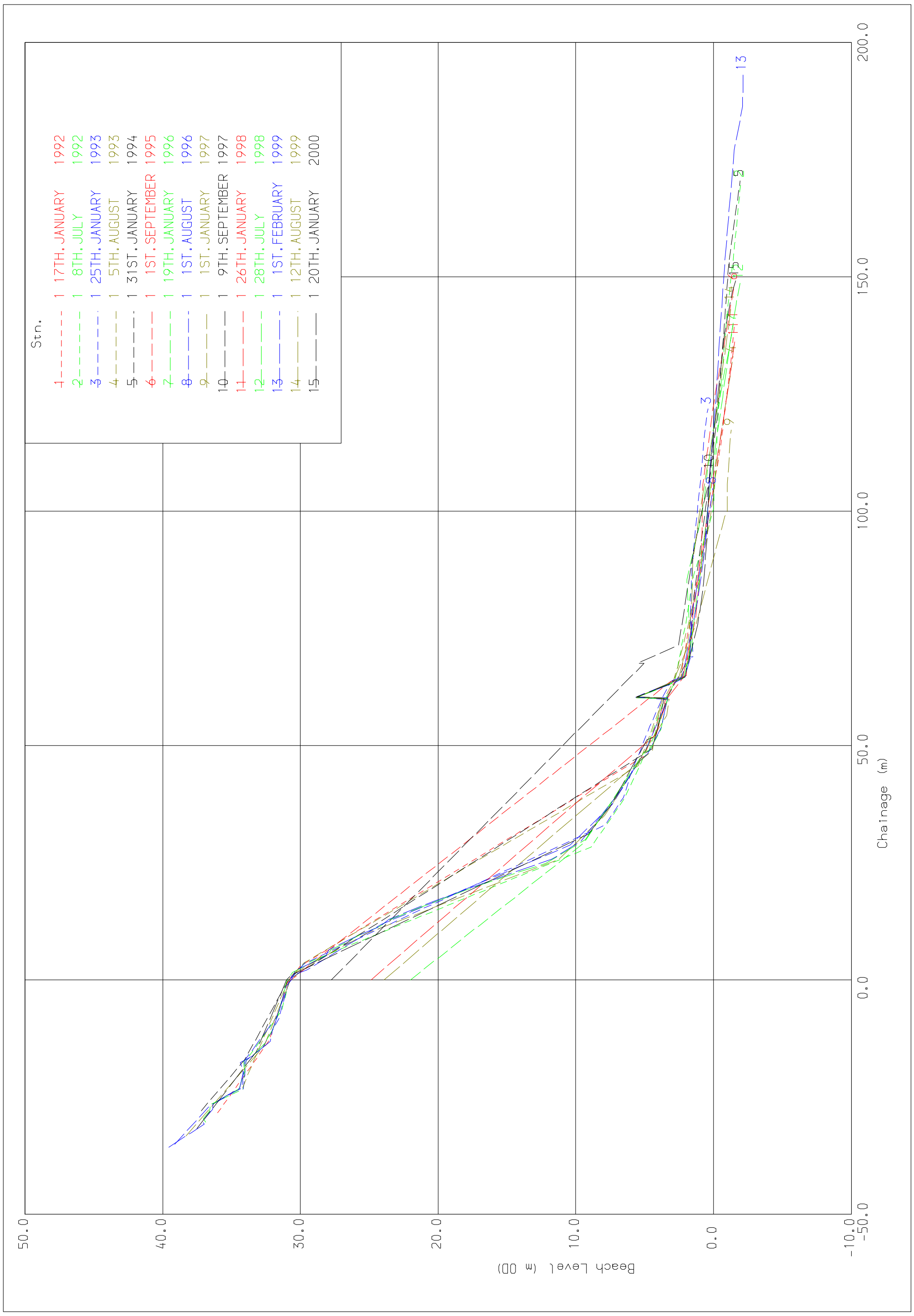


Fig 1 Overstrand Beach Profiles, Station 1.

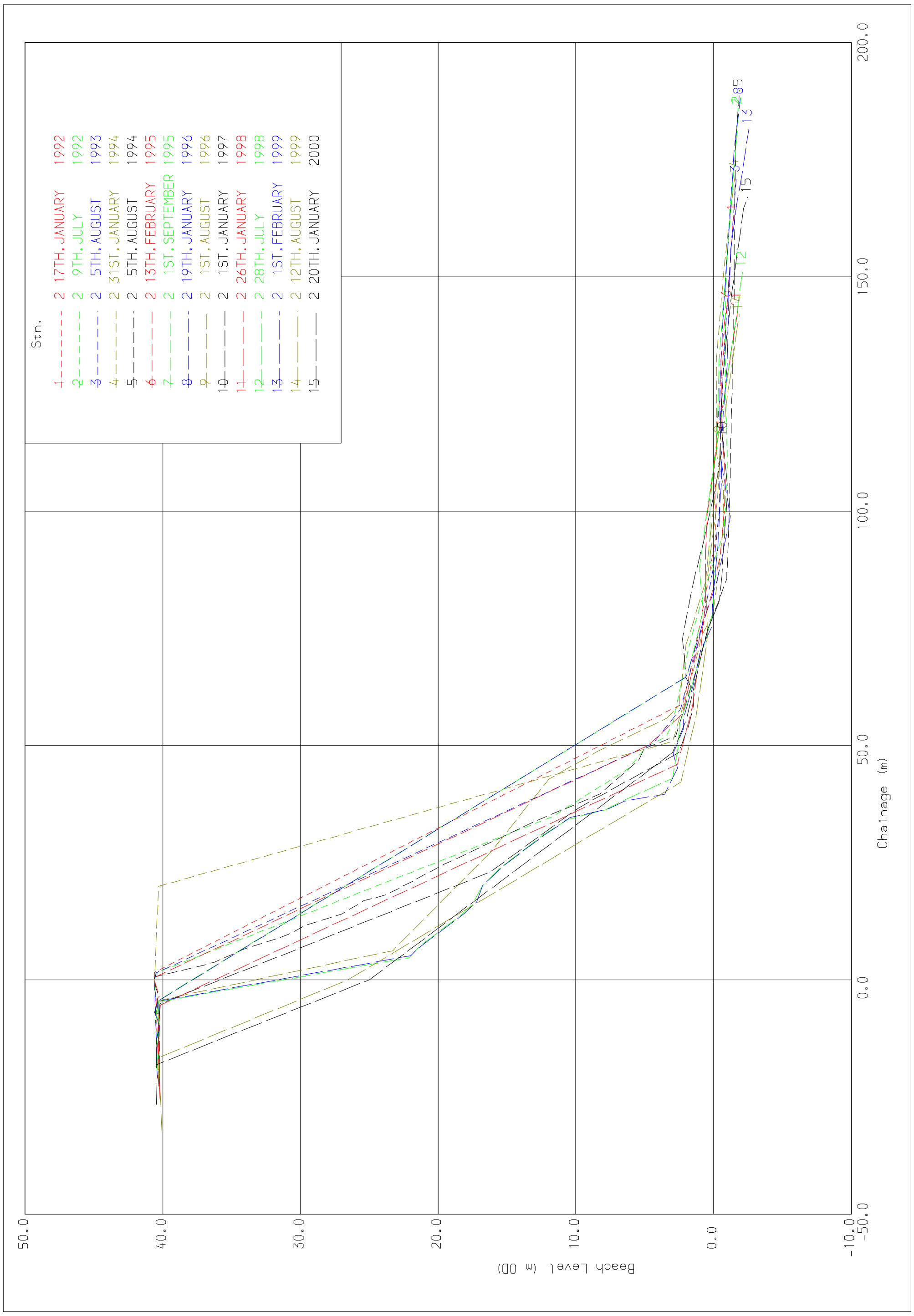


Fig 2 Overstrand Beach Profiles, Station 2.

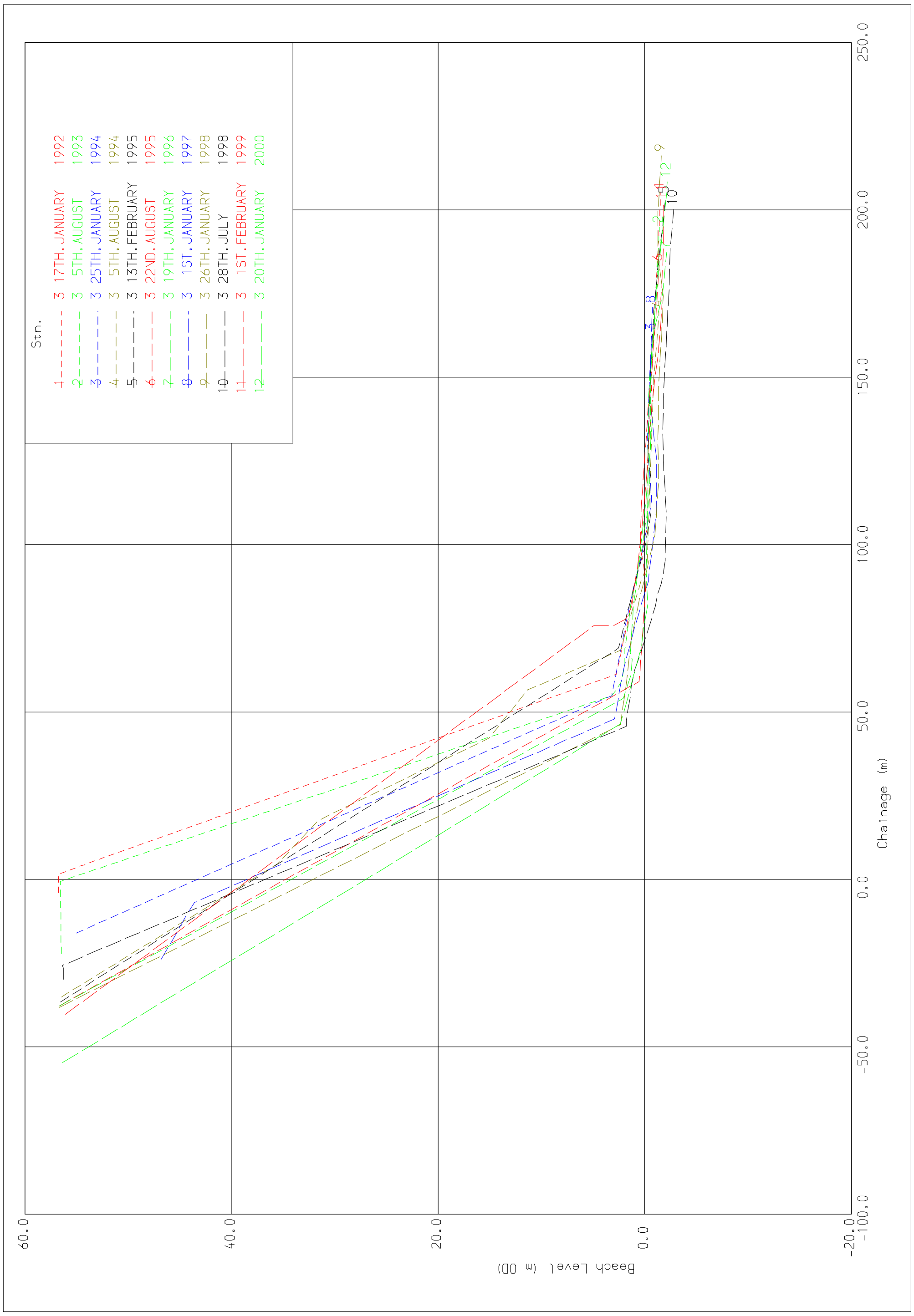


Fig 3 Overstrand Beach Profiles, Station 3.

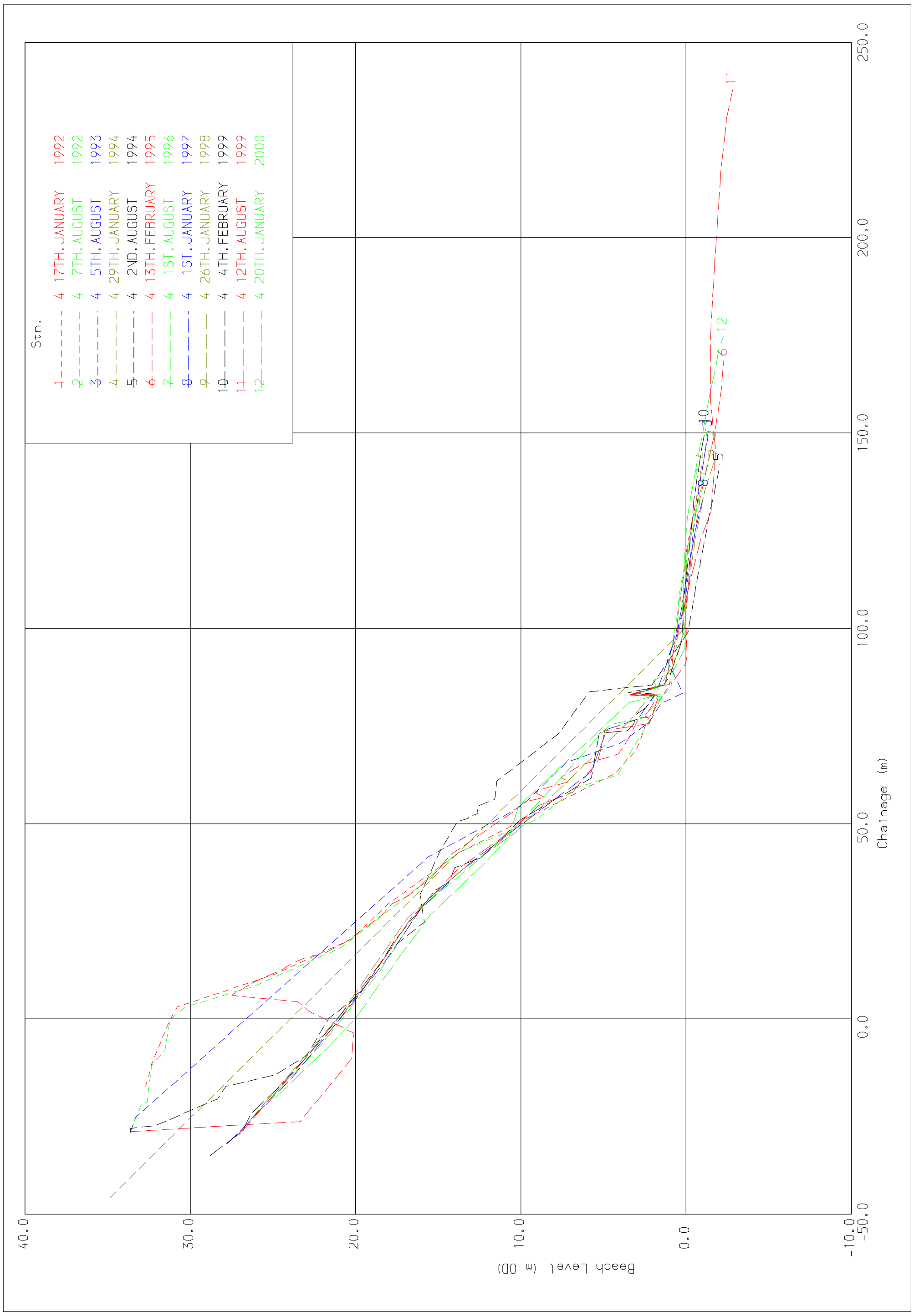


Fig 4 Overstrand Beach Profiles, Station 4.

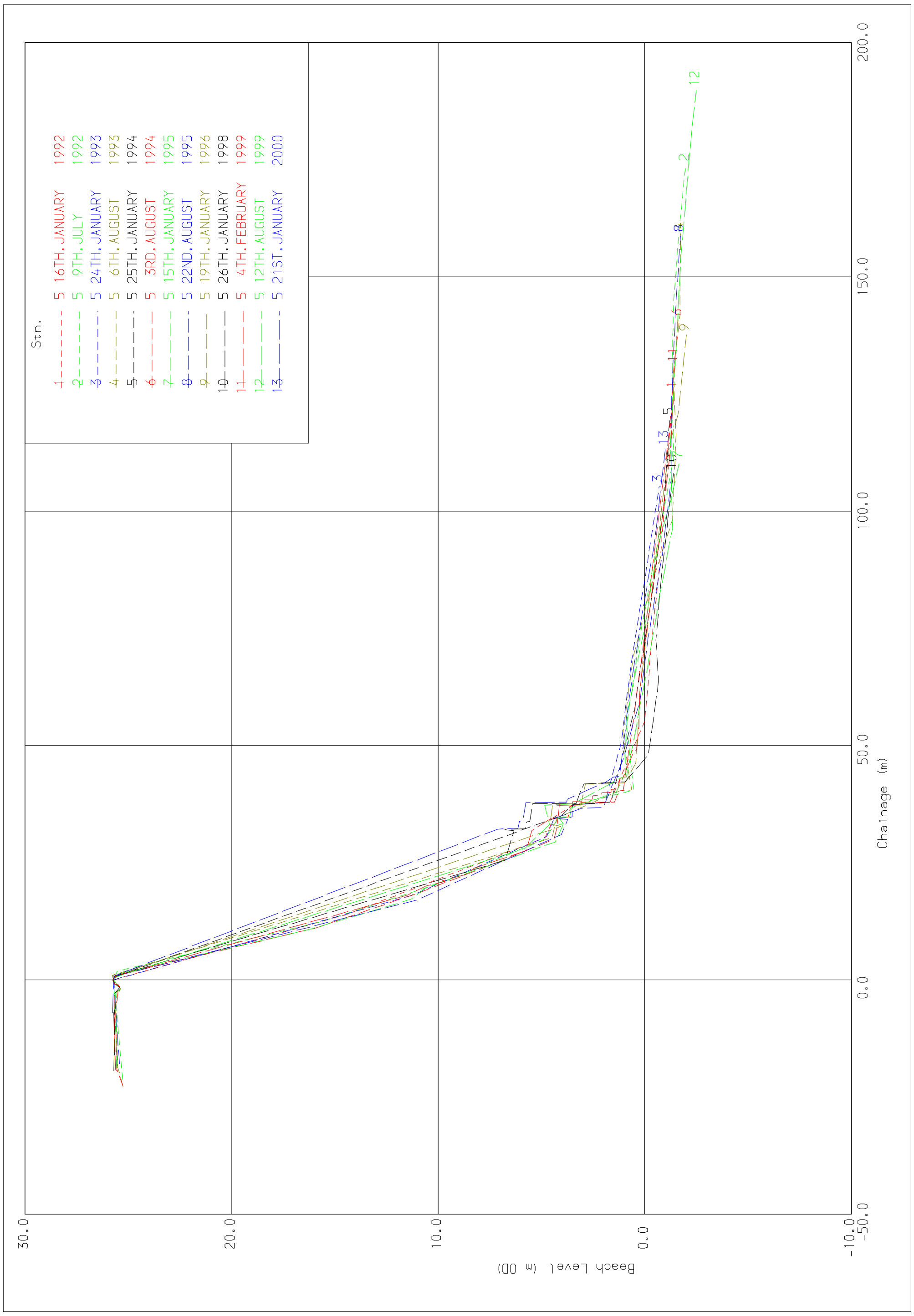


Fig 5 Overstrand Beach Profiles, Station 5.

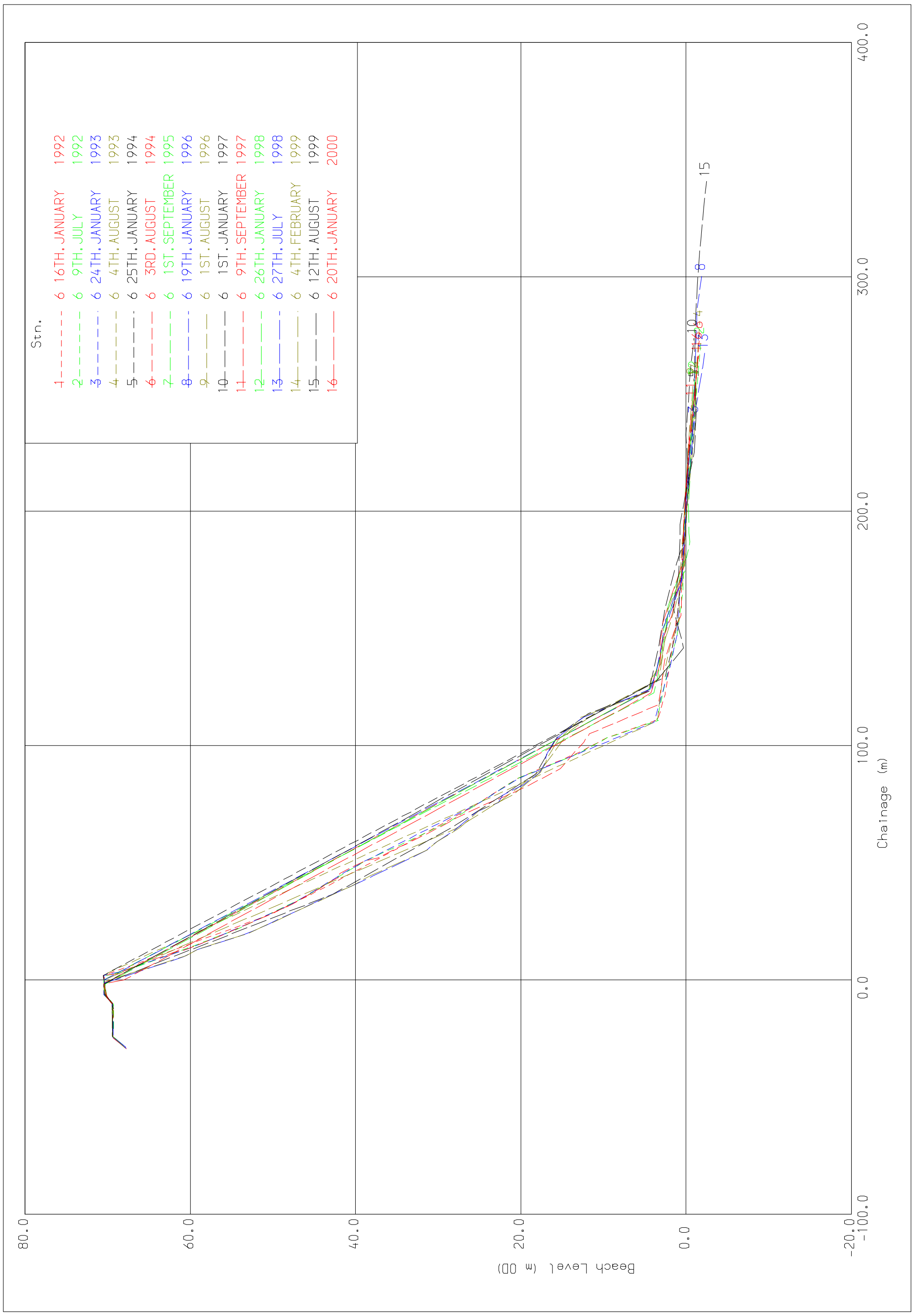


Fig 6 Overstrand Beach Profiles, Station 6.

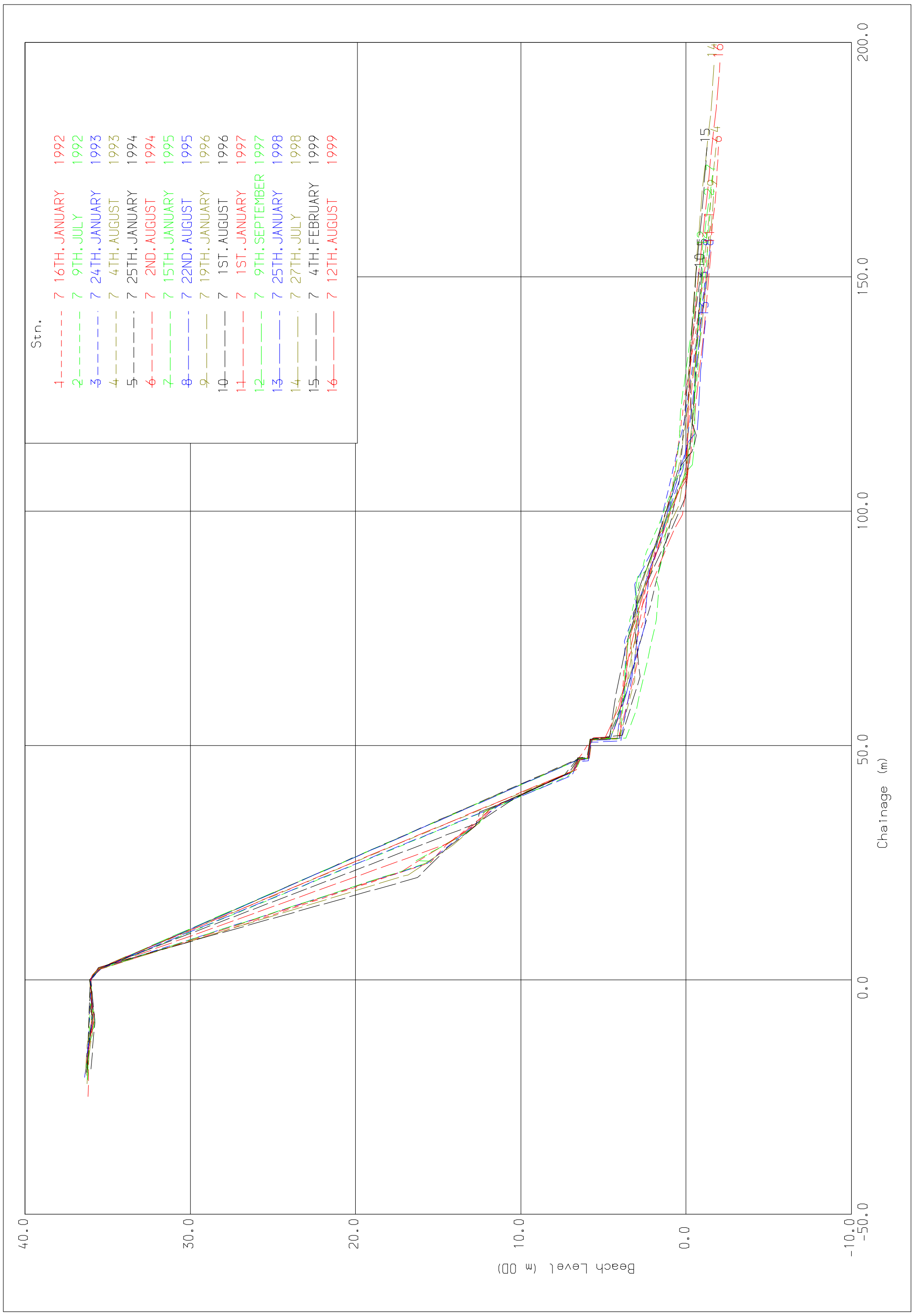


Fig 7 Overstrand Beach Profiles, Station 7.

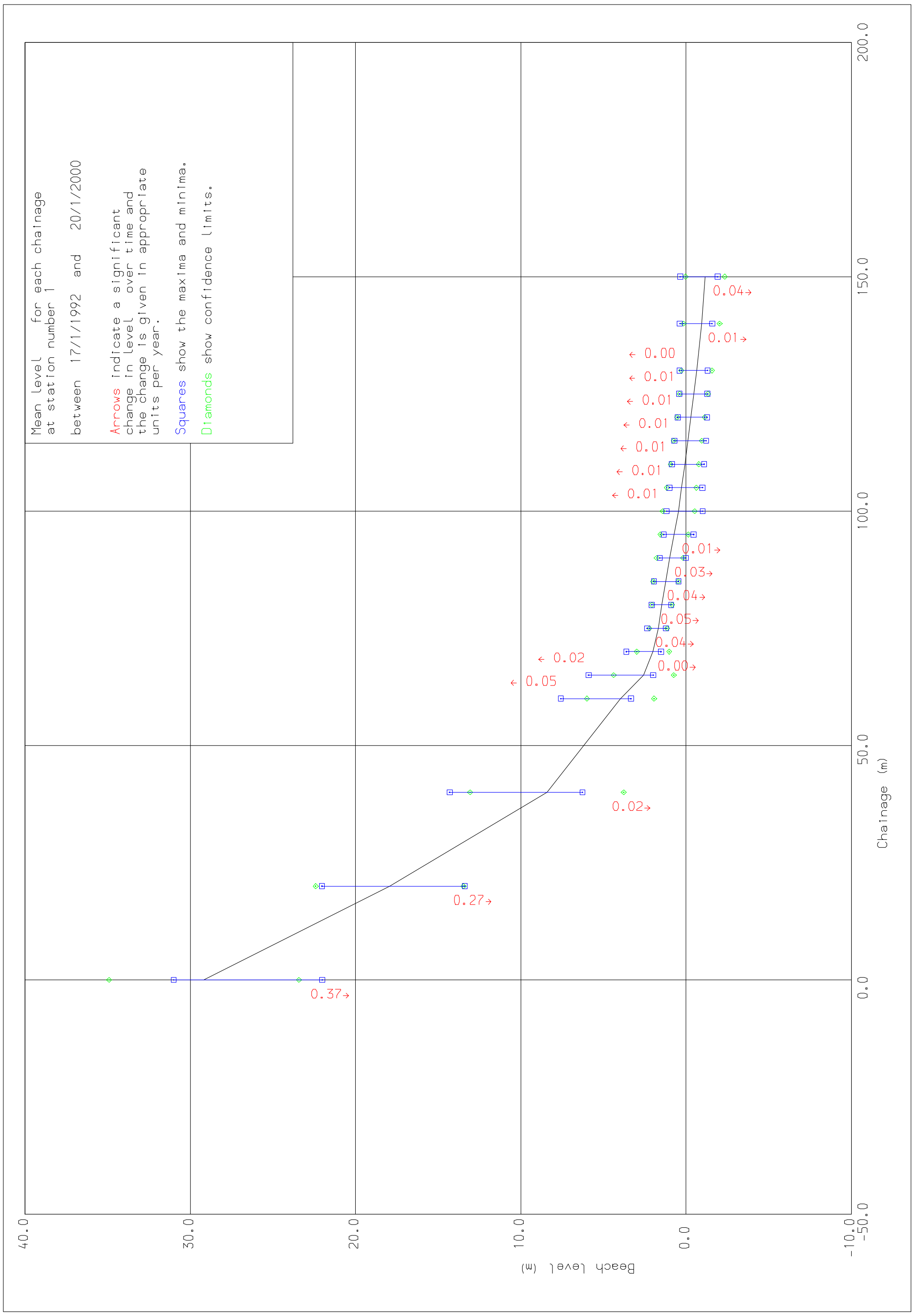


Fig 8 Overstrand Mean Profile, Station 1.

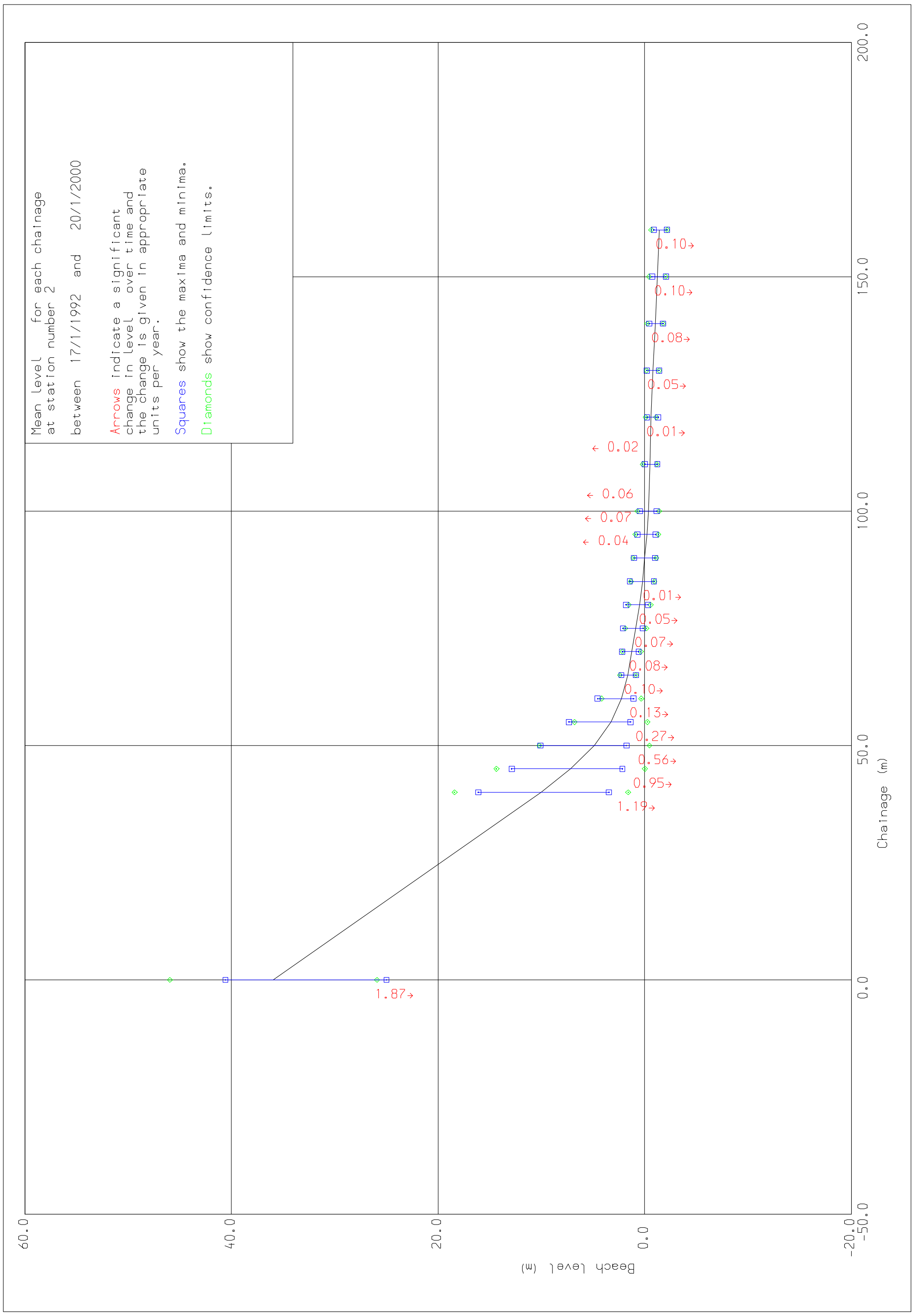


Fig 9 Overstrand Mean Profile, Station 2.

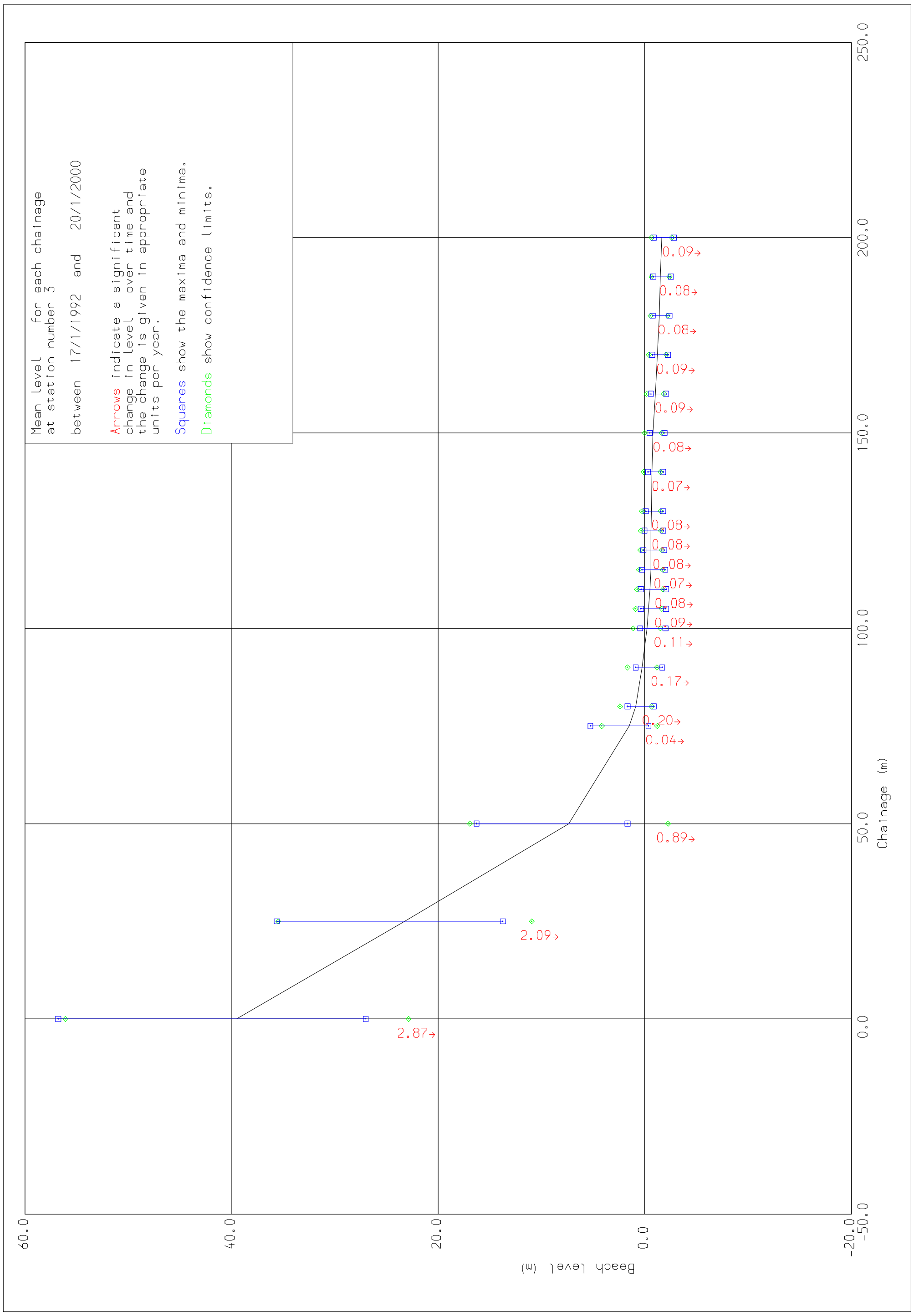


Fig 10 Overstrand Mean Profile, Station 3.

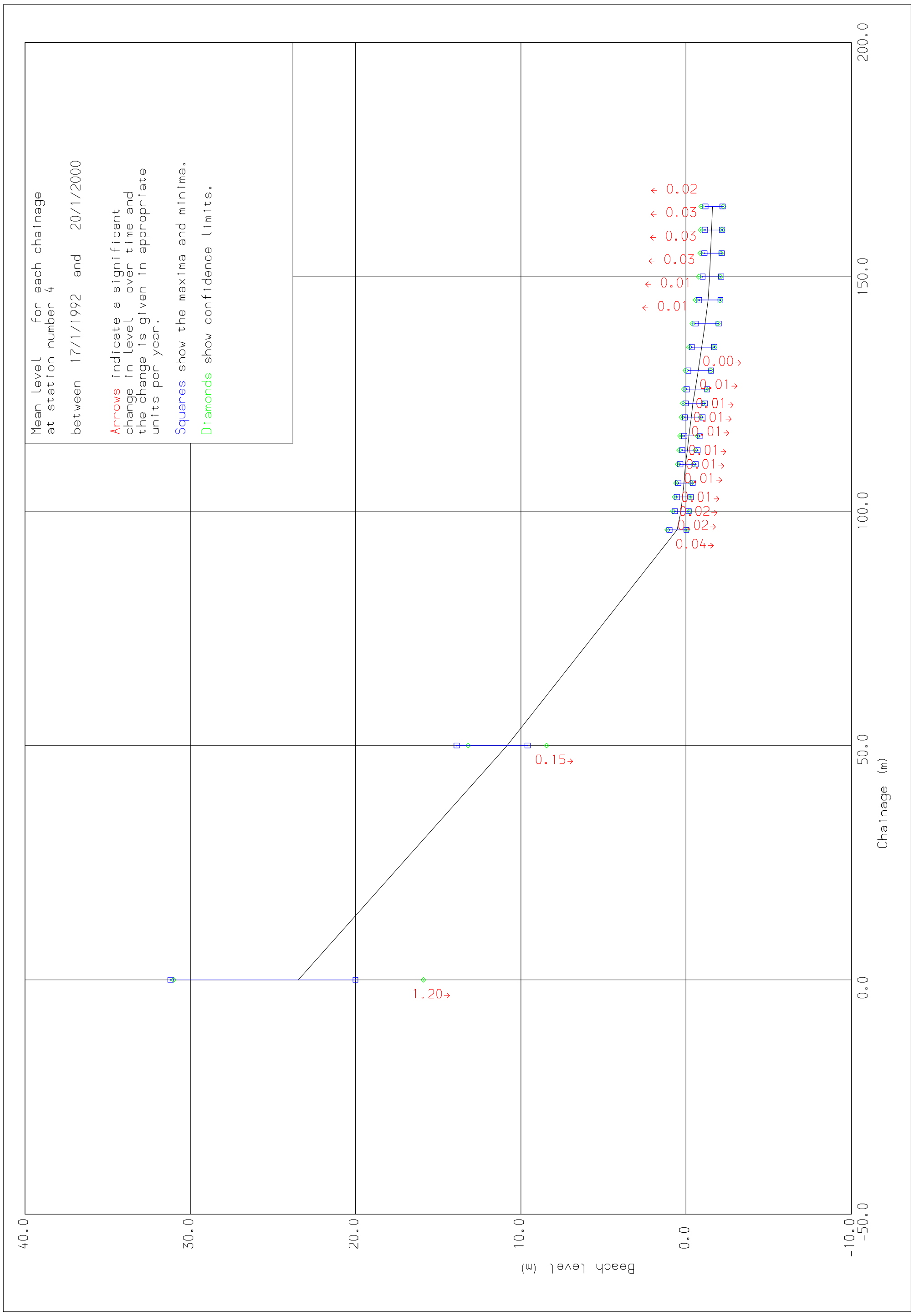


Fig 11 Overstrand Mean Profile, Station 4.

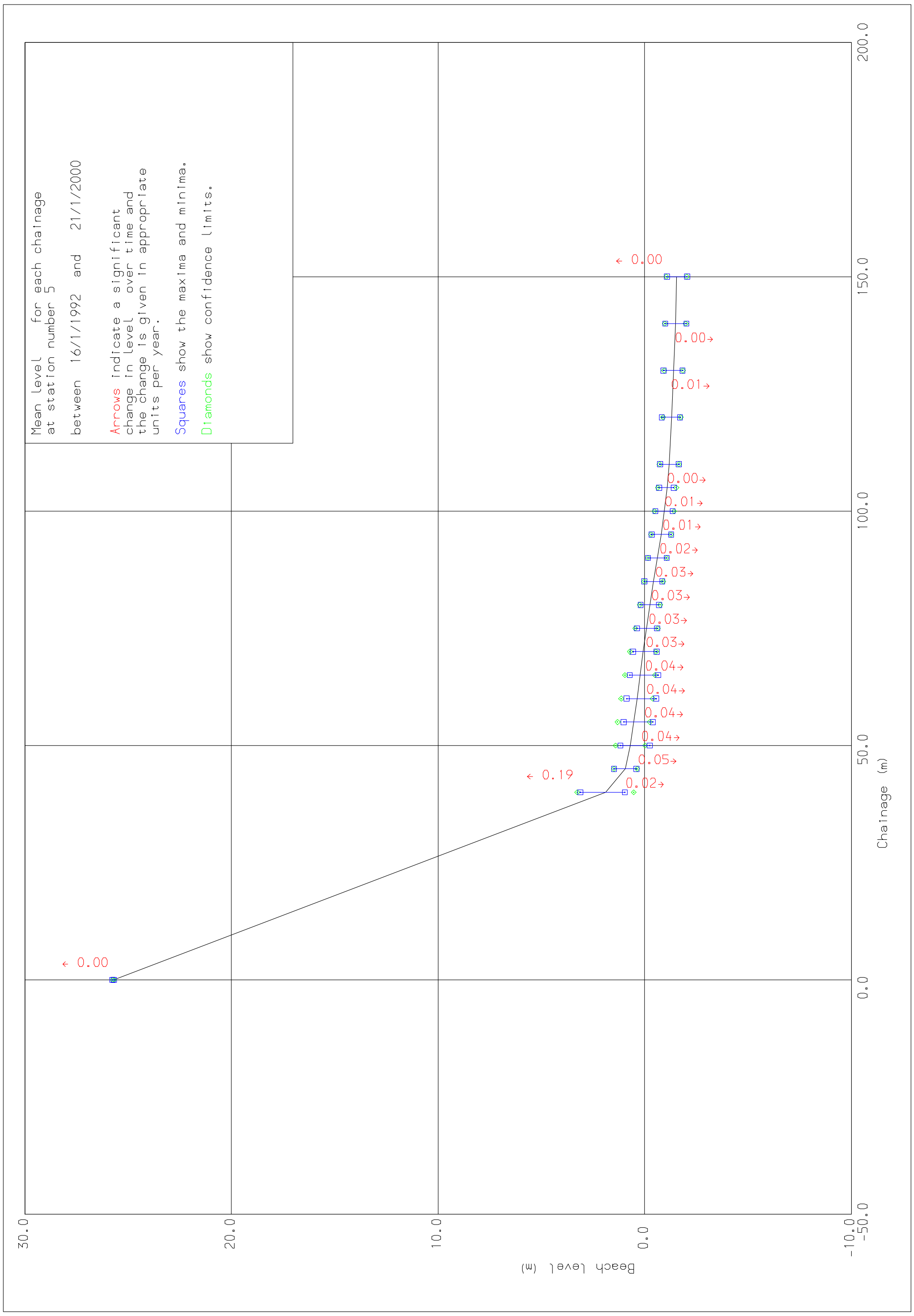


Fig 12 Overstrand Mean Profile, Station 5.

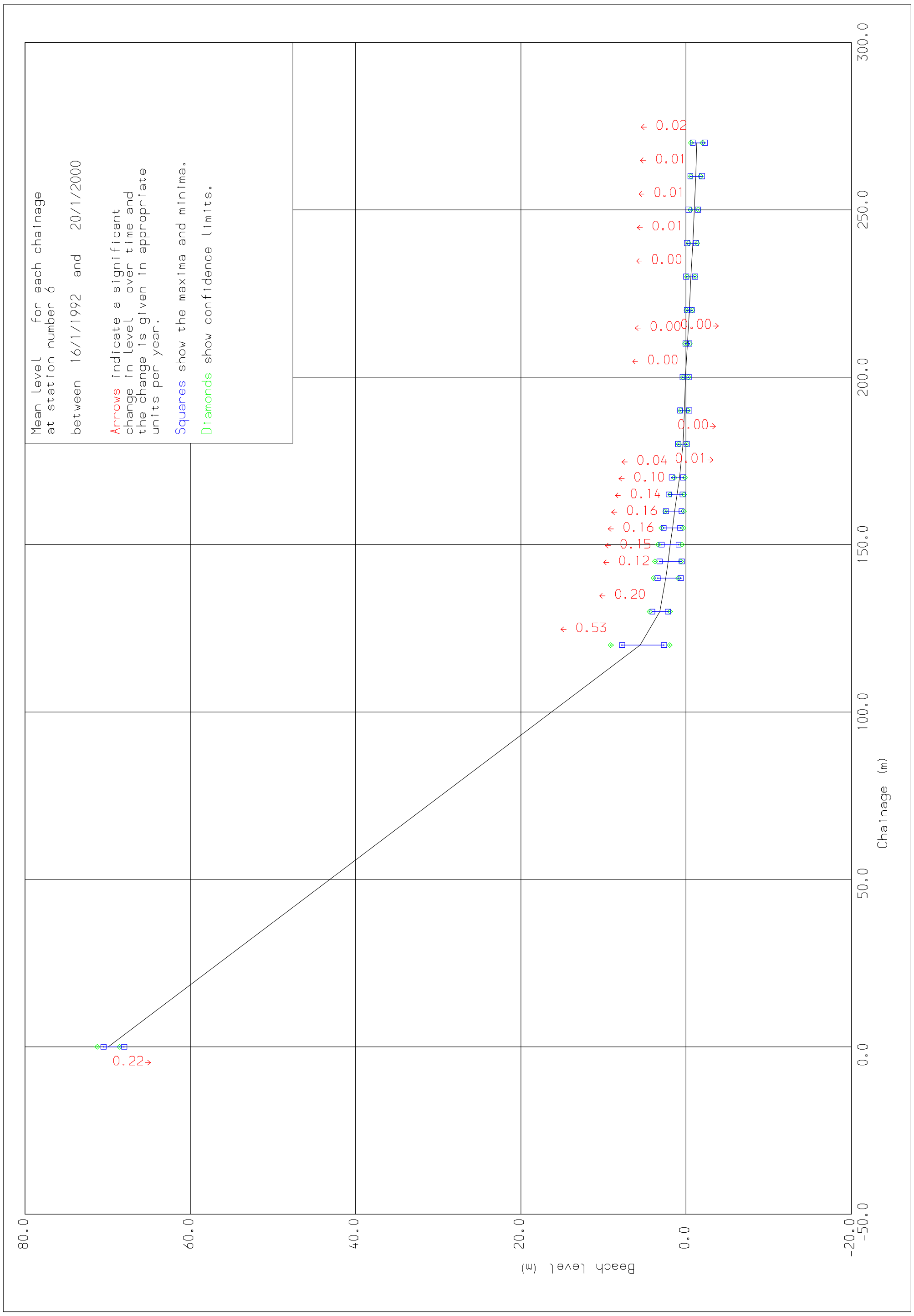


Fig 13 Overstrand Mean Profile, Station 6.

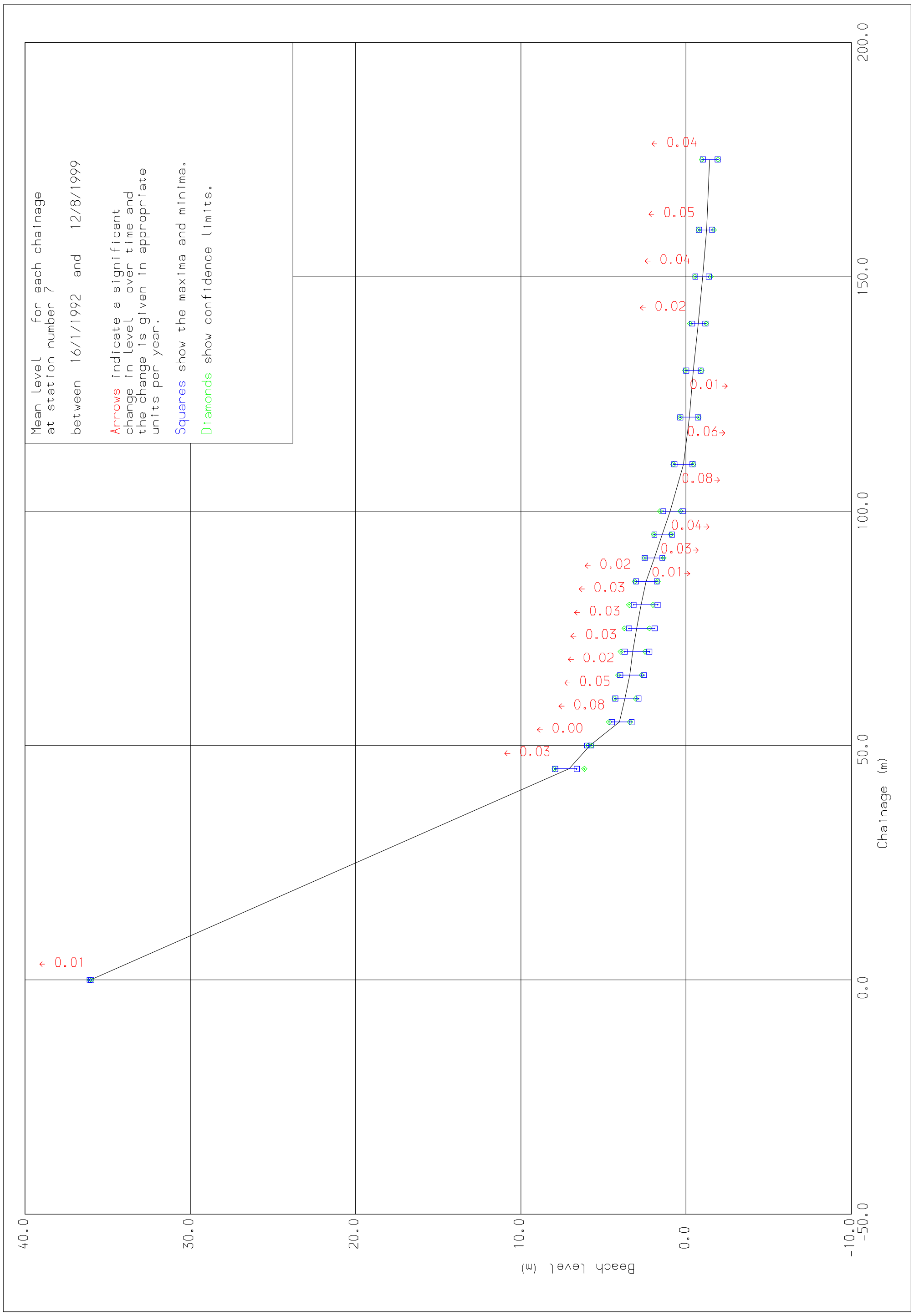


Fig 14 Overstrand Mean Profile, Station 7.

Mundesley

Stations N3C5, N3C4, N3C3, N3C2, N3C1, N3D6, N3D5.
Wave points E, F, G, H.

Mundesley

Station 1: N3C5
Chainages for calculation of the mean profile:
0-15-25-35-40-45-50-55-60-75-80-85-90-95-100-105-110-120-135-150
Values for the area calculation: 26 / 100 / -3
Height changes per year: 0.117 m/yr
Length of active beach and width of present section: 400/1100
Volume changes in m^3/year: 51,490

Station 2: N3C4
Chainages for calculation of the mean profile:
0-15-25-35-40-45-50-55-60-65-70-75-80-85-90-95-100-110-125-140
Values for the area calculation: 35 / 108 / -3
Height changes per year: 0.021 m/yr
Length of active beach and width of present section: 460/933
Volume changes in m^3/year: 8,830

Station 3: N3C3
Chainages for calculation of the mean profile:
0-25-35-45-50-55-60-65-75-85-90-95-100-105-110-115-125-135-150-165
Values for the area calculation: 32 / 104 / -3
Height changes per year: -0.062 m/yr
Length of active beach and width of present section: 520/885
Volume changes in m^3/year: -28,610

Station 4: N3C2
Chainages for calculation of the mean profile:
0-15-25-30-35-40-45-50-55-60-65-70-75-80-85-90-95-100-110-125
Values for the area calculation: 25 / 75 / -3
Height changes per year: -0.02 m/yr
Length of active beach and width of present section: 250/861
Volume changes in m^3/year: -4,510

Station 5: N3C1
Chainages for calculation of the mean profile:
0-35-40-45-50-55-60-65-70-75-80-85-90-95-100-110-120-130-140-150
Values for the area calculation: 38 / 100 / -3
Height changes per year: -0.057 m/yr
Length of active beach and width of present section: 450/1028
Volume changes in m^3/year: -26,440

Station 6: N3D6
Chainages for calculation of the mean profile:
0-10-15-20-25-30-35-40-45-50-55-60-65-70-75-80-85-90-95-100
Values for the area calculation: 12 / 68 / -3
Height changes per year: -0.089 m/yr
Length of active beach and width of present section: 290/1028
Volume changes in m^3/year: -23,550

Station 7: N3D5
Chainages for calculation of the mean profile:
0-50-80-85-90-95-100-105-110-115-120-125-130-135-140-145-150-160-170-175
Values for the area calculation: 105 / 150 / -3
Height changes per year: -0.058 m/yr
Length of active beach and width of present section: 370/1028
Volume changes in m^3/year: -22,520

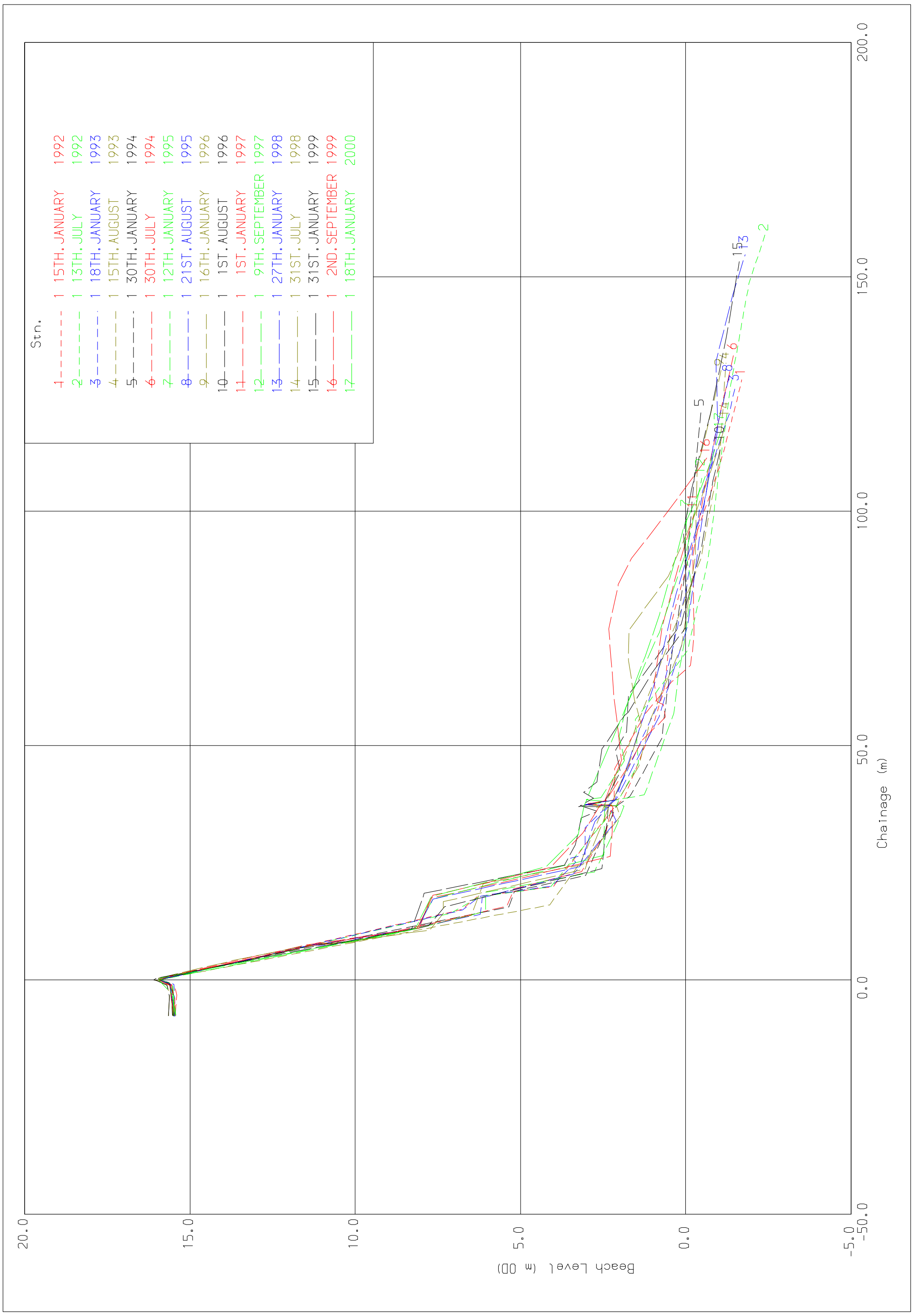


Fig 1 Mundesley Beach Profiles, Station 1.

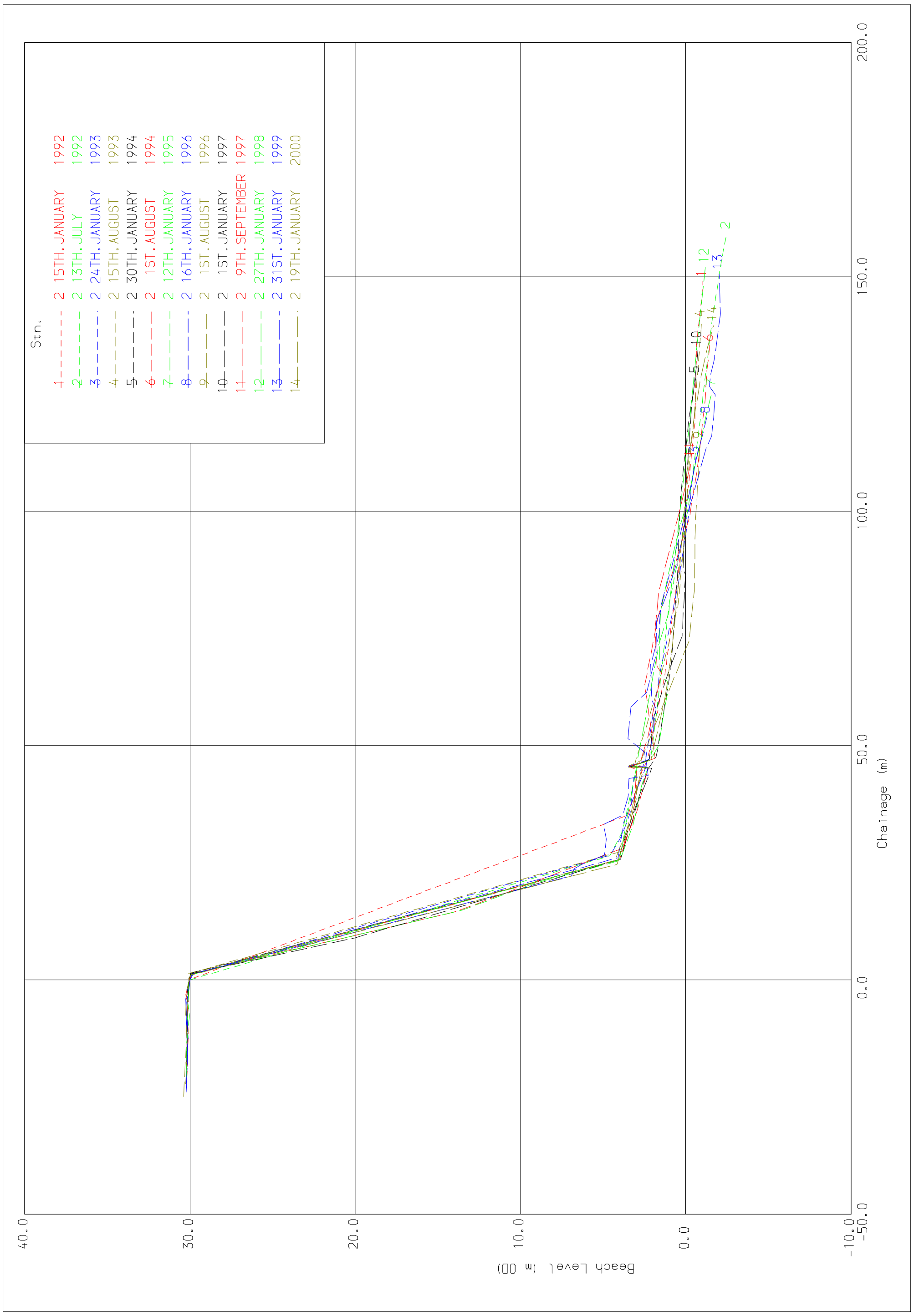


Fig 2 Mundesley Beach Profiles, Station 2.

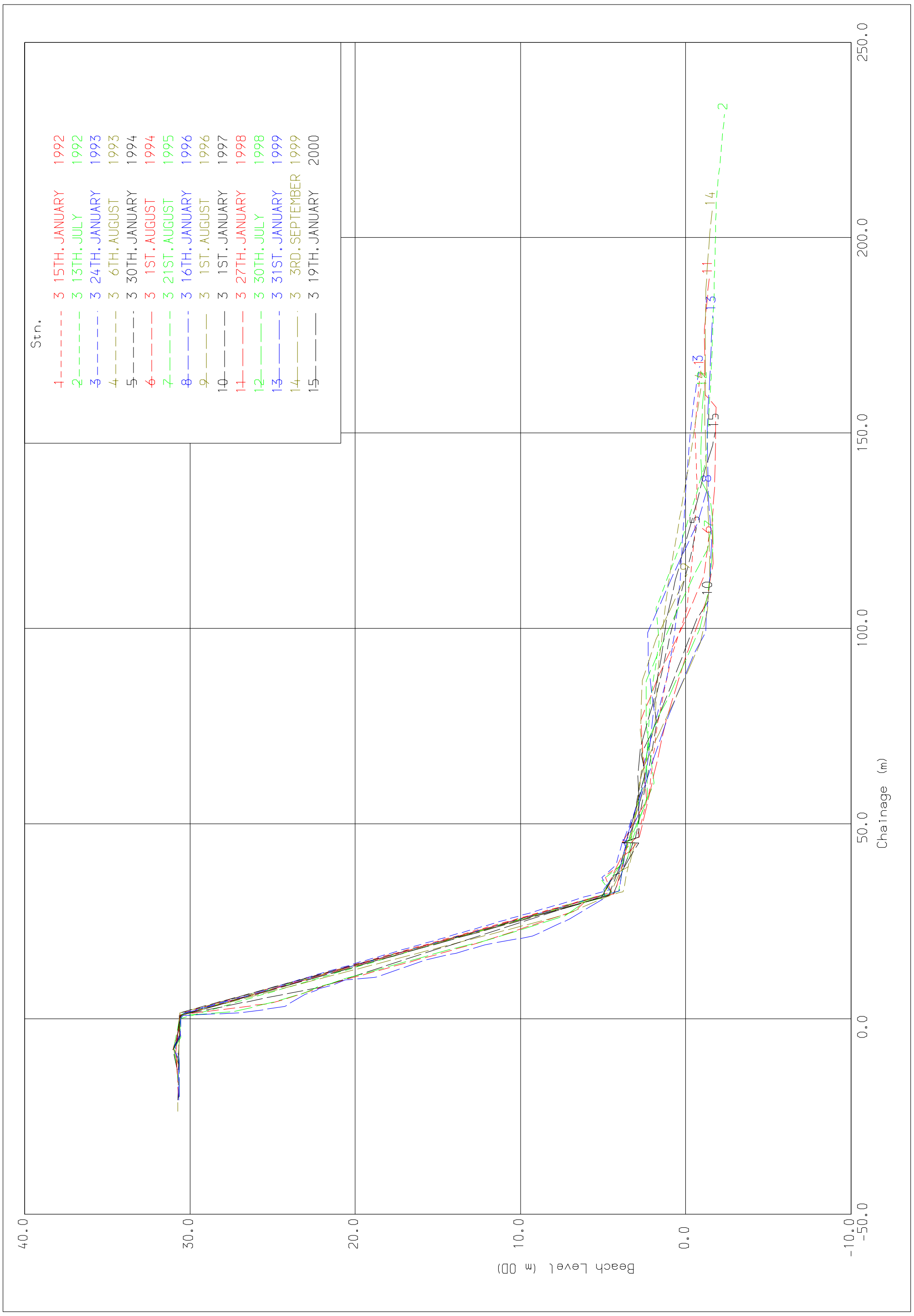


Fig 3 Mundesley Beach Profiles, Station 3.

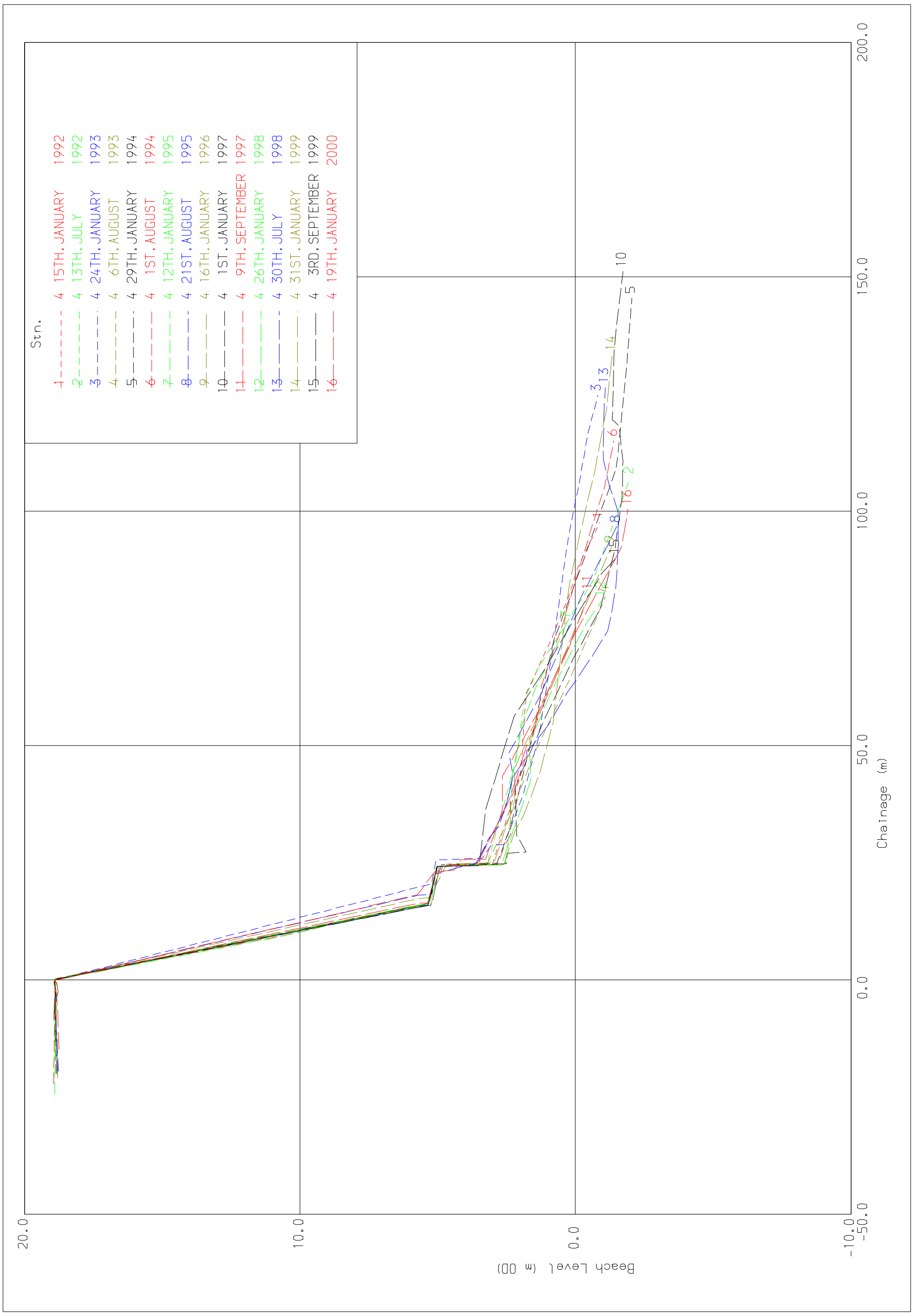


Fig 4 Mundesley Beach Profiles, Station 4.

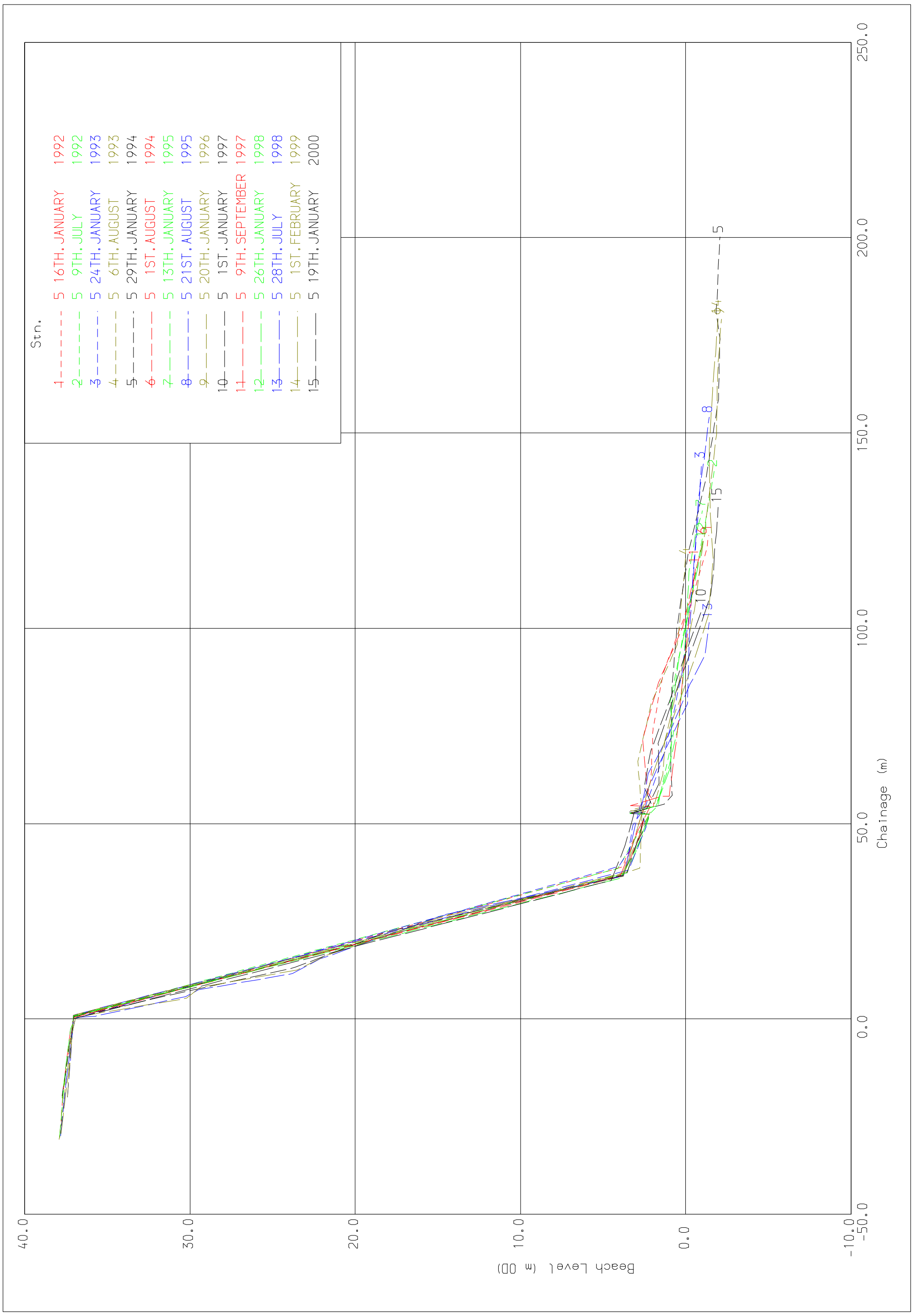


Fig 5 Mundesley Beach Profiles, Station 5.

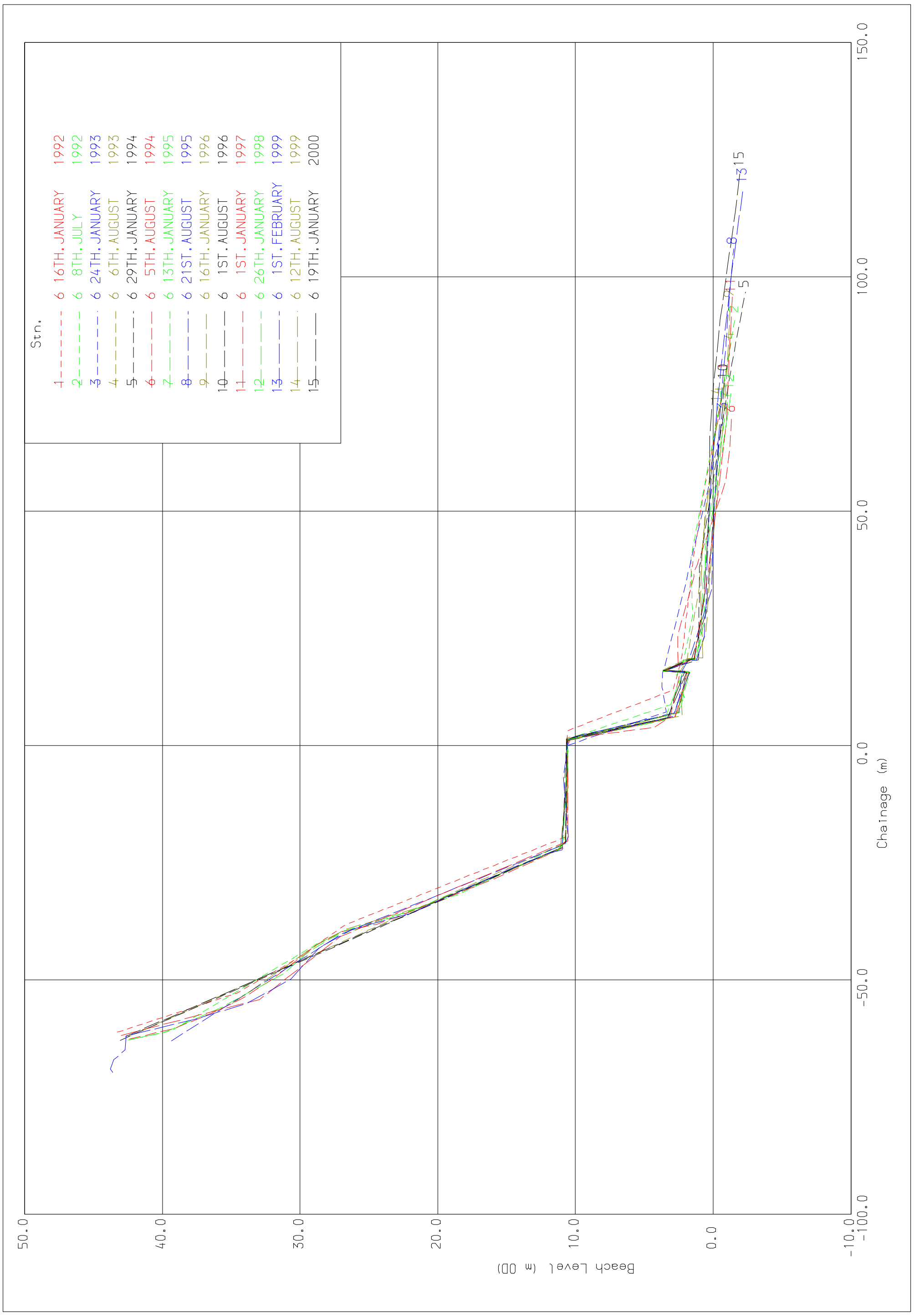


Fig 6 Mundesley Beach Profiles, Station 6.

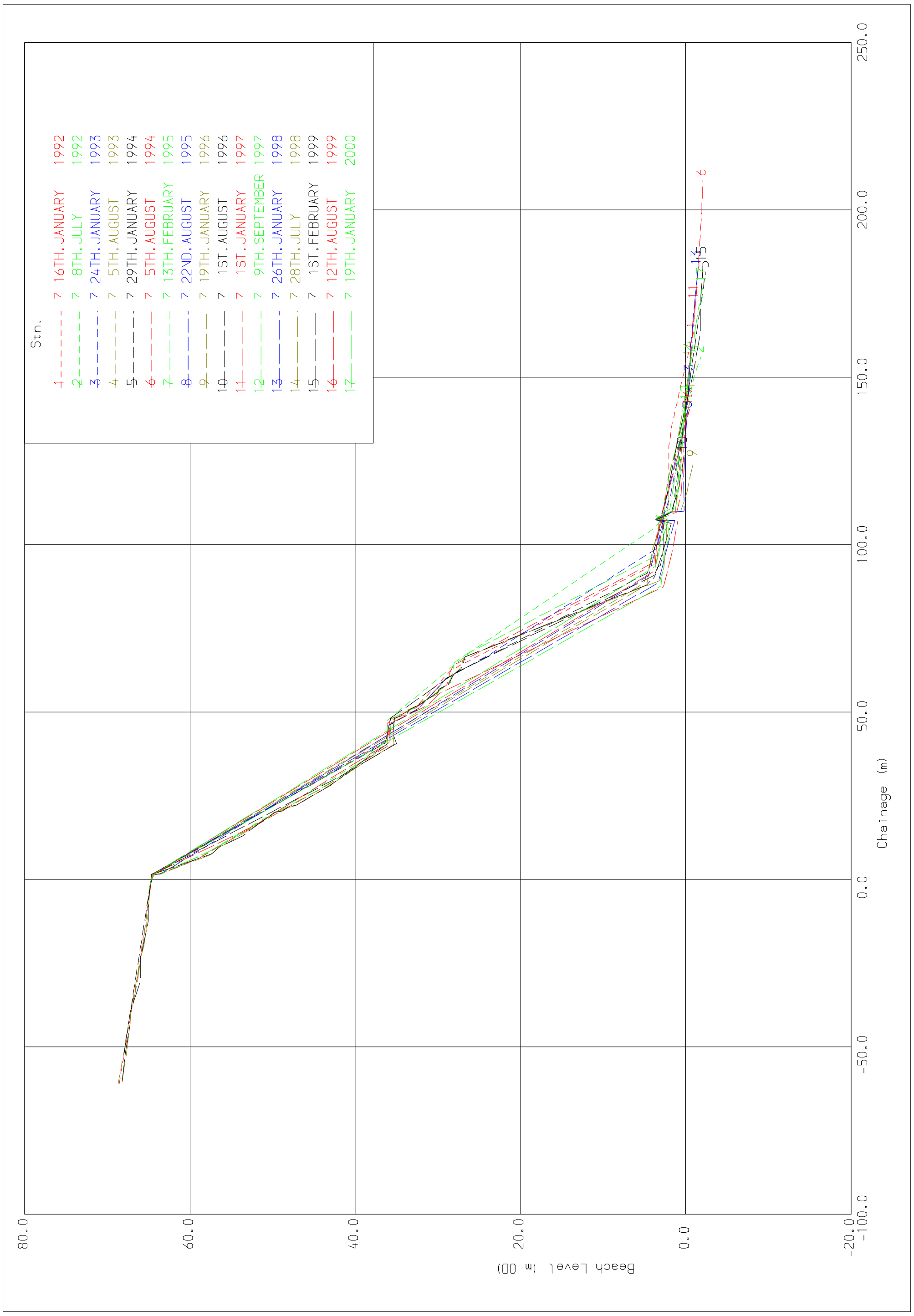


Fig 7 Mundesley Beach Profiles, Station 7.

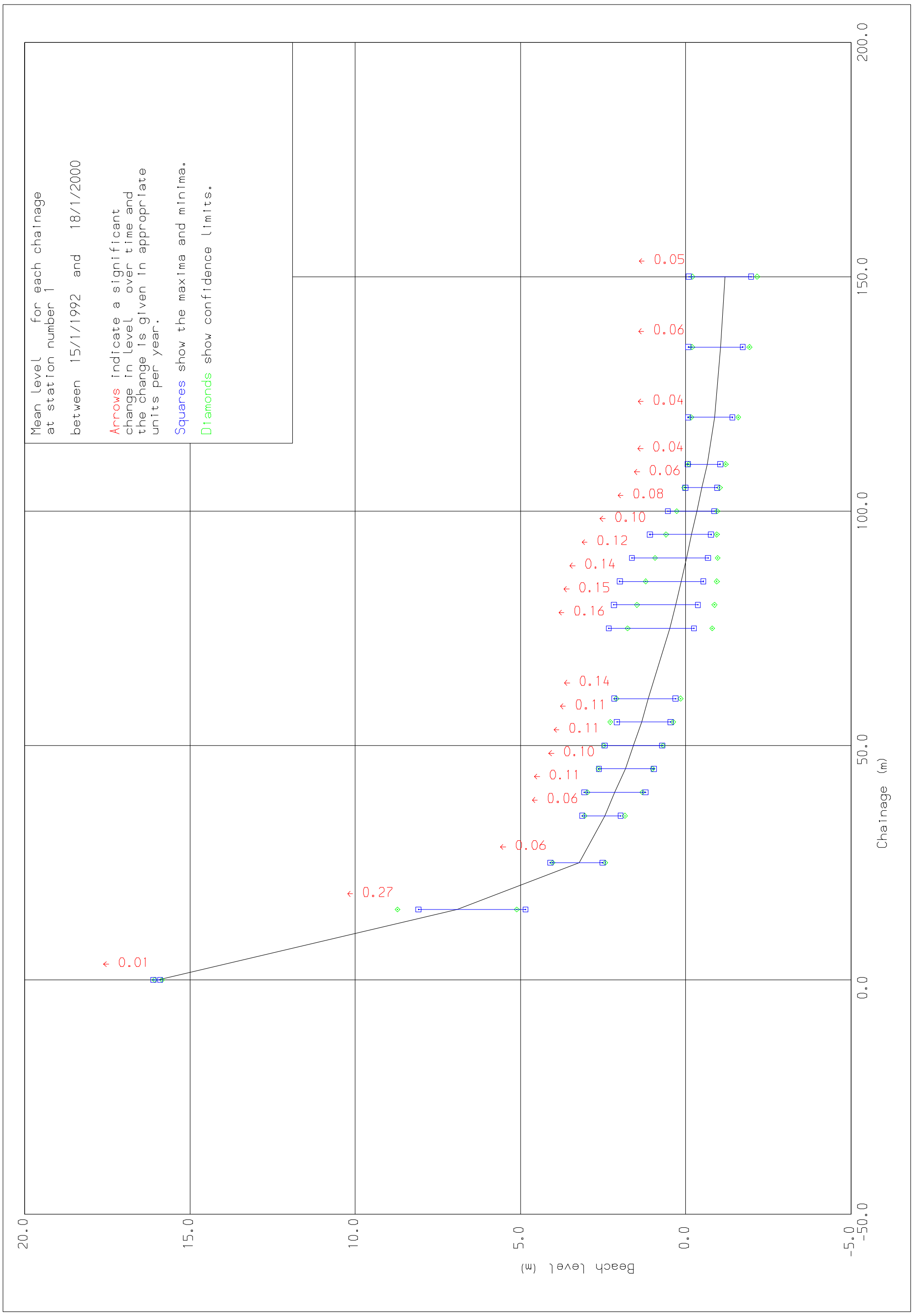


Fig 8 Mundesley Mean Profile, Station 1.

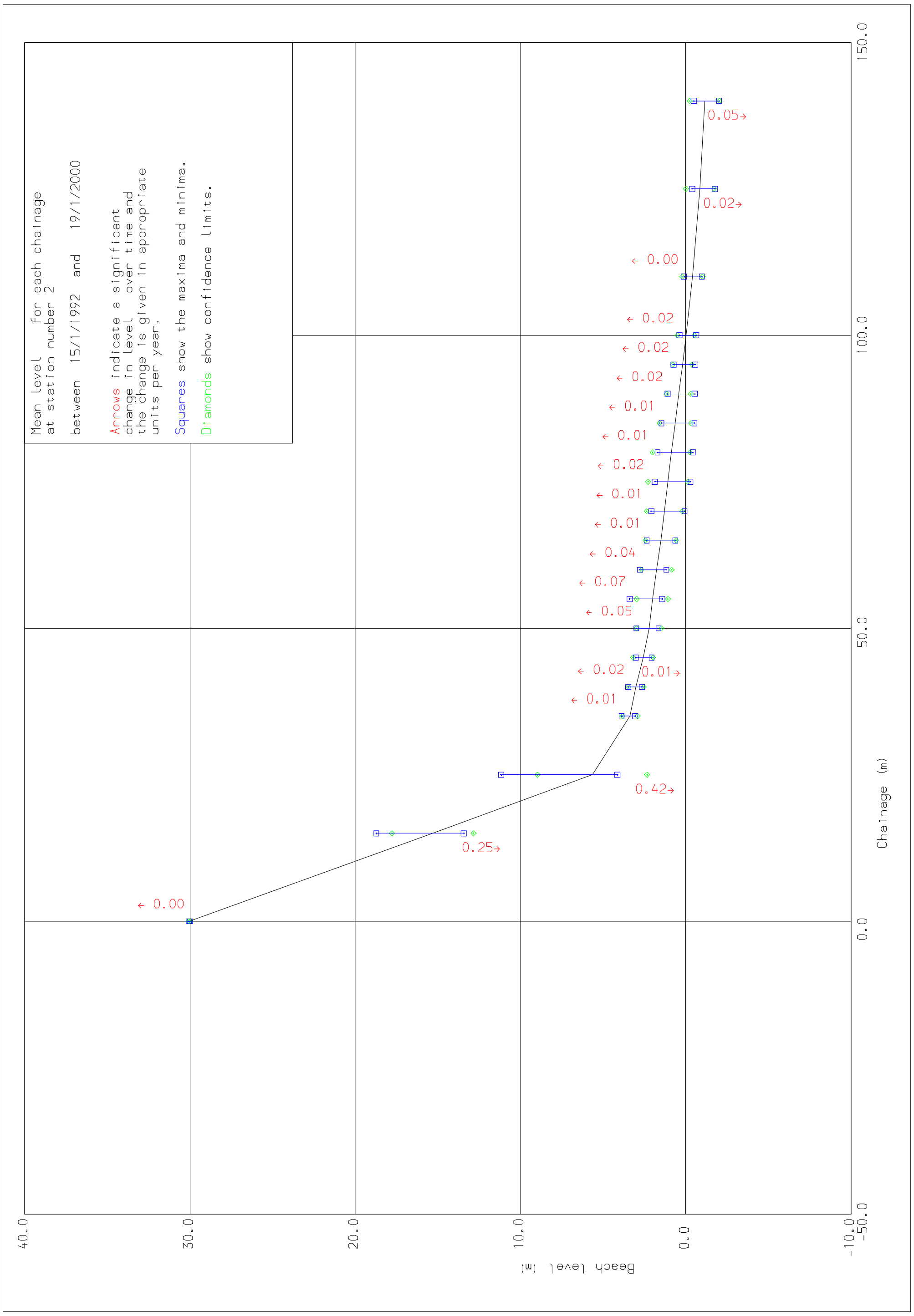


Fig 9 Mundesley Mean Profile, Station 2.

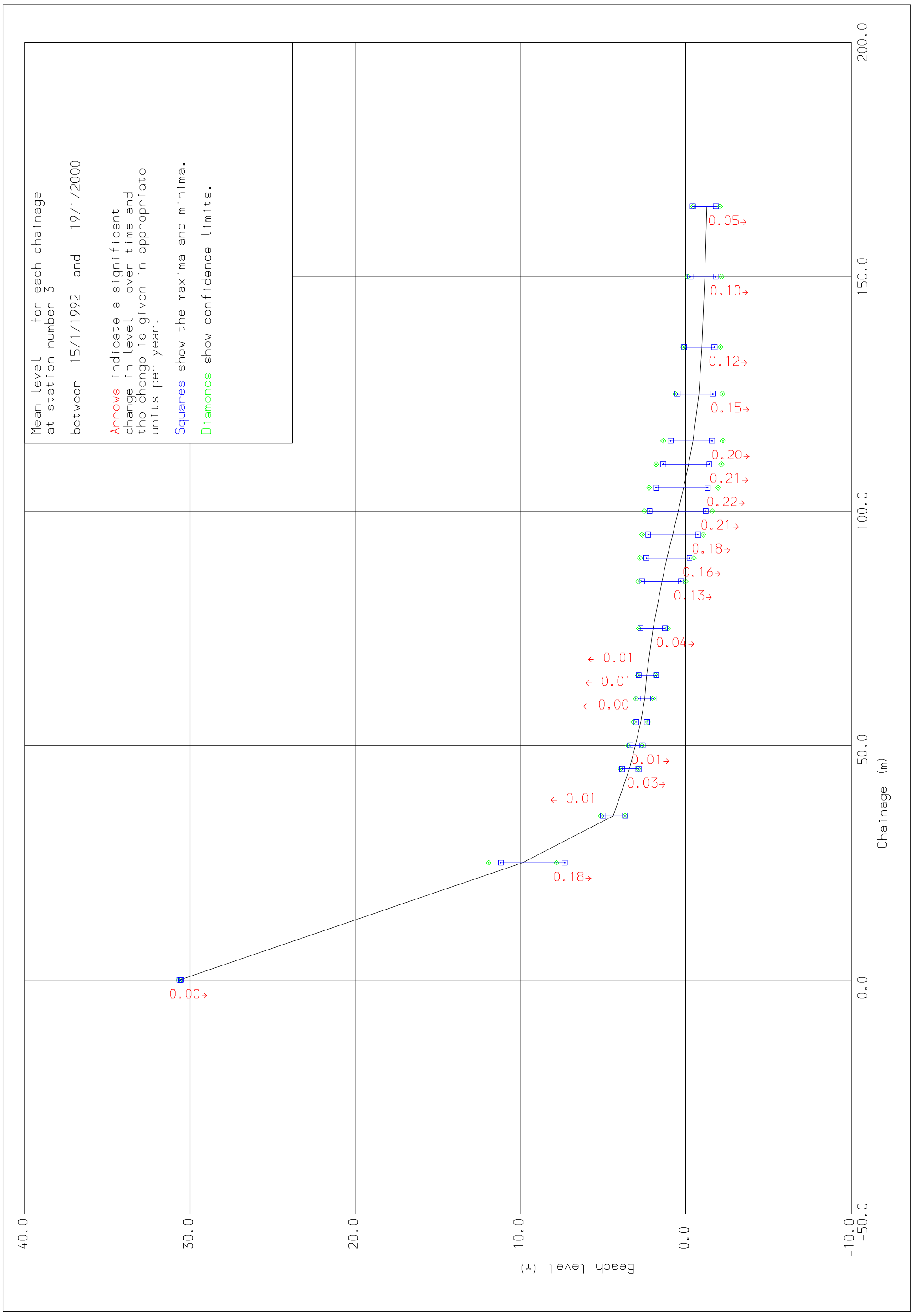


Fig 10 Mundesley Mean Profile, Station 3.

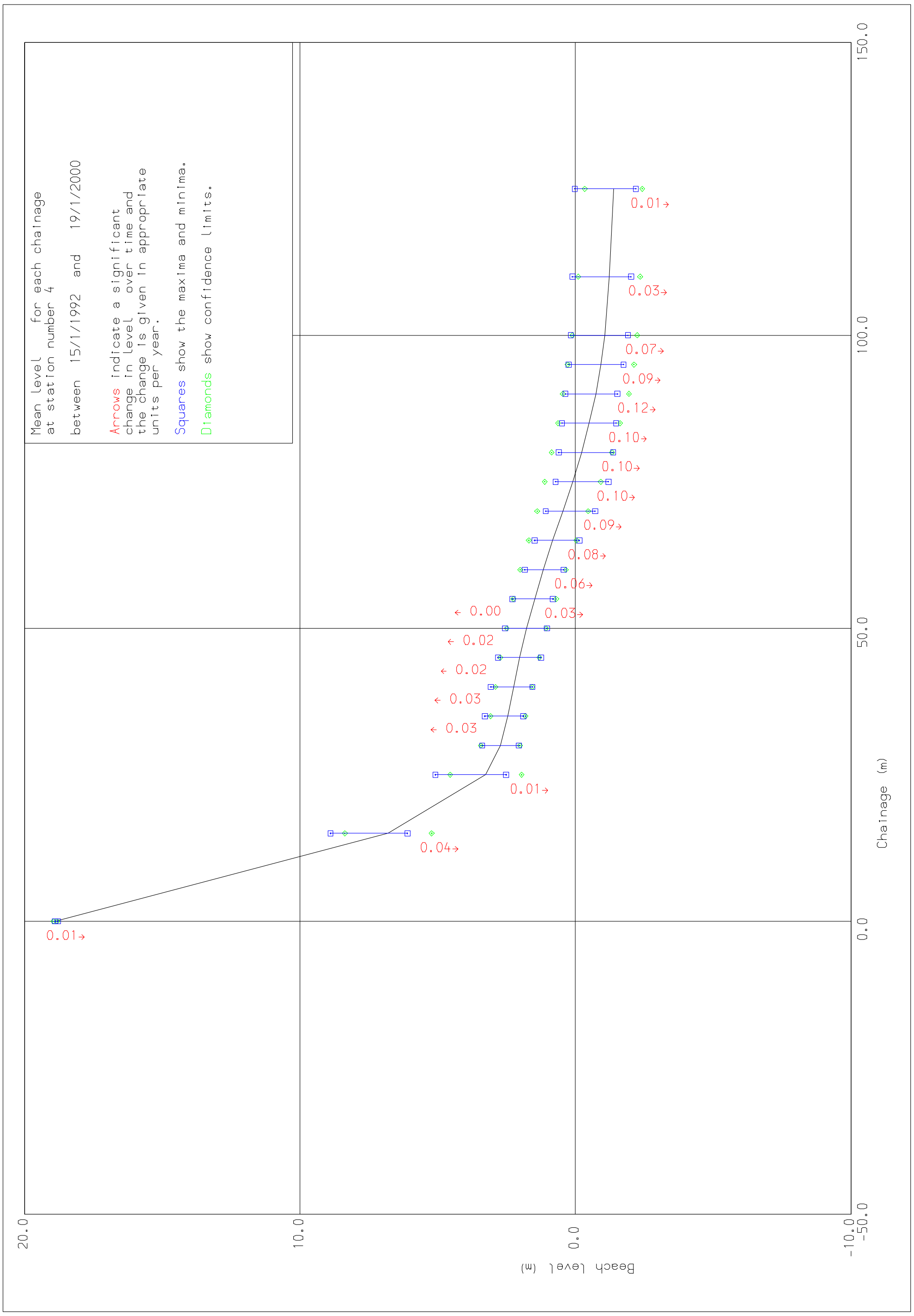


Fig 11 Mundesley Mean Profile, Station 4.

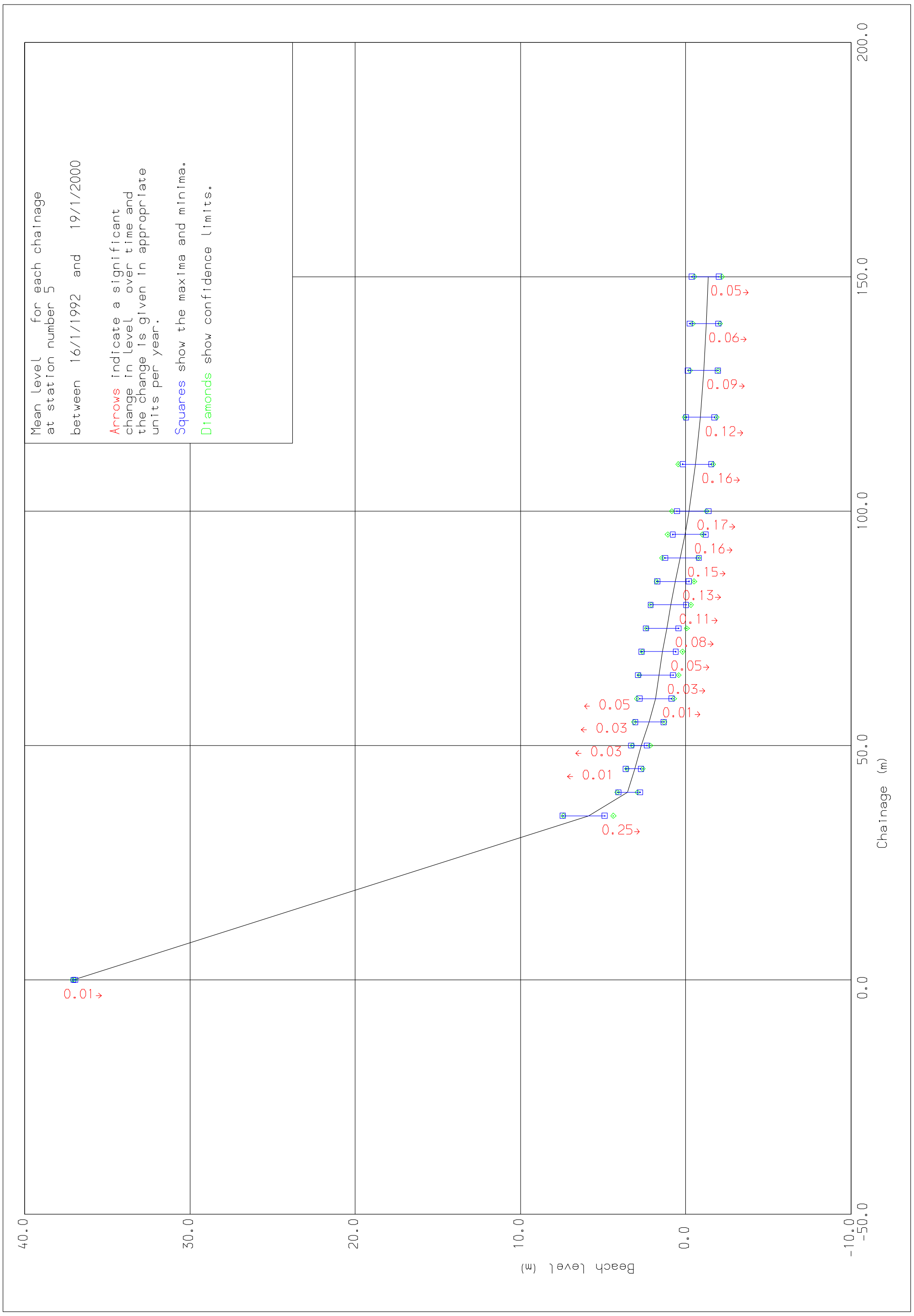


Fig 12 Mundesley Mean Profile, Station 5.

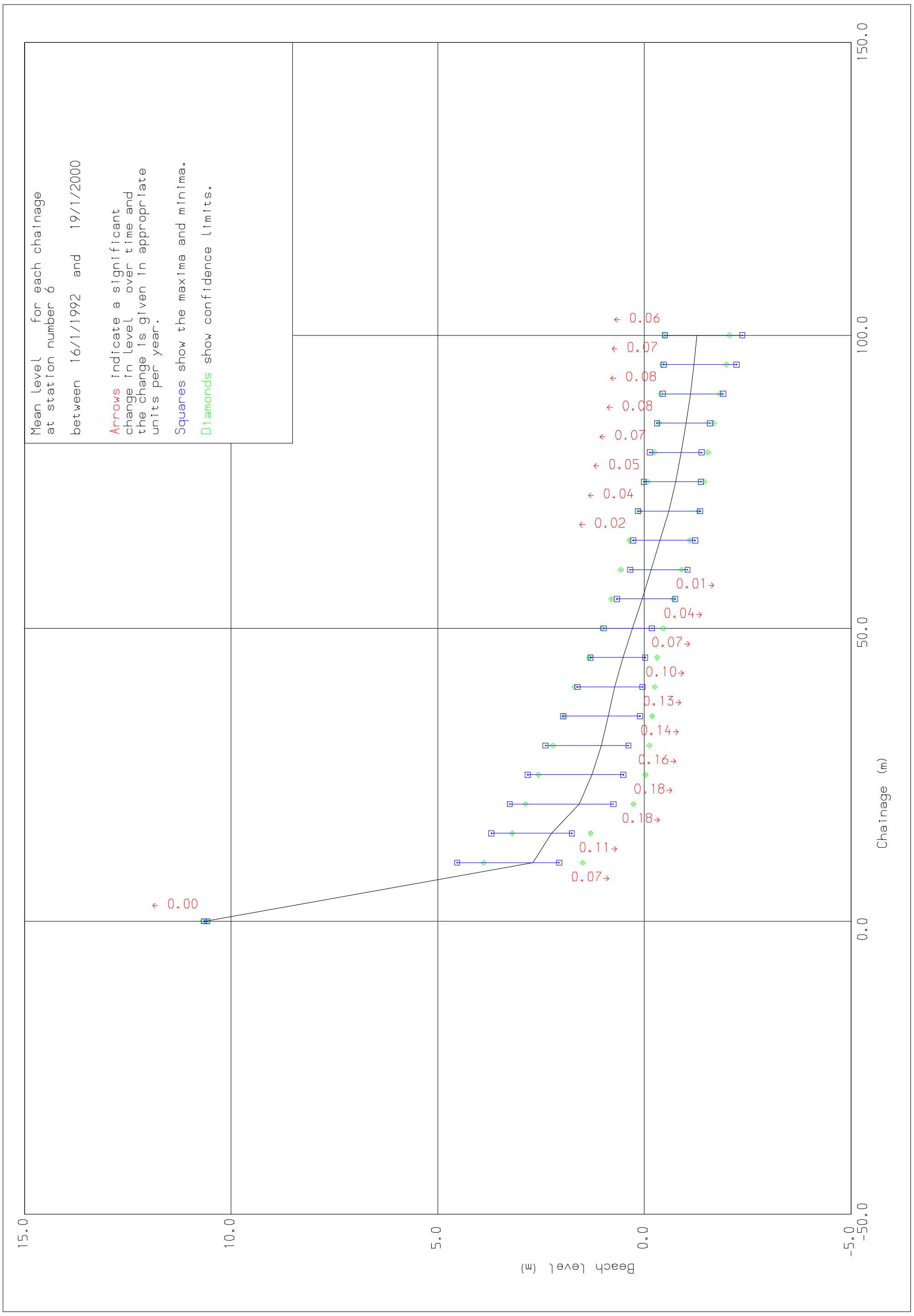


Fig 13 Mundesley Mean Profile, Station 6.

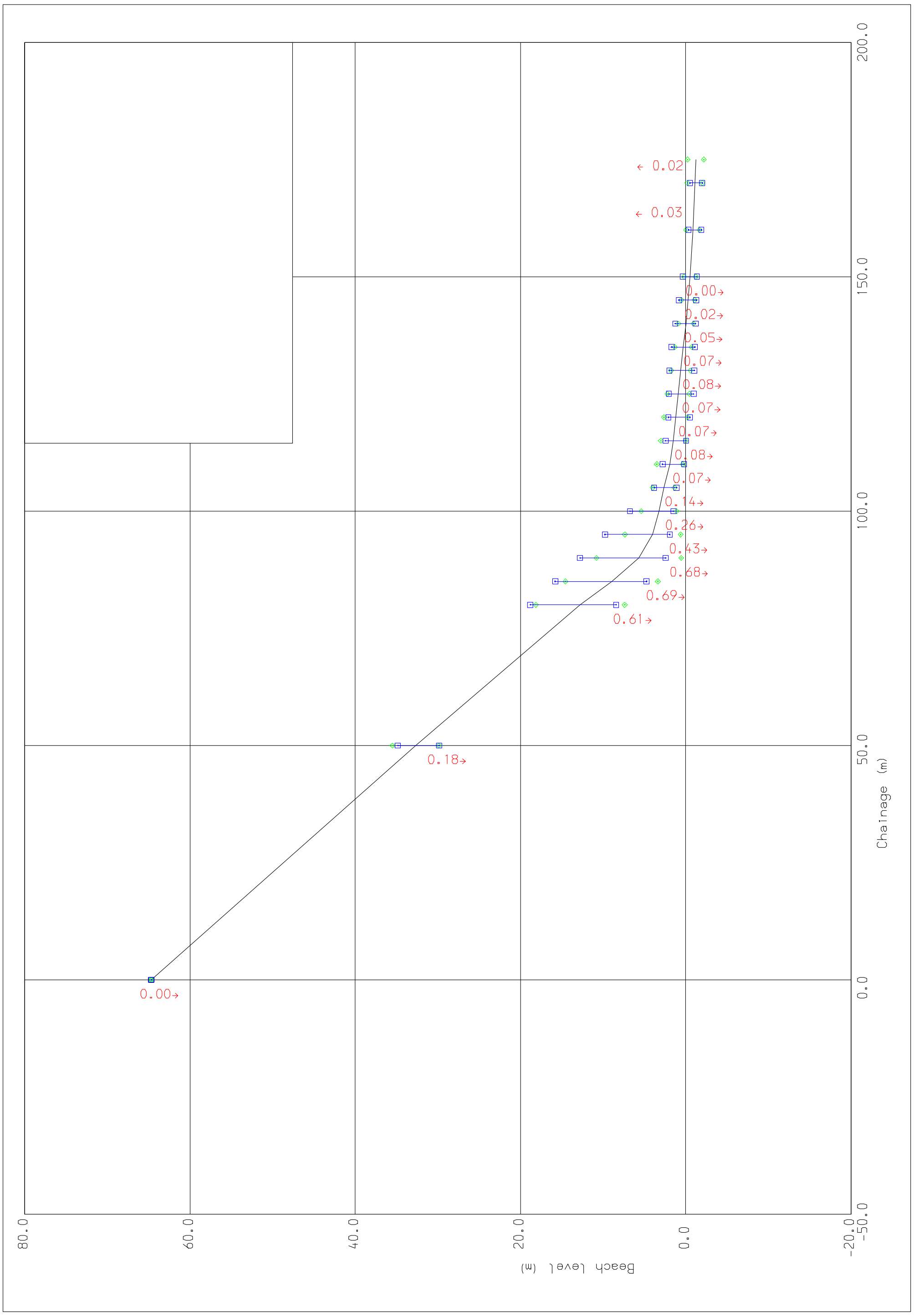


Fig 14 Mundesley Mean Profile, Station 7.

Bacton

Stations N3B1, N3C8, N3C7, N3C6.
Wave points I, J.

Bacton

Station 1: N3C6
Chainages for calculation of the mean profile:
0-2-4-6-8-10-13-16-19-25-30-35-40-45-50-55-60-65-70-75
Values for the area calculation: 10 / 51.5 / -1
Height changes per year: 0.084 m/yr
Length of active beach and width of present section: 625/1052
Volume changes in m^3/year: 54,980

Station 2: N3C7
Chainages for calculation of the mean profile:
0-3-6-9-12-15-18-21-25-29-33-37-41-45-50-55-60-65-70-80
Values for the area calculation: 10 / 62 / -1.5
Height changes per year: 0.005 m/yr
Length of active beach and width of present section: 565/956
Volume changes in m^3/year: 2,700

Station 3: N3C8
Chainages for calculation of the mean profile:
0-10-12-14-16-18-21-24-27-30-33-36-40-44-48-52-56-60-65-70
Values for the area calculation: 10 / 50 / -2
Height changes per year: -0.014 m/yr
Length of active beach and width of present section: 660/1028
Volume changes in m^3/year: -9,160

Station 4: N3B1
Chainages for calculation of the mean profile:
0-5-10-12-14-16-18-21-24-27-30-34-38-42-46-50-55-60-65-75
Values for the area calculation: 8.5 / 71.5 / -1.5
Height changes per year: -0.020 m/yr
Length of active beach and width of present section: 600/992
Volume changes in m^3/year: -11,810

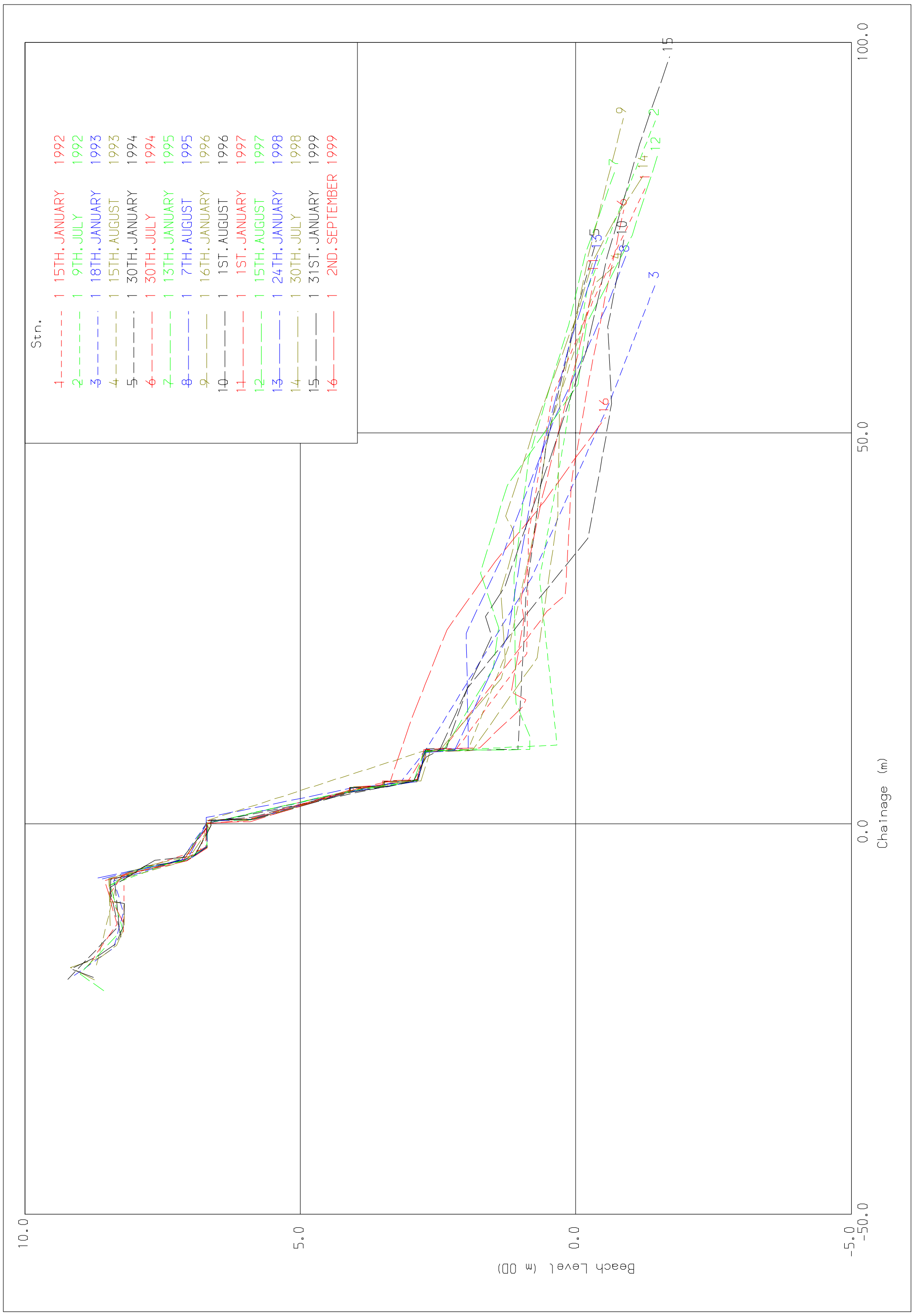


Fig 1 Bacton Beach Profiles, Station 1.

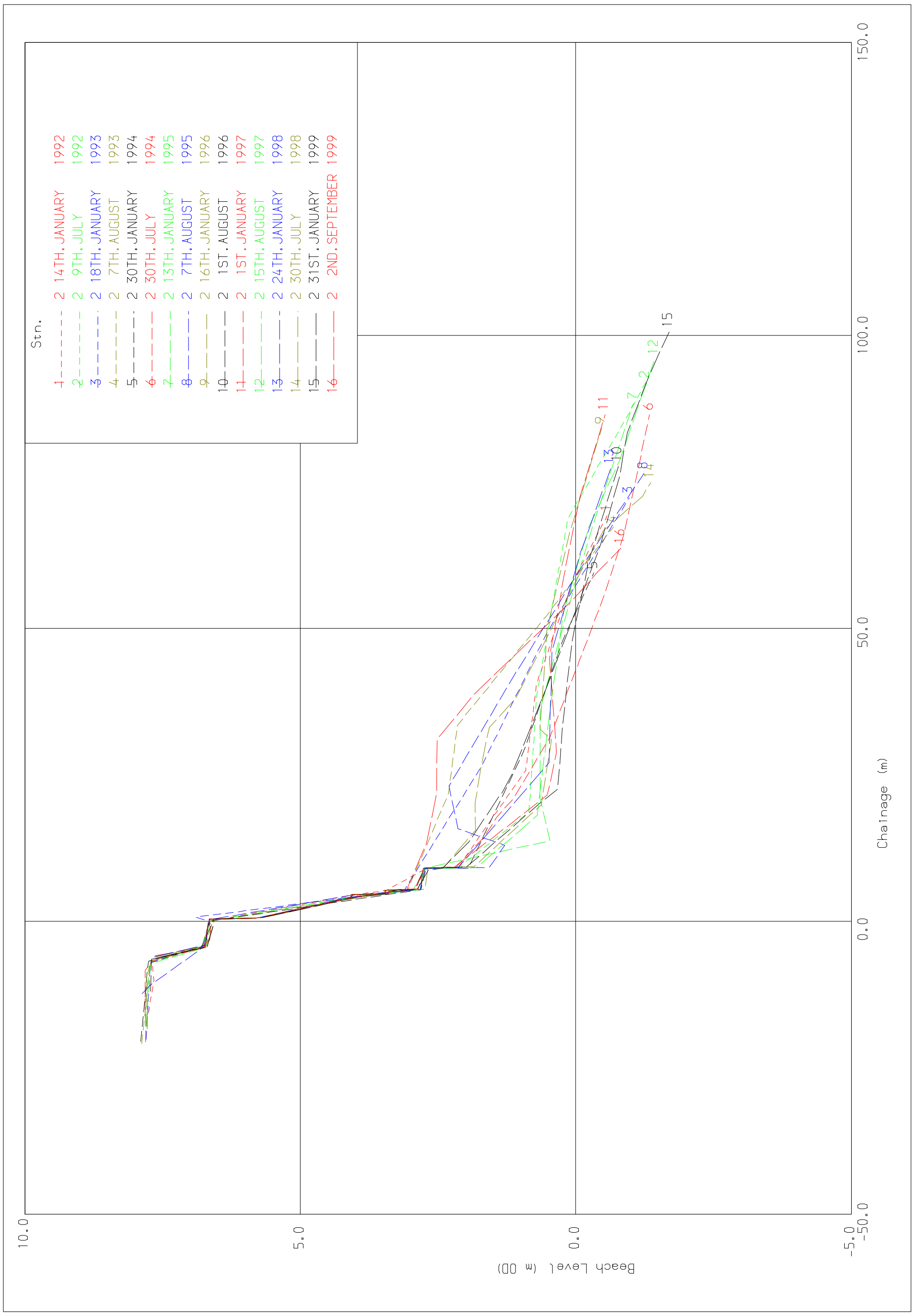


Fig 2   Bacton Beach Profiles, Station 2.

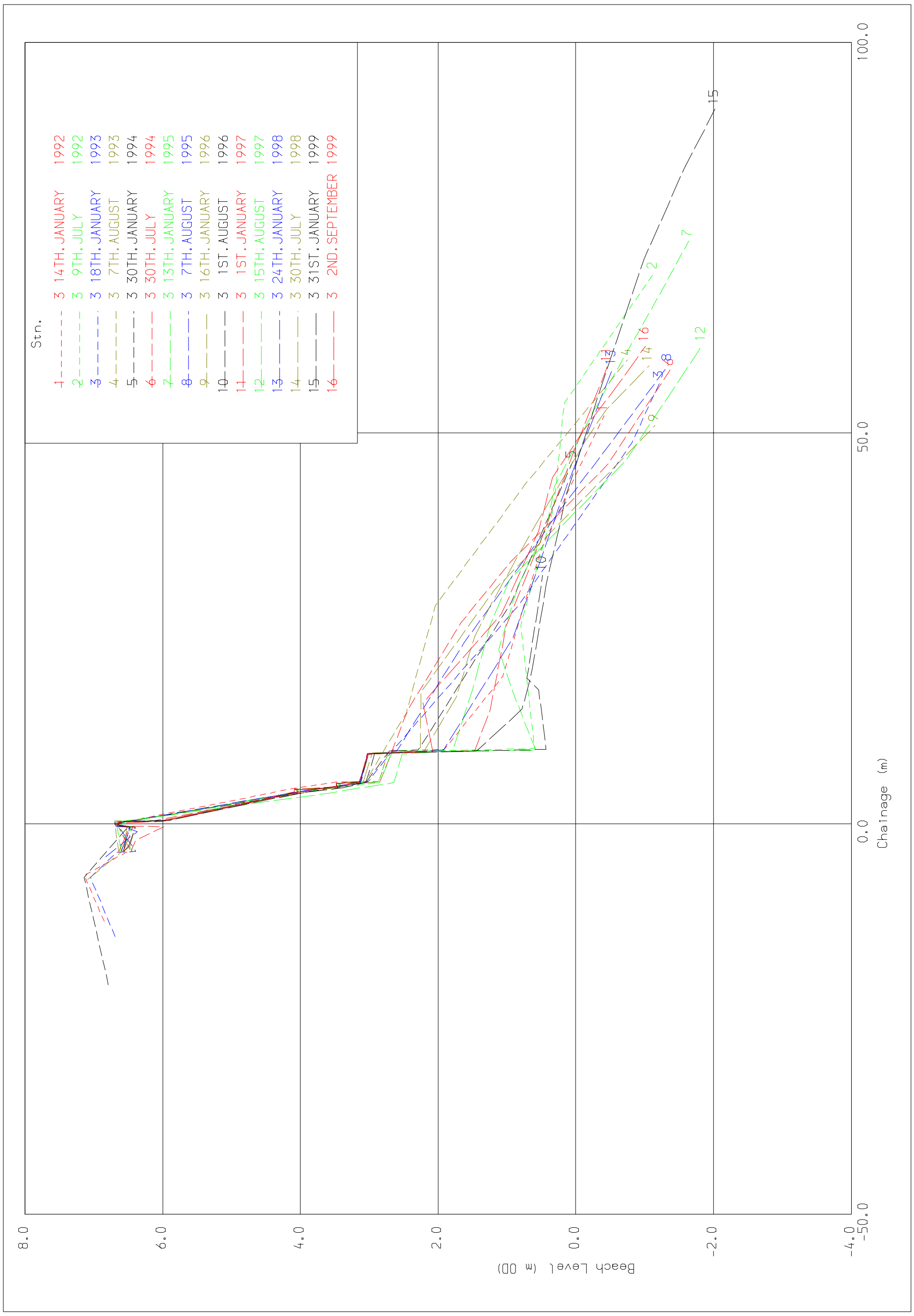


Fig 3 Bacton Beach Profiles, Station 3.

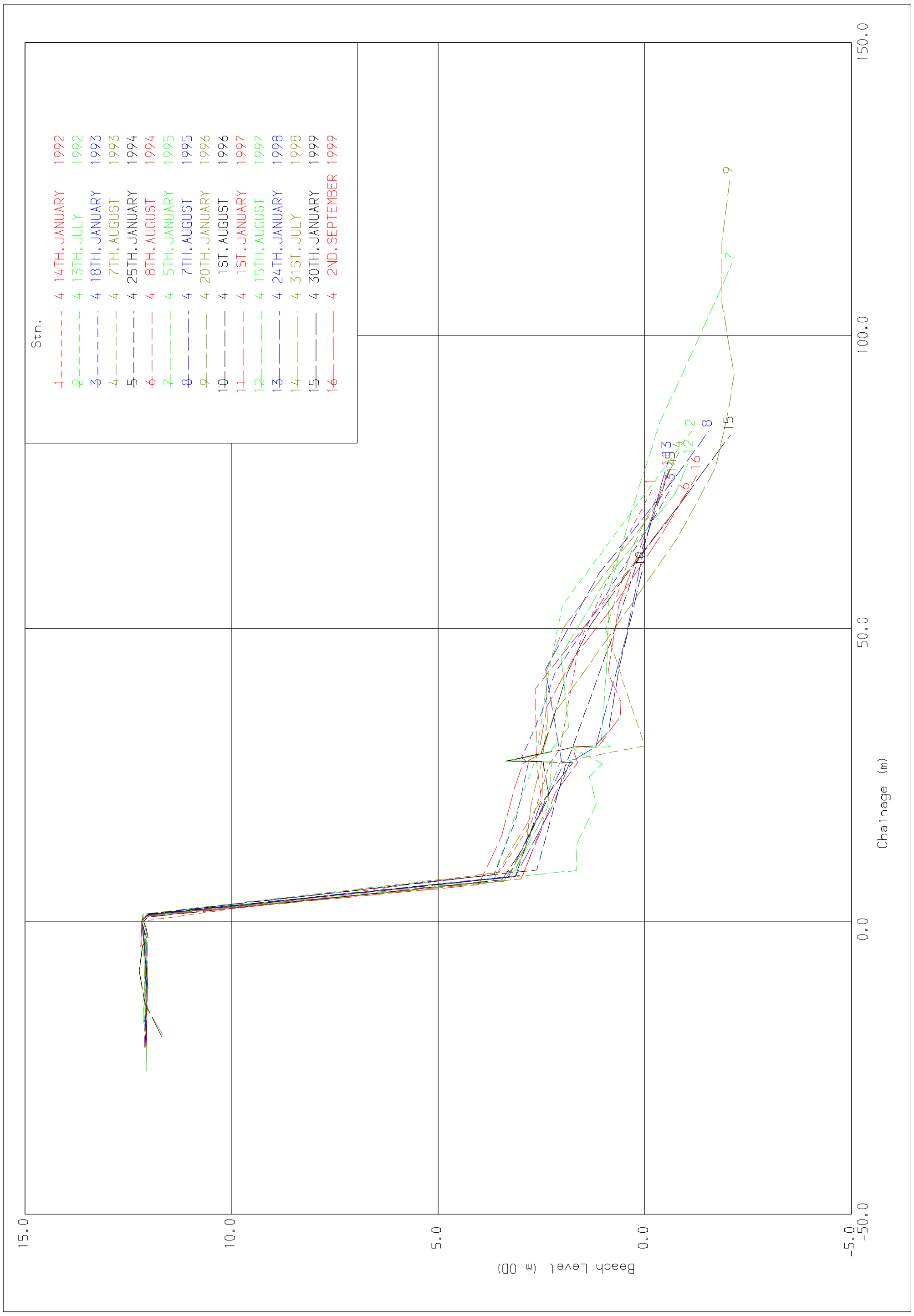


Fig 4 Bacton Beach Profiles, Station 4.

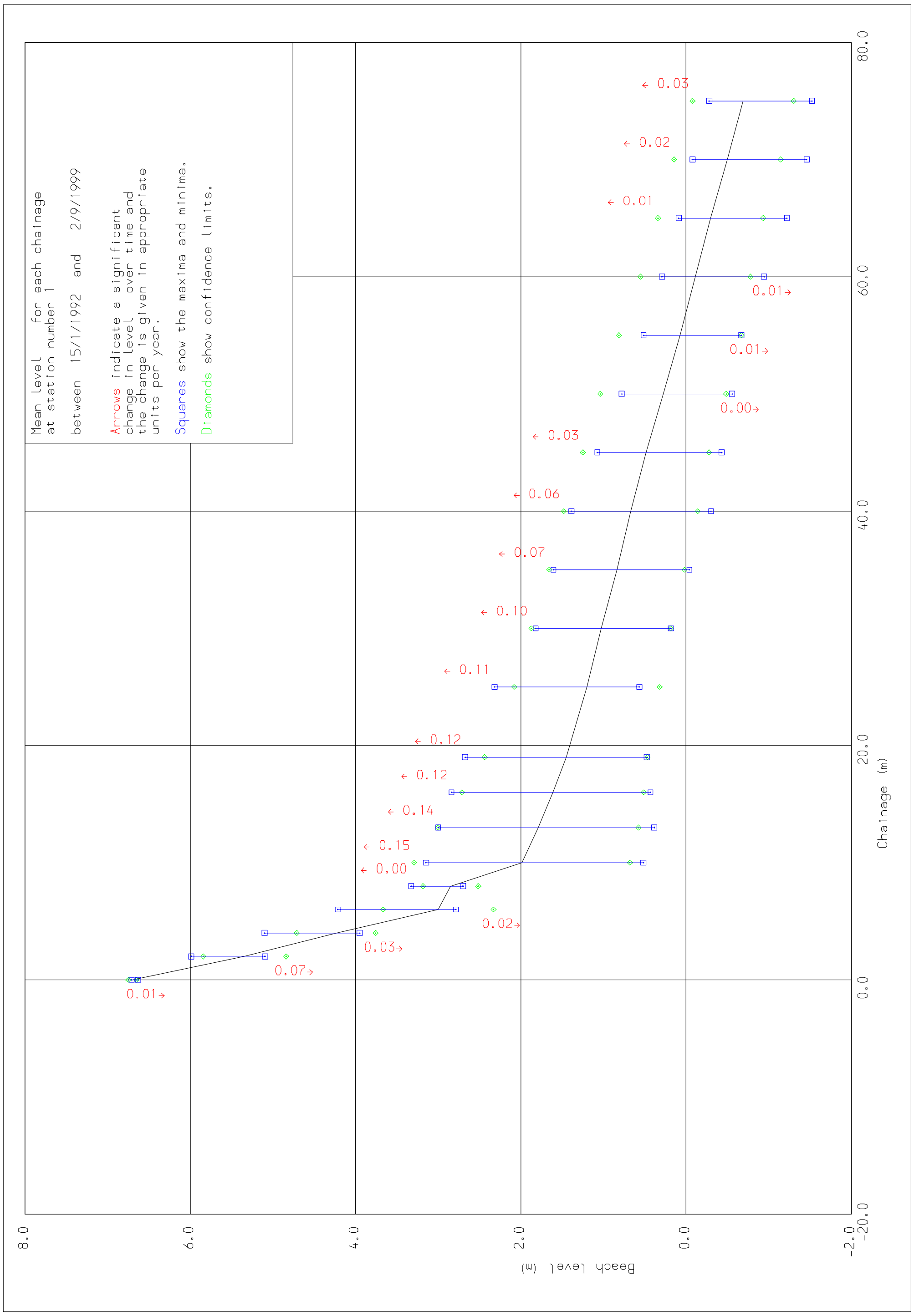


Fig 5 Mean Profile, Station 1.

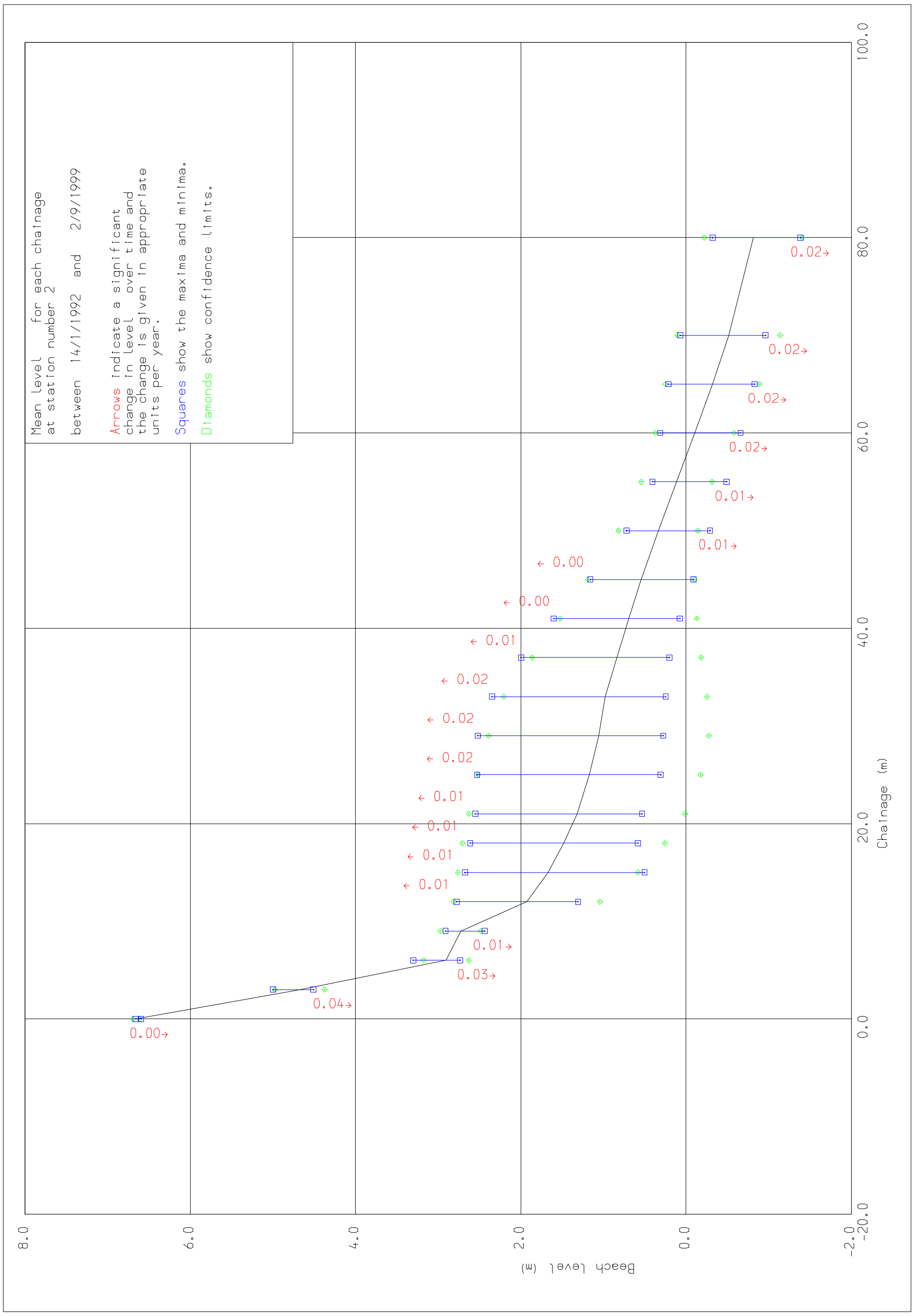


Fig 6 Mean Profile, Station 2.

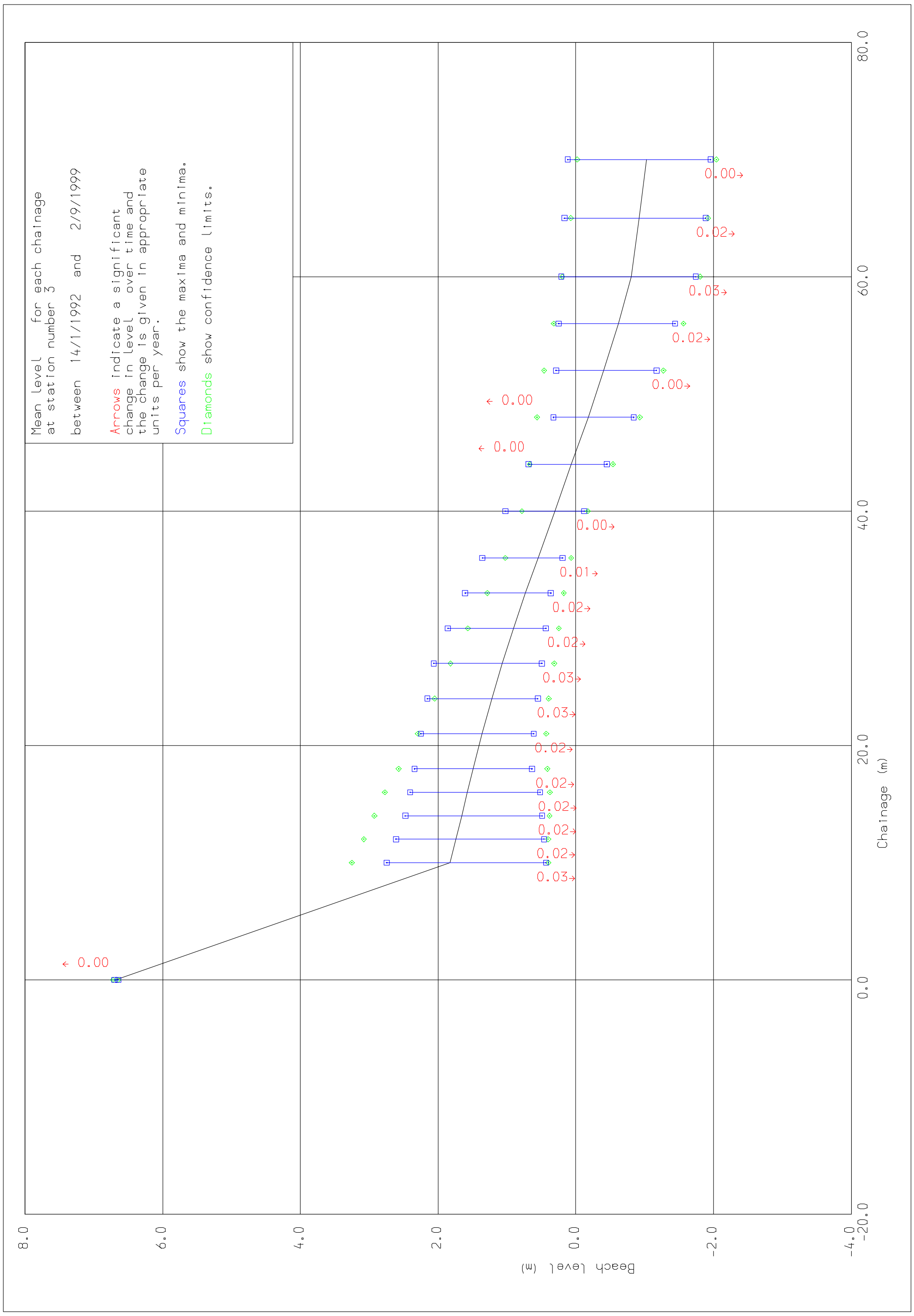


Fig 7 Mean Profile, Station 3.

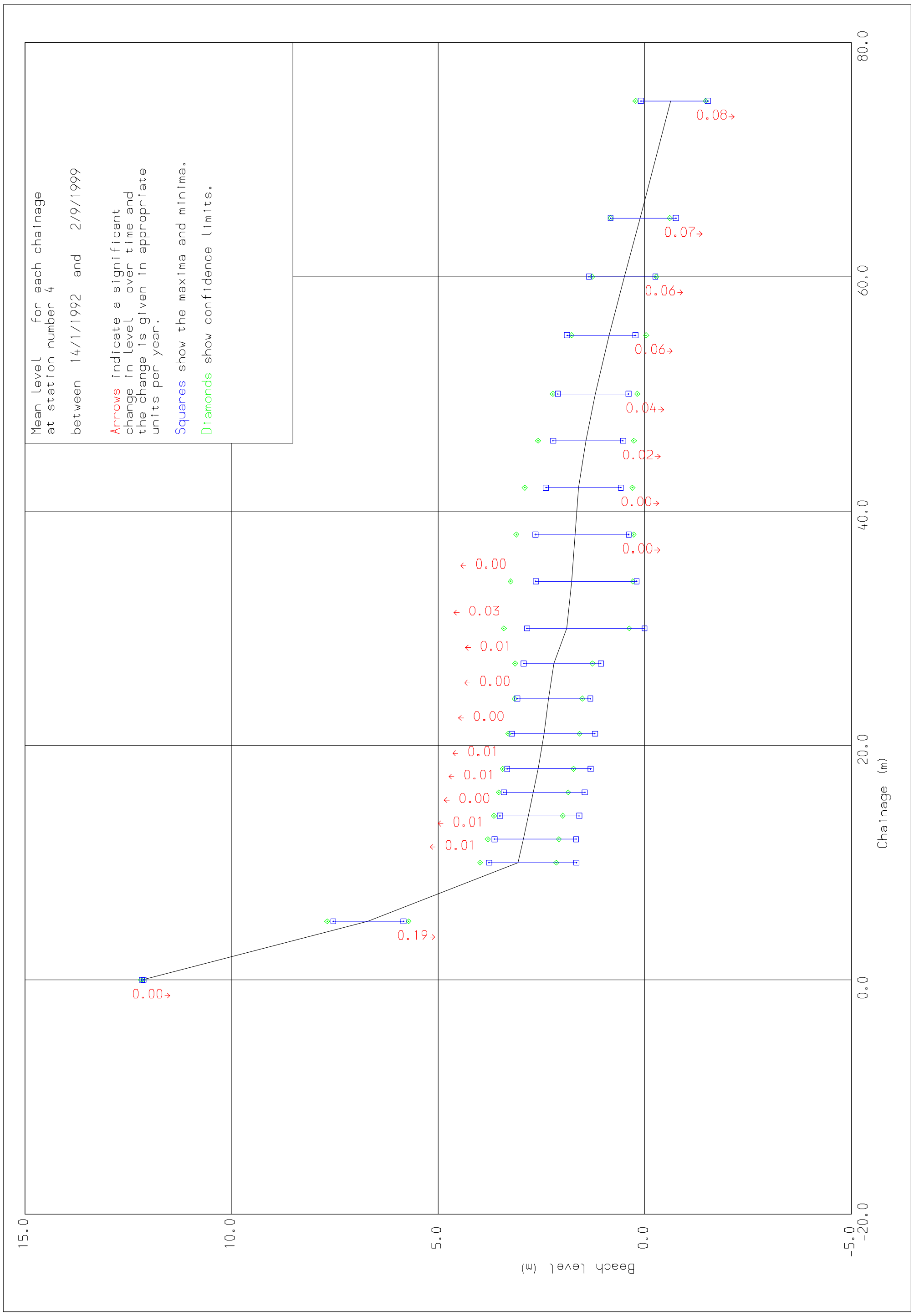


Fig 8 Mean Profile, Station 4.

Appendix B

The Beach Data Analysis System (BDAS)

Appendix B The Beach Data Analysis System (BDAS)

Surveying a beach along a fixed cross-section is a standard monitoring method that provides a quick check on its "health". Experience has shown, however, that unusual weather conditions can produce substantial, if temporary, changes in level which make it difficult to identify long-term trends. To separate gradual changes from these short-term fluctuations, it is necessary to repeat surveys, ideally several times a year, for some years, but this soon produces a large volume of information to be stored and analysed.

The Beach Data Analysis System (BDAS) has been developed at HR Wallingford to store, recall, present and analyse large volumes of cross-section beach survey data. The main functions of the system are as follows:

- To store beach profile data, from different sites and dates, in a standard format, in a computer database.
- To add extra profile information to the database as it becomes available, with in-built data quality checking procedures.
- To recall profile data and present it "on-screen" or graphically.
- To carry out statistical analyses of beach levels, gradients, cross-sectional areas and other parameters usually as a function of time.

Cross-sections are normally repeated at different dates along the same "line"; to avoid confusion with nomenclature, we define each "line" as a "station", and generally give it a number and name (e.g. Station 7, Town Beach - west). Surveys at different dates are then stored together for each station, for later analysis. Apart from the surveys, a station number and title, BDAS has the capacity to store further information for each station. This information includes the National Grid co-ordinates of the zero-chainage point, the bearing (Grid North) looking seaward down the profile line, and a "base" profile which can show the promenade, sea wall and, if known, the level of the solid rock stratum below the beach. This supplementary information is useful both to ensure consistency from survey to survey, and to examine beach level changes in the context of the solid defences and the underlying rock stratum.

Provided the surveys have been carried out consistently, however, this extra information is optional, and analysis of the profile data can proceed without it. For each profile, data is stored as a set of chainage-level pairs together with the survey date. Beach levels are normally reduced to Ordnance Datum, and chainages measured to a fixed point near the beach crest, often at the face of a seawall.

Data quality checking

Before any calculations are started, quality control checks on the cross-sectional profiles have to be carried out. For each of the stations, BDAS itself is used to produce plots of all the surveyed profiles. Apparent errors, such as the occasional "rogue" beach level, consistent shifts in chainage values, or simple data input errors, are then identified visually, and necessary corrections made, within the computer database, i.e. without having to re-enter the data. Further checks are carried out as the analysis proceeds, and the same approach to amending the data is adopted. If further information is available to correct, or confirm the data questioned in this part of the process, the database can be altered, and any analysis can be repeated, at a future time.

Presentation of results

The primary use of BDAS is to gather together profiles from the same station, surveyed on different dates, and then carry out comparisons and statistical analyses of them. Changes over time can be separated into long-term trends, seasonal changes and short-term fluctuations. This type of analysis provides predictions of future beach changes, and a more detailed understanding of past events.

The most straightforward way to present such a statistical analysis of the beach data is by a "mean profile plot" for each station. In this type of plot, information is given on maximum, minimum and mean beach levels, and on the long-term rate of change in beach level, during the period considered. The long-term trend is calculated using a least-squares analysis method, and shown in metres/year upward (accretion) or downward (erosion). The graphs also show the statistical "confidence limits", within which 95% of the survey values can be expected to fall.

However, many other forms of presentation are available, for example graphs showing the changes in beach cross-sectional area over time. The BDAS software has the capacity to calculate a "trend' line which both identifies an underlying linear long-term (secular) trend and/ or any seasonal variations (using a sinusoidal function with a period of one year). Both of these components are calculated using multi-linear regression methods.

BDAS can produce time-series plots for a number of other parameters, for example:

- beach levels at specific locations (i.e. chainage values)
- beach slopes at specific locations (i.e. chainage values)
- the distance (i.e. chainage) to a particular beach contour level
- the distance to the crest of the first beach "bar" or the first "trough"

Further analysis techniques
Following on from the analyses described above, a number of further types of calculation are possible. The most obvious is the calculation of beach volumes, produced by combining information from various stations. We have not tried to generalise this type of analysis, because each beach is likely to be different, i.e. the distance and orientation changes between adjacent profiles, the discontinuities in beach levels caused by groynes, breakwaters etc. However, such calculations can usually be carried out readily using a spread-sheet, and BDAS has been organised in a way that results can be output in a format compatible with such subsequent analysis methods.

Appendix C

High and low water recession rates

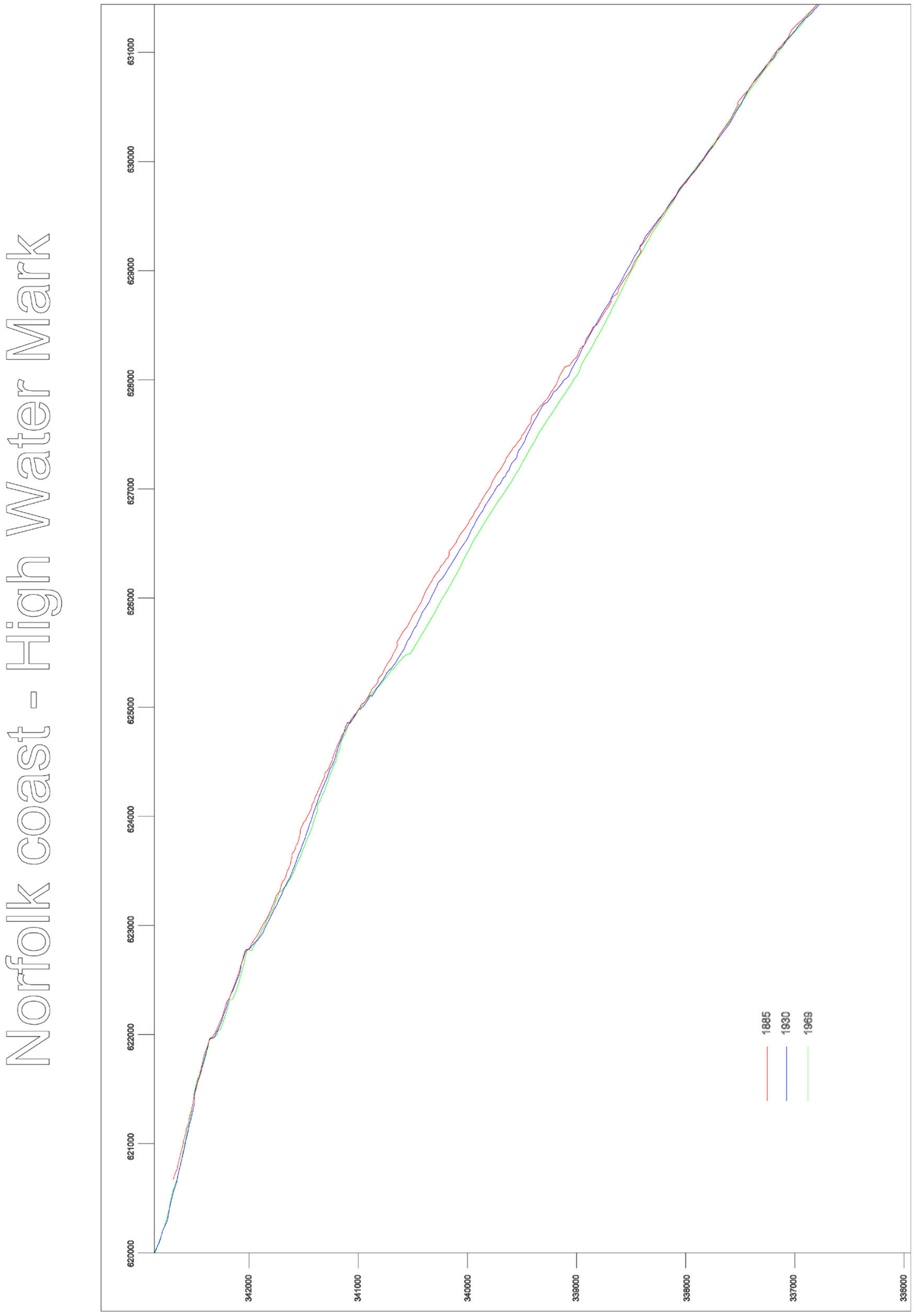


Figure B1 **High water mark between Cromer and Mundesley**

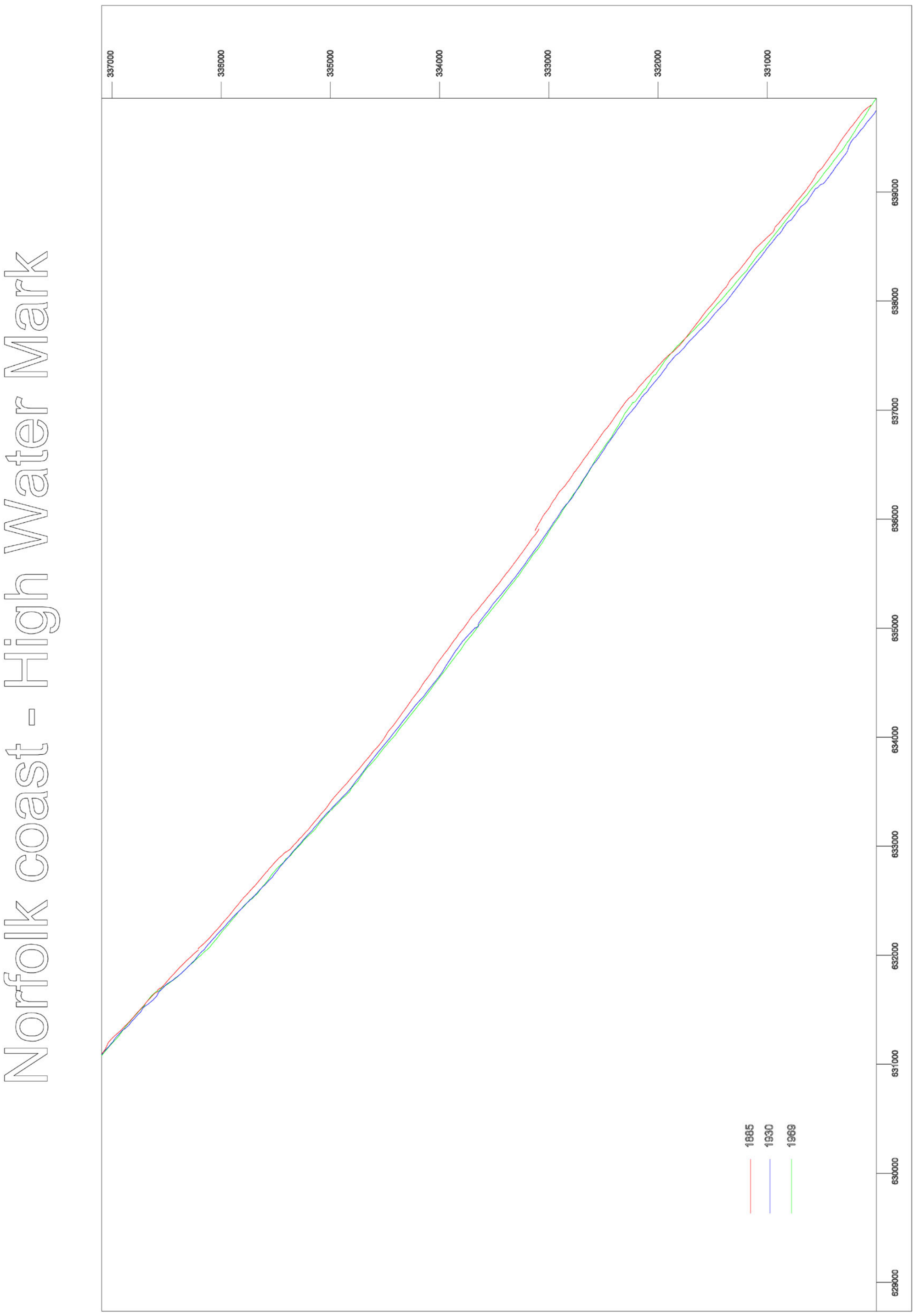


Figure B2 High water mark between Mundesley and Walcott

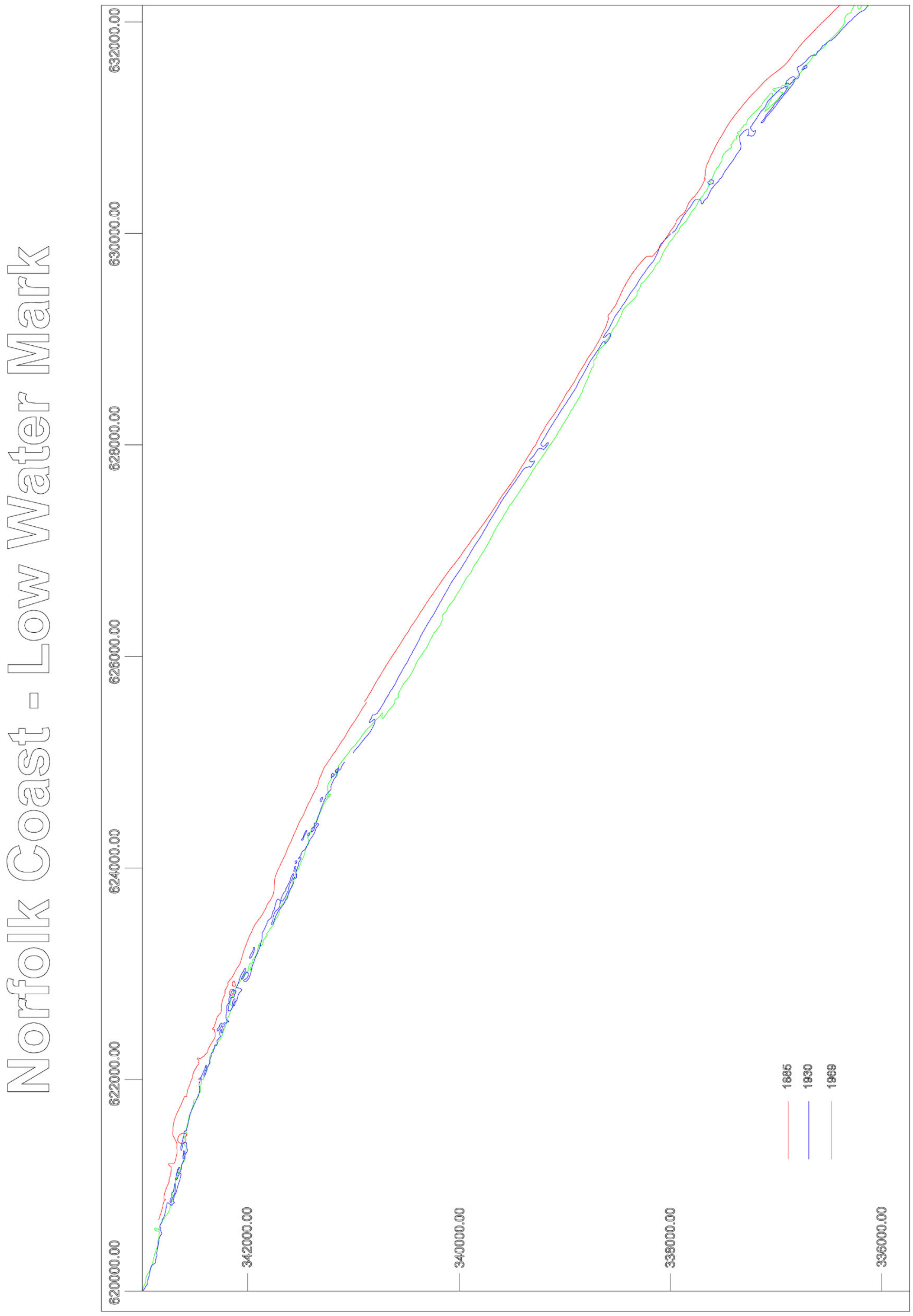


Figure B3 **Low water mark between Cromer and Mundesley**

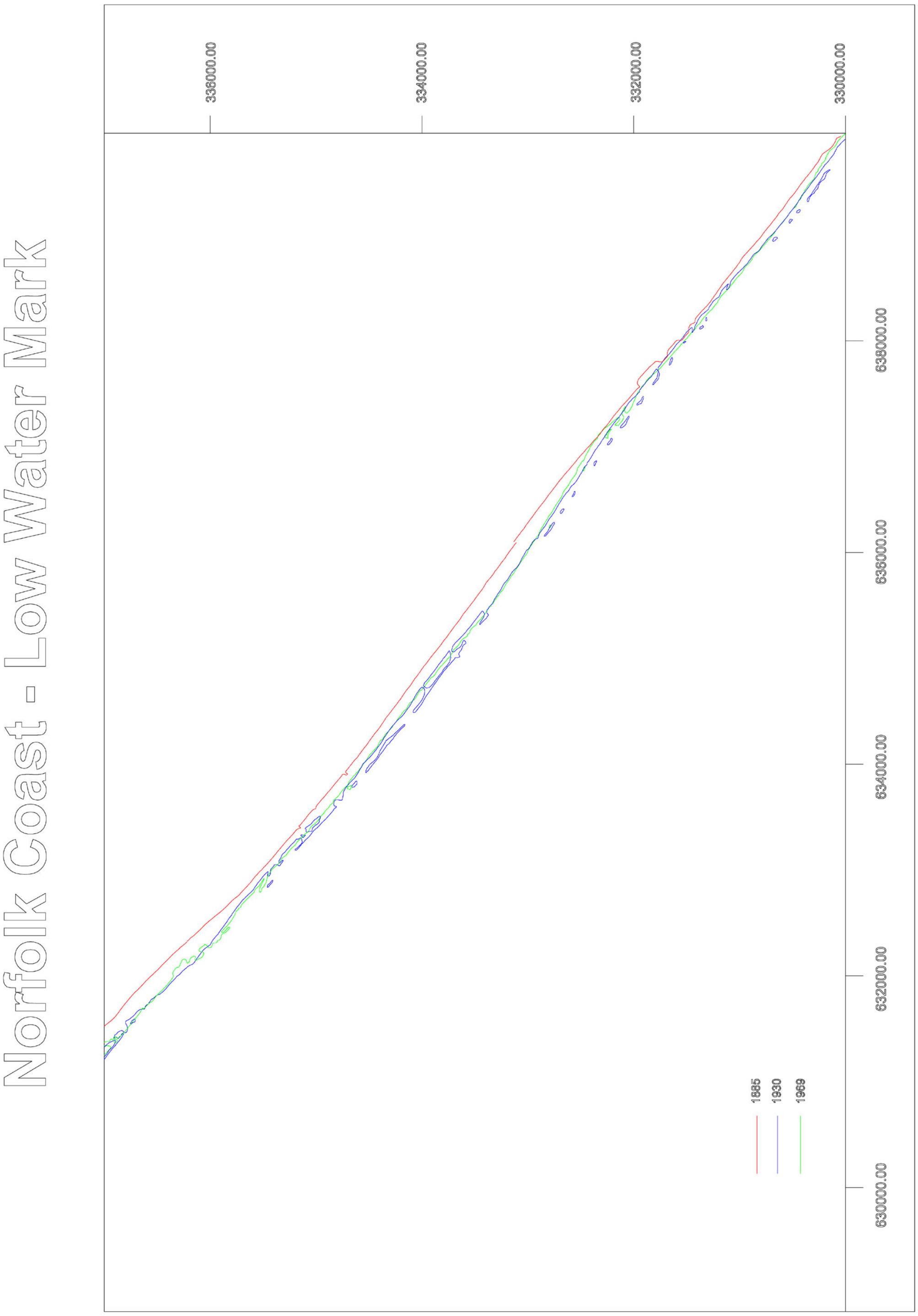


Figure B4 Low water mark between Mundesley and Walcott

Appendix D

Potential sediment yields from cliffs

Table C.1 Potential sediment yields from cliffs by location

Location *	Grid Ref.	Mud % (BGS 1996)	Sand % (BGS 1996)	Gravel % (BGS 1996)	Sediment yield** m^3/ m (BGS 1996)	Recession rate m/year (Clayton 2002)	Sand yield*** m^3/year
Ostend N3C8 to N3B1	636480 332570 636854 332307	70.3	29.2	0.5	6,989	1.16	2,367
Bacton N3C7 to N3C8	635151 333493 636480 332570	64.7	35.3	0	5,315	1.22	2,289
Bacton N3C6 to N3C7	634461 334024 635151 333493	36.9	63.1	0	4,353	1.09	2,994
Bacton N3C5 to N3C6	633431 334805 634461 334024	24.0	66.0	10.0	9,695	1.09	6,975
Bacton N3C4 to N3C5	633151 335080 633431 334805	33.2	64.7	2.1	18,480	0.93	11,120
Mundesley N3C4 to N3C3	633151 335080 631997 336089	35.6	63.77	0.7	20,912	0.73	9,735
Mundesley N3C2 to N3C3	631700 336460 631997 336089	27.5	72.5	0	12,933	0.63	5,907
Mundesley N3C1 to N3C2	631220 336900 631700 336460	32.5	67.4	0.1	19,564	0.11	1,450

Note:
* N3E5 etc. refer to EA Marker Numbers.
** Sediment yield per metre of cliff recession.
*** Sand yield = Sediment yield × Recession rate × Sand %.

Table C.1 Potential sediment yields from cliffs by location (continued)

Location *	Grid Ref.	Mud % (BGS 1996)	Sand % (BGS 1996)	Gravel % (BGS 1996)	Sediment yield** m^3/ m (BGS 1996)	Recession rate m/year (Clayton 2002)	Sand yield*** m^3/year
Trimingham N3D6 to N3C1	630420 337480 631220 336900	34.2	65.5	0.3	34,454	0.36	8,124
Trimingham N3D5 to N3D6	628899 338399 630420 337480	30.3	65.6	4.1	47,134	0.42	12,986
Trimingham N3D5 to N3D4	627870 339024 628899 338399	36.6	55.5	7.9	72,236	0.85	34,027
Trimingham N3D3 to N3D4	627260 339361 627870 339024	62.5	37.5	0	27,876	1.27	13,276
Sidestrand N3D2 to N3D3	626310 339910 627260 339361	82.8	17.1	0.1	24,155	1.53	6,320
Overstrand N3D1 to N3D2	625890 340180 626310 339910	43.6	55.4	1.0	27,577	1.55	23,680
Overstrand N3E6 to N3D1	624751 341064 625890 340180	69.0	30.0	1.0	21,330	0.92	5,887
Overstrand N3E5 to N3E6	624440 341170 624751 341064	40.2	59.5	0.3	50,748	0.38	11,474
Cromer N3E5 – N3E4	623380 341485 622641 341972	21.6	78.4	0	48,677	0.68	25,951

Note:
* N3E5 etc. refer to EA Marker Numbers.
** Sediment yield per metre of cliff recession.
*** Sand yield = Sediment yield × Recession rate × Sand %.

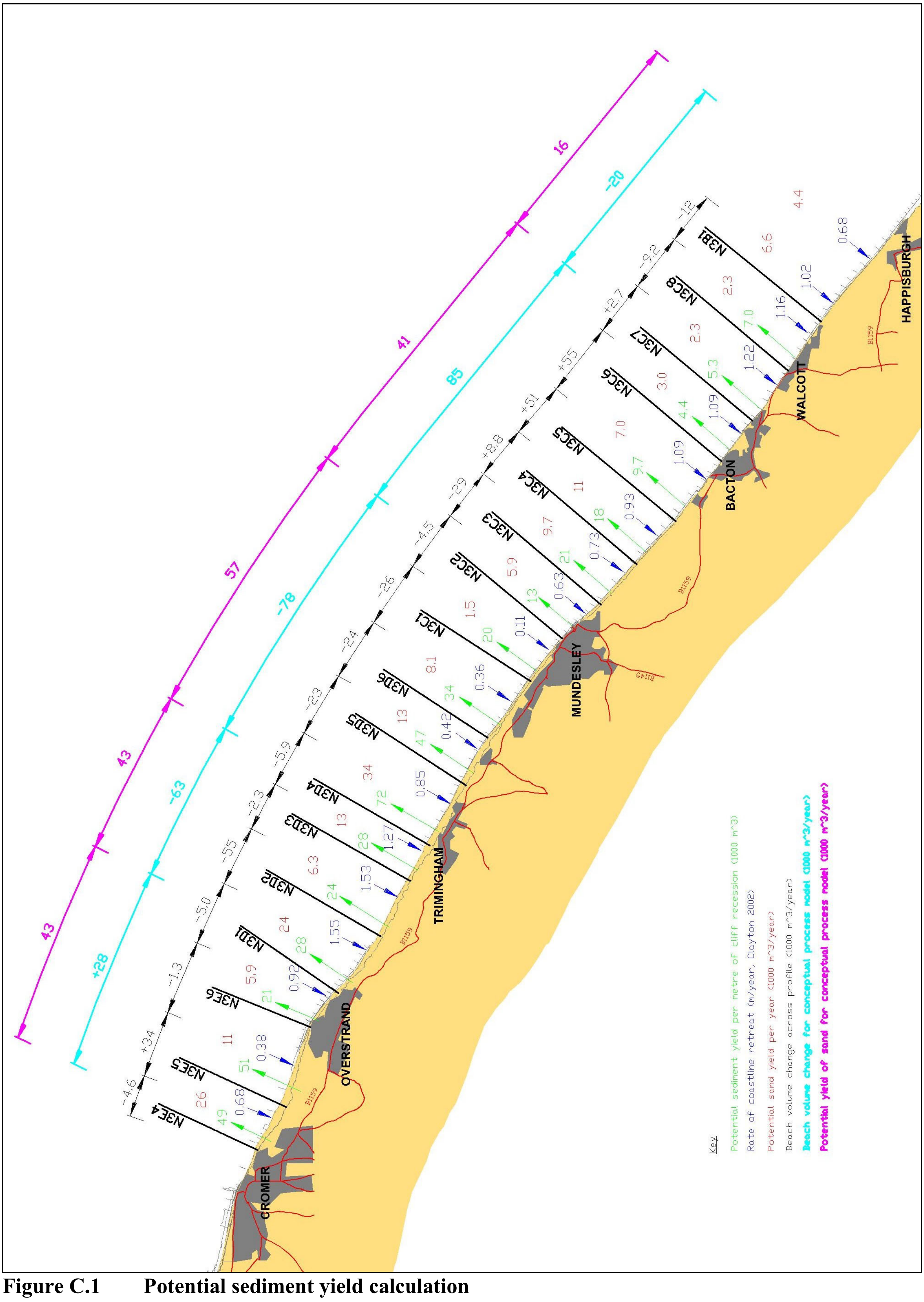


Figure C.1 Potential sediment yield calculation

Appendix E

Sediment analyses

Appendix E Sediment analyses

Sediment samples were taken at multiple locations across the frontage, with locations shown in Figures E.1 to E.5b. Taken from trial pits dug by St La Haye, the sediment samples were sieve analysed by HR Wallingford. Figures E.6 to E. 34 show the resulting grading curves as well as values for d_{10} d_{50} and d_{50}, where d_n is the sediment diameter for which n percent of the sample (by weight) has diameter less than or equal to d_n. A summary of the sediment diameters for surface samples is shown in Table E.1.

Table E.1 Summary of principal sediment characteristics for surface samples. (All distances mm)

Location	Overstrand			Mean
Sample	OW/S2	OW/S4	OW/S5	
Figure	E.6	E.8	E.9	
Depth	500	600	500	
d_{90}	15	0.65	0.57	5.3
d_{50}	0.58	0.32	0.32	0.41
d_{10}	0.20	0.20	0.20	0.20

Location	Trimingham						Mean
Sample	W/S2	WS2 D1	WS11 D1	U1 SS	U2 SS	U3 SS	
Figure	E.12	E.16	E.20	E.23	E.24	E.25	
Depth	500	0	0	0	0	0	
d_{90}	16.	6.8	1.2	13	0.67	0.42	6.4
d_{50}	0.65	0.50	0.29	0.45	0.32	0.29	0.42
d_{10}	0.23	0.26	0.19	0.26	0.20	0.19	0.22

Location	Bacton						Mean
Sample	SS D	SS E	SS F	SS G	SS H	SS I	
Figure	E.29	E.30	E.31	E.32	E.33	E.34	
Depth	0	0	0	0	0	0	
d_{90}	21.	0.64	0.57	0.66	17	0.70	6.8
d_{50}	0.39	0.32	0.39	0.42	1.1	0.42	0.52
d_{10}	0.26	0.21	0.26	0.28	0.31	0.30	0.27

Location	Walcott			Mean
Sample	SS A	SS B	SS C	
Figure	E.26	E.27	E.28	
Depth	0	0	0	
d_{90}	9.3	5.9	15	10
d_{50}	0.47	0.38	0.80	0.55
d_{10}	0.25	0.24	0.30	0.26

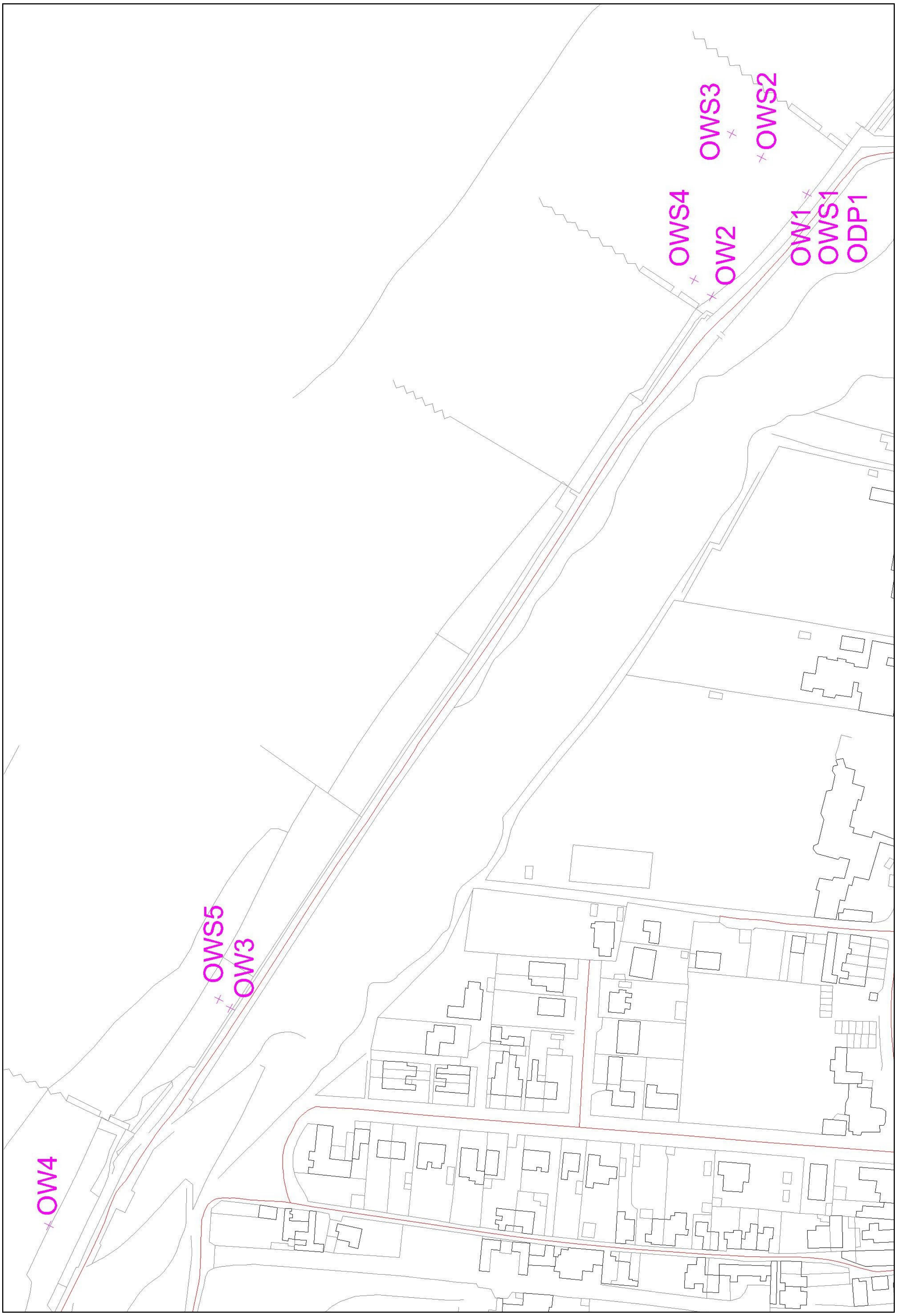


Figure E.1 Location of sediment samples at Overstrand

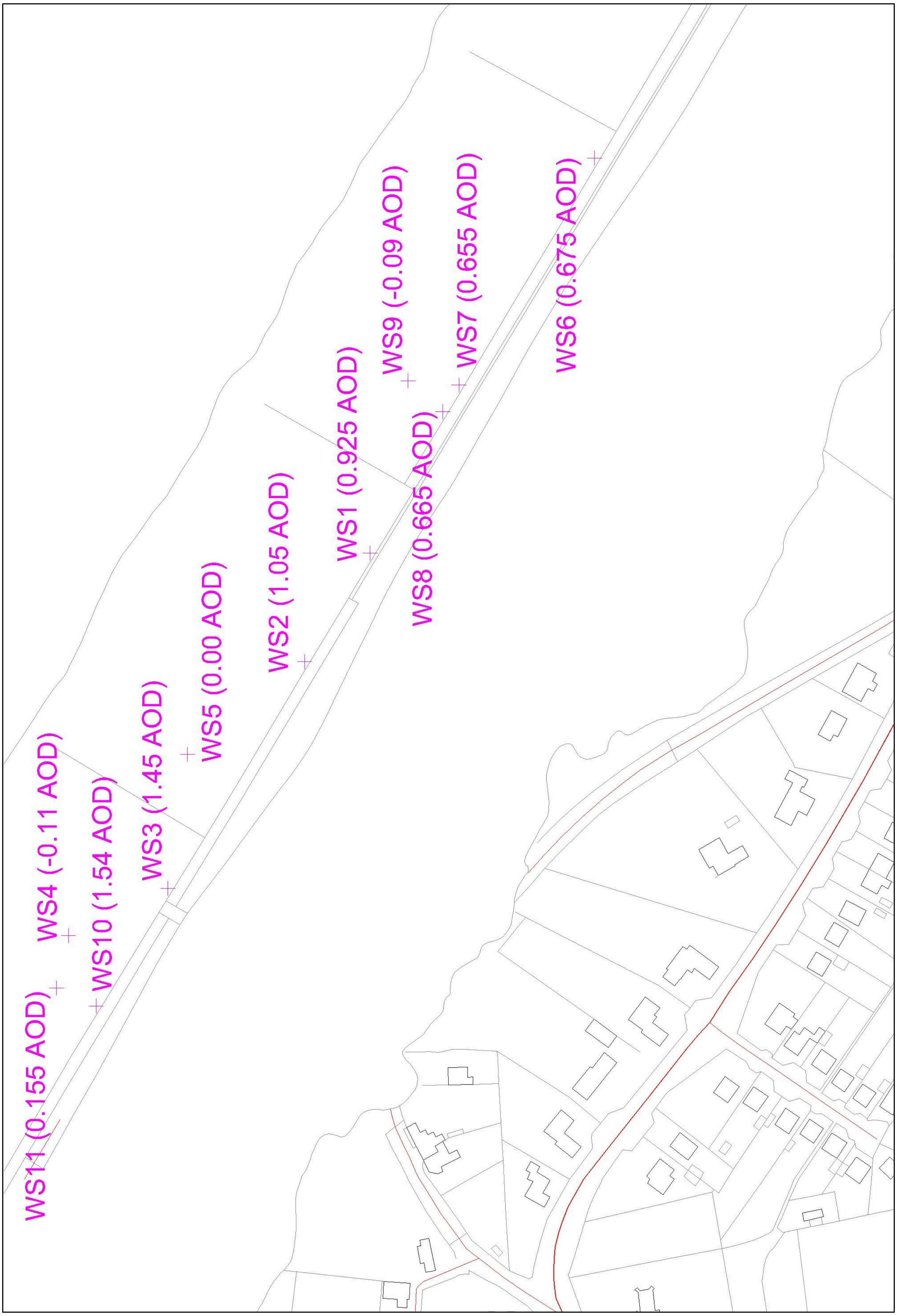


Figure E.2a Location of sediment samples at Trimingham

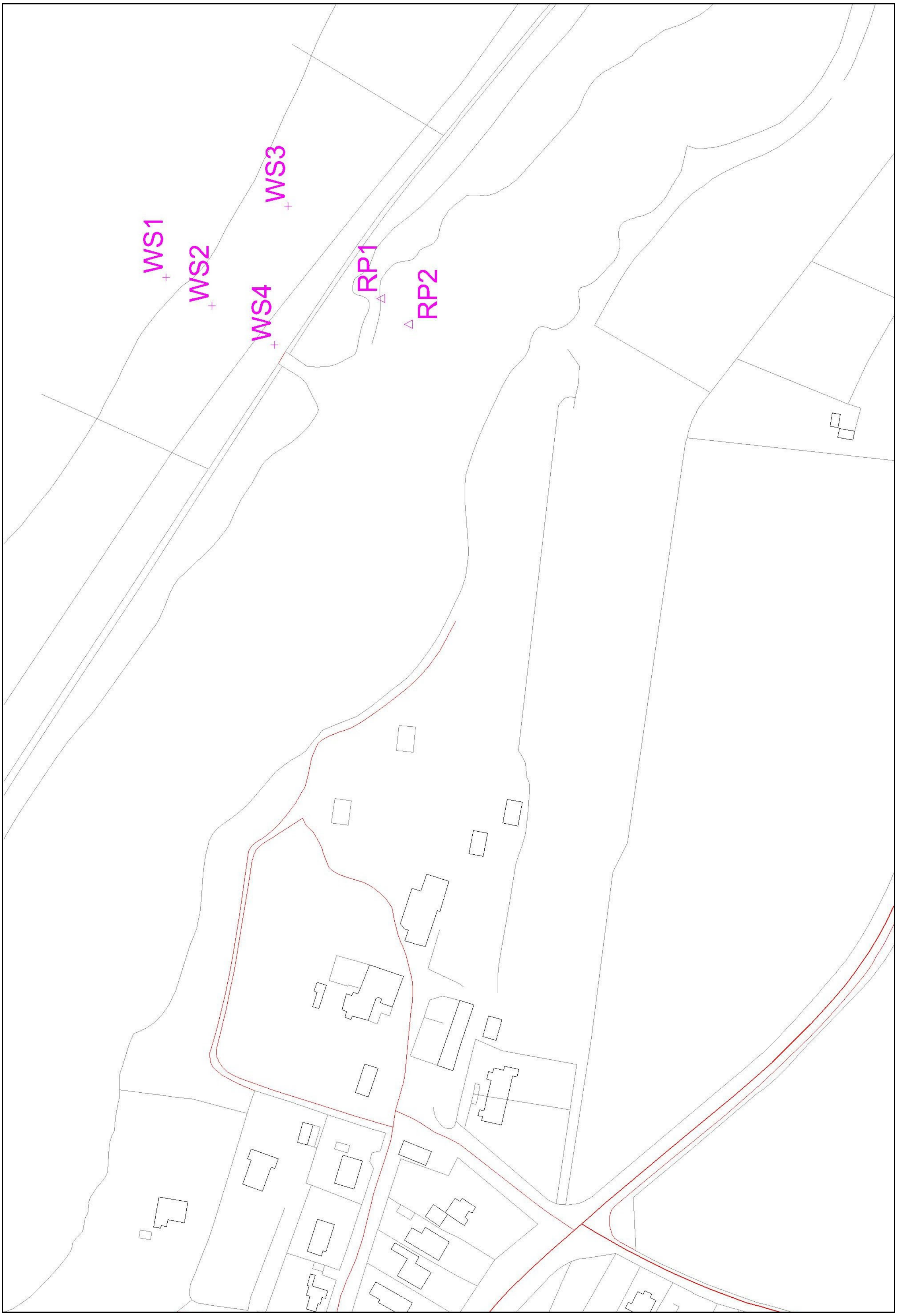


Figure E.2b Location of sediment samples at Trimingham

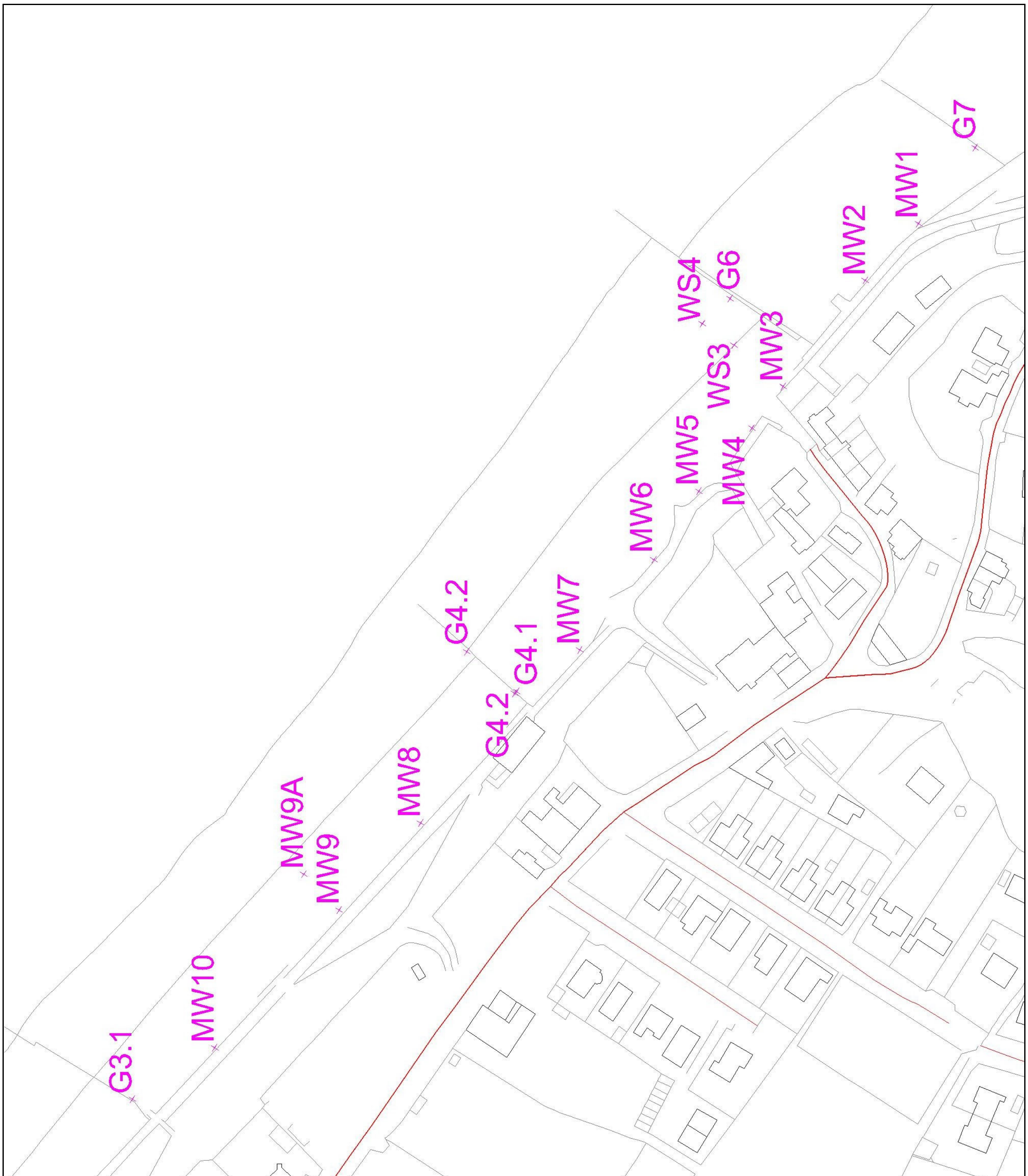


Figure E.3 Location of sediment samples at Mundesley

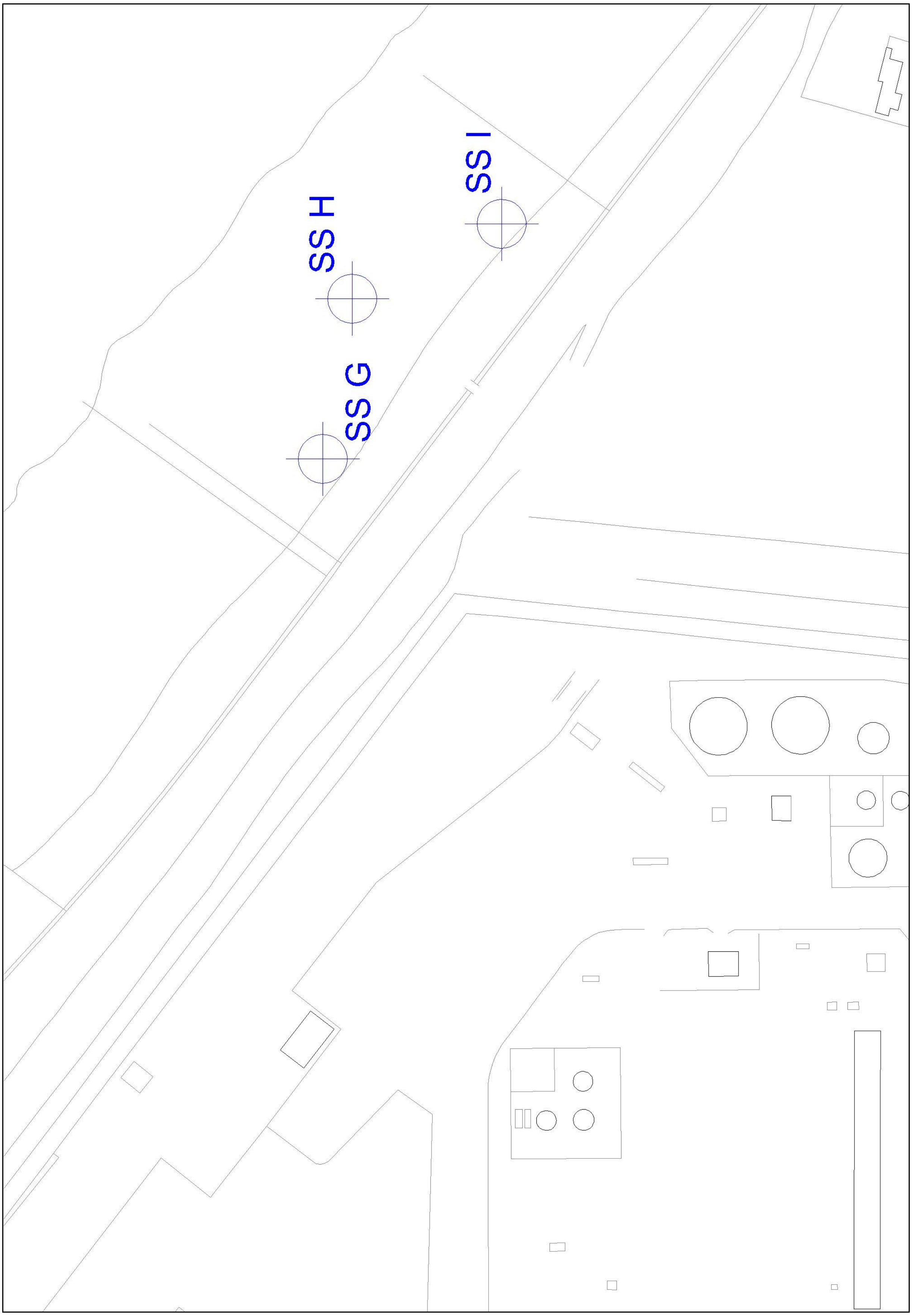


Figure E.4 Location of sediment samples at Bacton

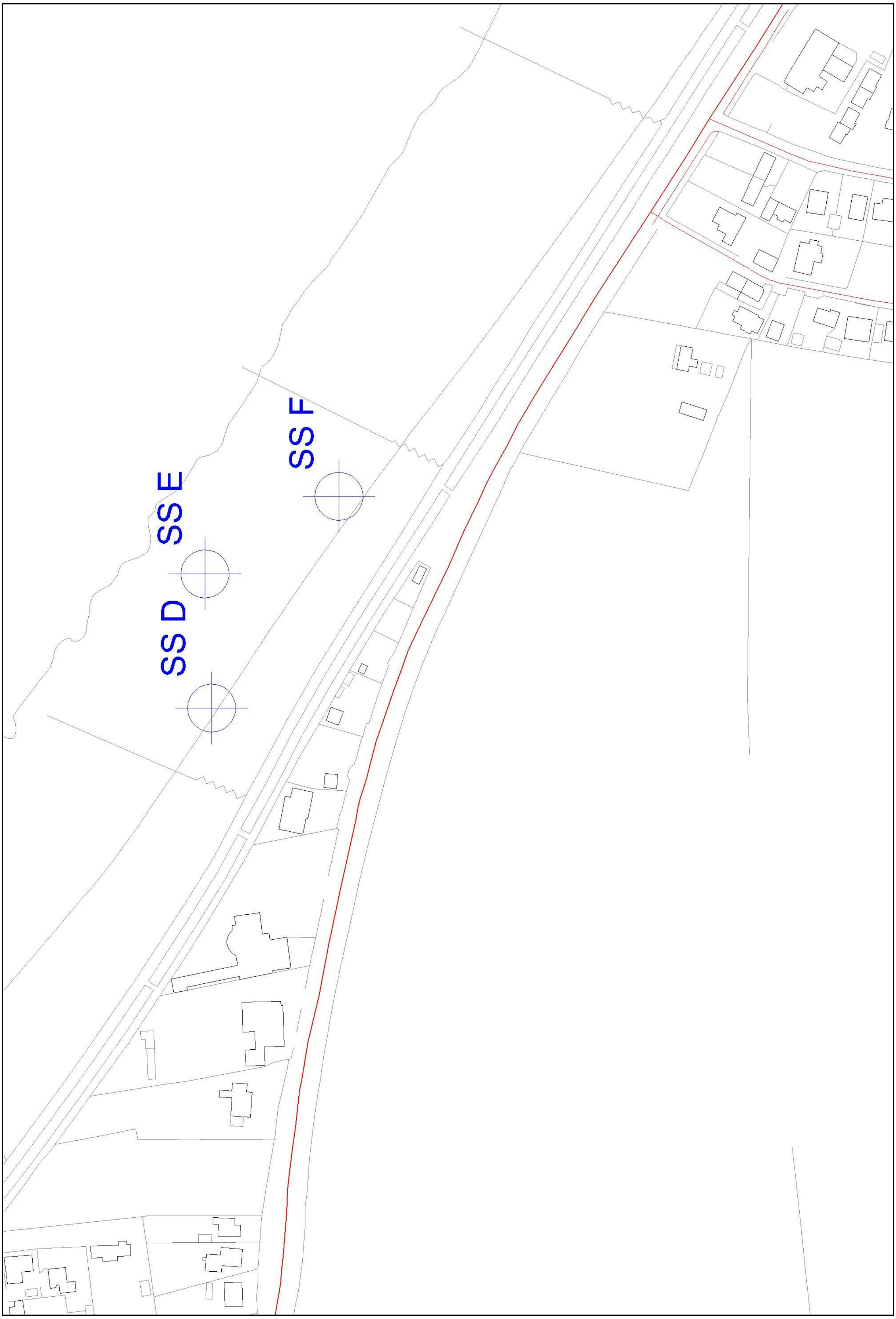


Figure E.5a Location of sediment samples at Walcott

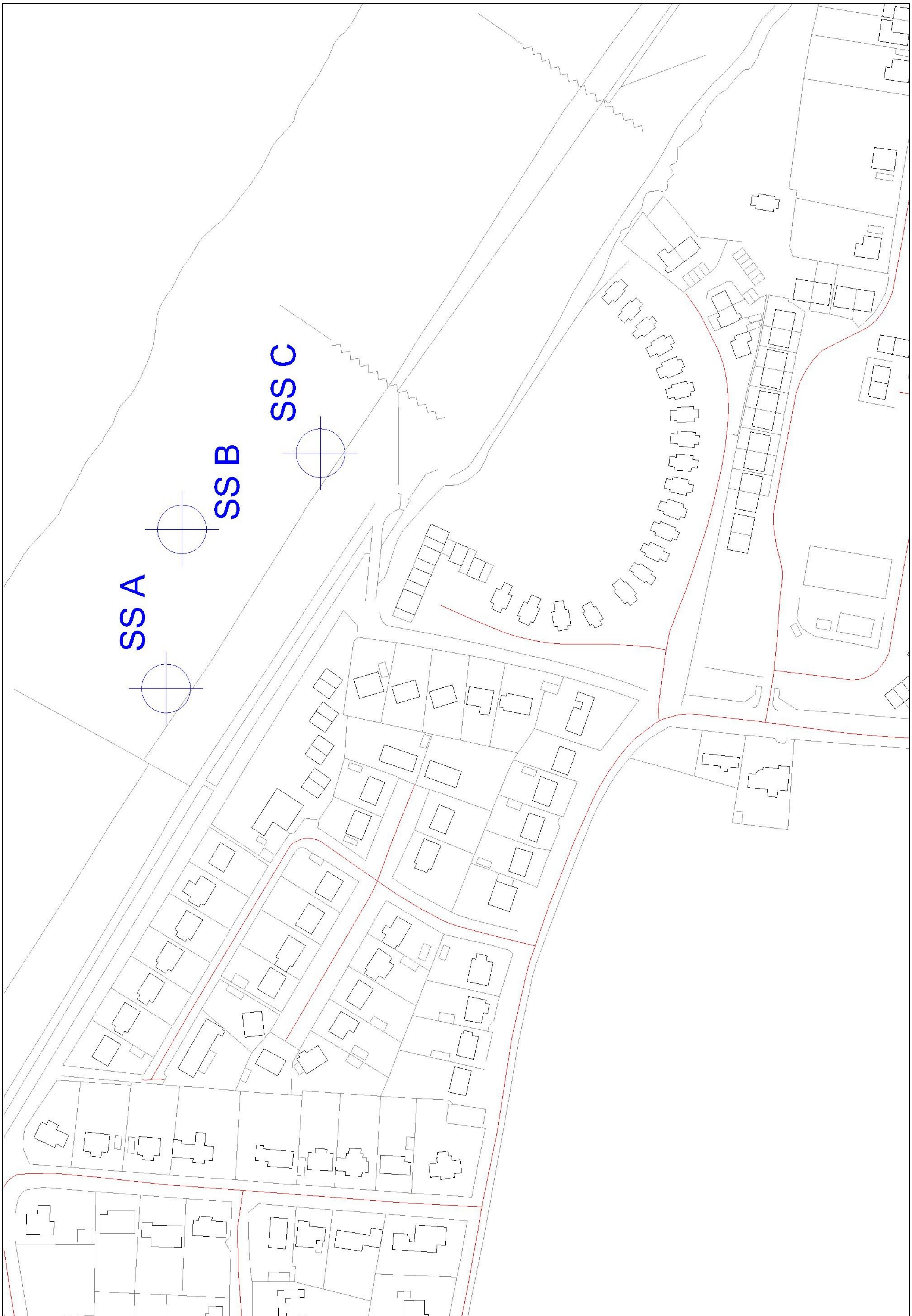
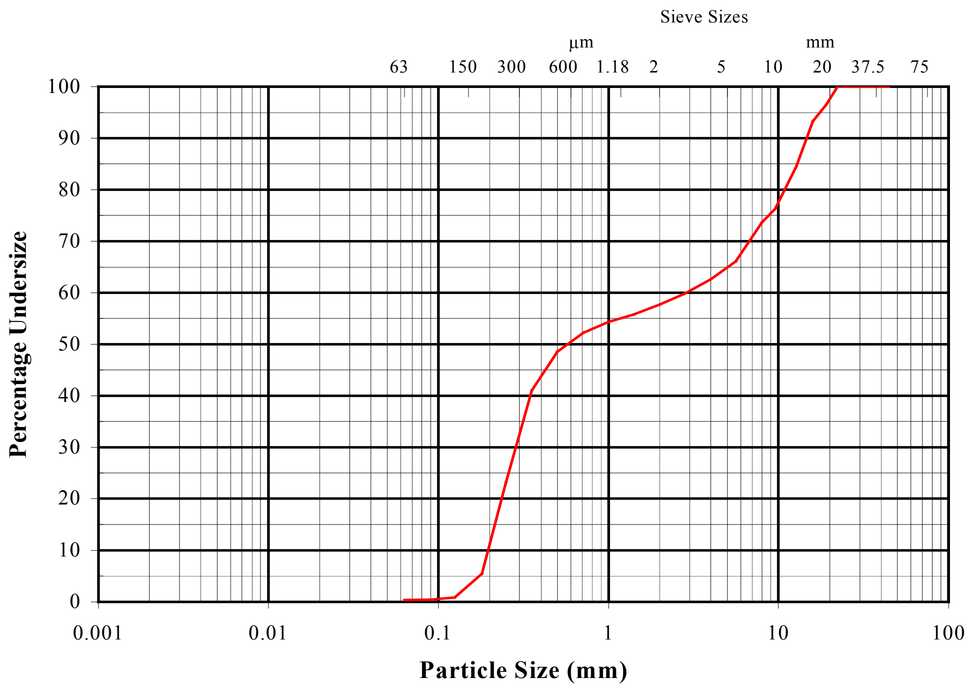


Figure E.5b Location of sediment samples at Walcott

OW / S2 - 0.5m   Lab. no. 18077



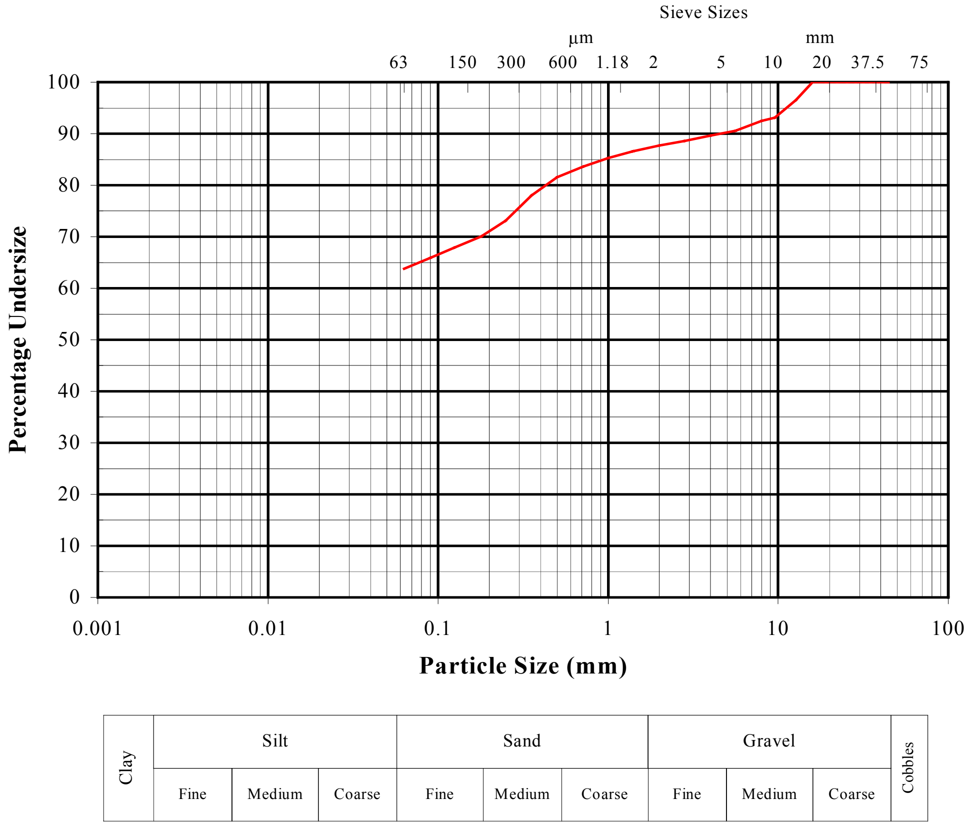
Clay	Silt			Sand			Gravel			Cobbles
	Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse	

Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	73.649	0.125	0.835		
41.280	100.000	5.600	66.090	0.090	0.452		
38.100	100.000	4.000	62.598	0.063	0.342		
34.930	100.000	2.800	59.851				
31.750	100.000	2.000	57.692				
28.580	100.000	1.400	55.798				
25.400	100.000	1.000	54.305				
22.230	100.000	0.710	52.238				
19.050	96.515	0.500	48.586				
15.880	93.292	0.355	41.041				
12.700	84.445	0.250	23.168				
9.520	76.259	0.180	5.447				

D_{90} (mm) 14.697	**Description:**
D_{50} (mm) 0.581	
D_{10} (mm) 0.198	

Figure E.6 Sediment analysis at Overstrand, location OW/S2 at a depth of 0.5m

OW / S2 - 3.7m Lab. no. 18078

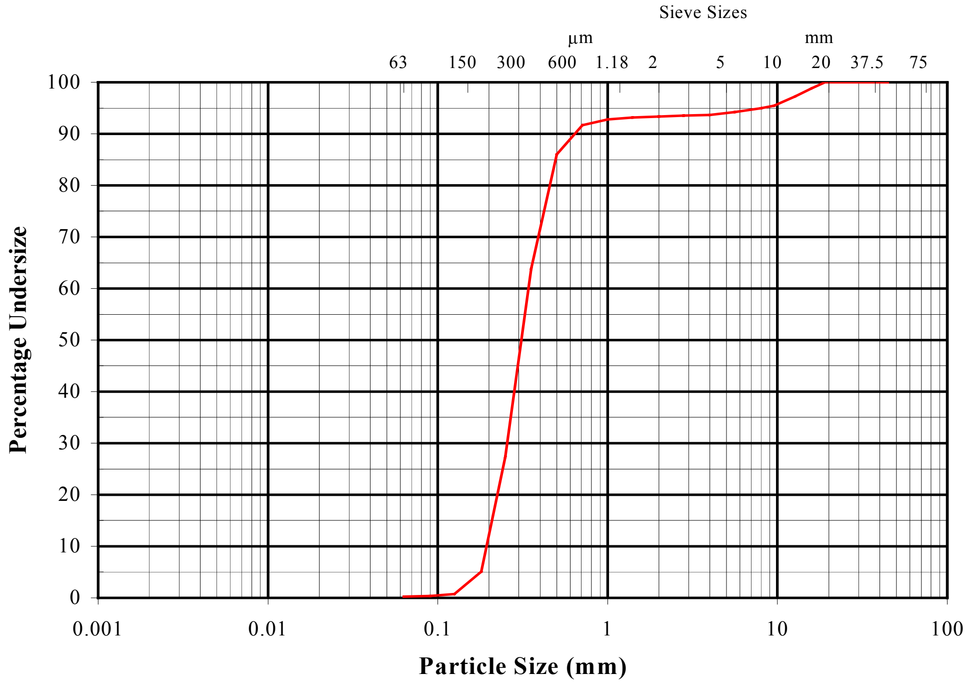


Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	92.526	0.125	67.866		
41.280	100.000	5.600	90.584	0.090	65.879		
38.100	100.000	4.000	89.634	0.063	63.786		
34.930	100.000	2.800	88.563				
31.750	100.000	2.000	87.700				
28.580	100.000	1.400	86.584				
25.400	100.000	1.000	85.309				
22.230	100.000	0.710	83.631				
19.050	100.000	0.500	81.531				
15.880	100.000	0.355	77.983				
12.700	96.505	0.250	73.066				
9.520	93.118	0.180	70.038				

D_{90} (mm) 4.616	**Description:**
D_{50} (mm) 0.049	
D_{10} (mm) 0.010	

Figure E.7 Sediment analysis at Overstrand, location OW/S2 at a depth of 3.7m

OW / S4 - 0.6m   Lab. no. 18079



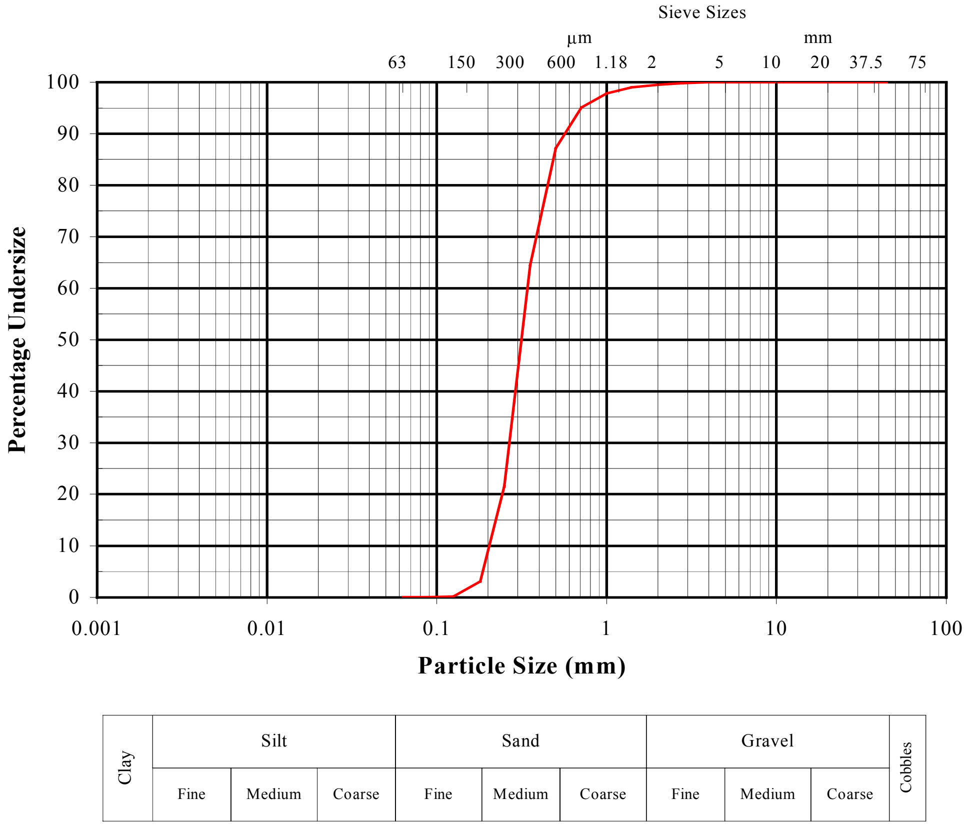
Clay	Silt			Sand			Gravel			Cobbles
	Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse	

Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	94.966	0.125	0.705		
41.280	100.000	5.600	94.197	0.090	0.335		
38.100	100.000	4.000	93.645	0.063	0.243		
34.930	100.000	2.800	93.536				
31.750	100.000	2.000	93.340				
28.580	100.000	1.400	93.137				
25.400	100.000	1.000	92.792				
22.230	100.000	0.710	91.628				
19.050	100.000	0.500	86.001				
15.880	98.780	0.355	63.848				
12.700	97.302	0.250	27.326				
9.520	95.483	0.180	5.065				

D_{90} (mm) 0.649	**Description:**
D_{50} (mm) 0.315	
D_{10} (mm) 0.196	

Figure E.8 Sediment analysis at Overstrand, location OW/S4, at a depth of 0.6m

OW / S5 - 0.5m   Lab. no. 18080

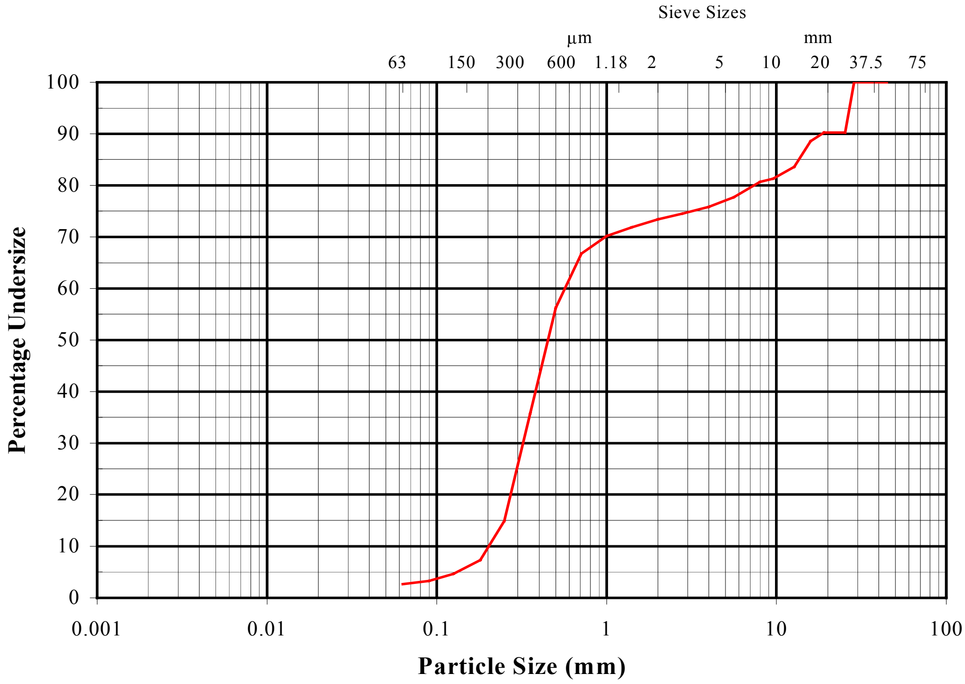


Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	100.000	0.125	0.193		
41.280	100.000	5.600	100.000	0.090	0.053		
38.100	100.000	4.000	99.971	0.063	0.036		
34.930	100.000	2.800	99.815				
31.750	100.000	2.000	99.535				
28.580	100.000	1.400	98.960				
25.400	100.000	1.000	97.838				
22.230	100.000	0.710	95.127				
19.050	100.000	0.500	87.185				
15.880	100.000	0.355	64.537				
12.700	100.000	0.250	21.519				
9.520	100.000	0.180	3.077				

D_{90} (mm) 0.574	**Description:**
D_{50} (mm) 0.320	
D_{10} (mm) 0.206	

Figure E.9 Sediment analysis at Overstrand, location OW/S5, at a depth of 0.5m

OW / S5 - 5.1m Lab. no. 18081

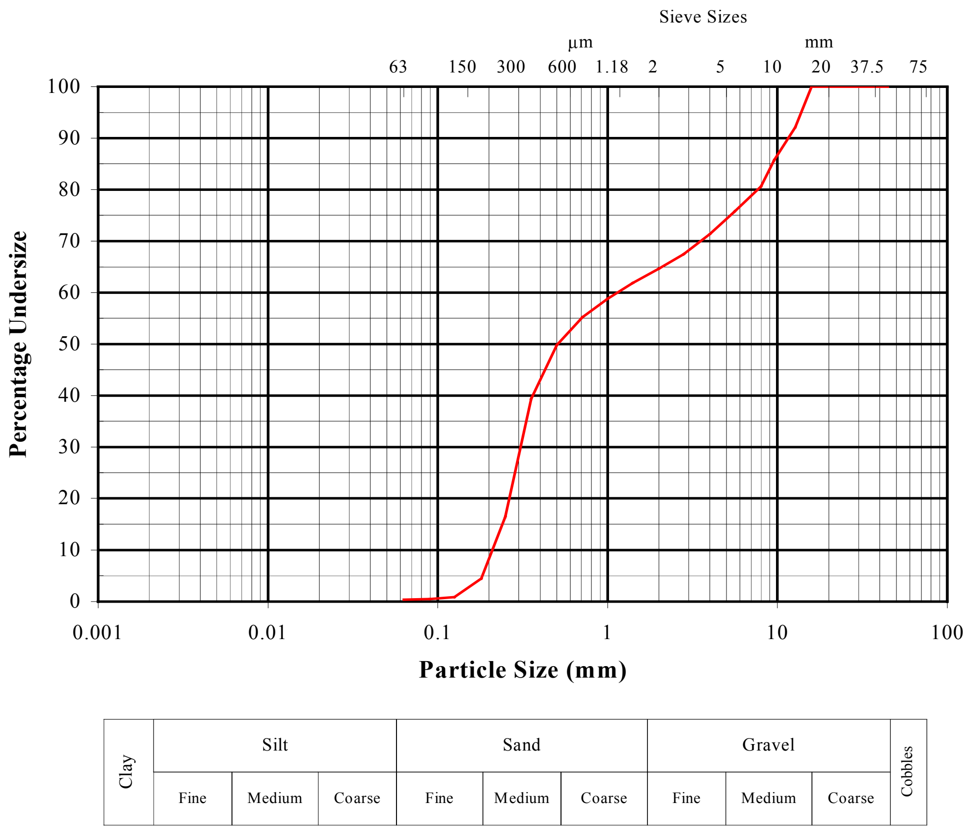


Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	80.701	0.125	4.651		
41.280	100.000	5.600	77.651	0.090	3.267		
38.100	100.000	4.000	75.780	0.063	2.669		
34.930	100.000	2.800	74.503				
31.750	100.000	2.000	73.361				
28.580	100.000	1.400	71.867				
25.400	90.249	1.000	70.170				
22.230	90.249	0.710	66.701				
19.050	90.249	0.500	56.259				
15.880	88.565	0.355	35.778				
12.700	83.589	0.250	14.856				
9.520	81.289	0.180	7.342				

D_{90} (mm) 18.580	**Description:**
D_{50} (mm) 0.456	
D_{10} (mm) 0.205	

Figure E.10 Sediment analysis at Overstrand, location OW/S5, at a depth of 5.1m

W / S1 - 1m   Lab. no. 18084

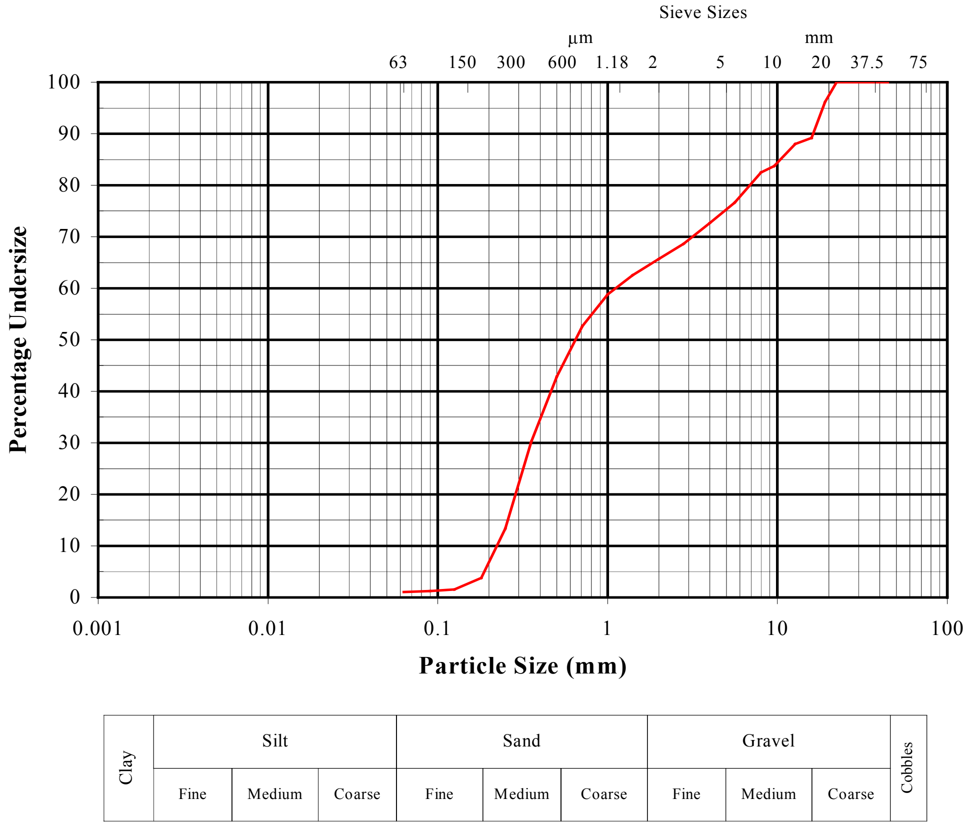


Sieve Size mm /µm	% Undersize	Sieve Size mm /µm	% Undersize	Sieve Size mm /µm	% Undersize	Sieve Size mm /µm	% Undersize
44.450	100.000	8.000	80.659	0.125	0.872		
41.280	100.000	5.600	75.755	0.090	0.489		
38.100	100.000	4.000	71.332	0.063	0.338		
34.930	100.000	2.800	67.453				
31.750	100.000	2.000	64.642				
28.580	100.000	1.400	61.820				
25.400	100.000	1.000	58.820				
22.230	100.000	0.710	55.218				
19.050	100.000	0.500	49.810				
15.880	100.000	0.355	39.395				
12.700	92.065	0.250	16.483				
9.520	85.737	0.180	4.460				

D_{90} (mm) 11.662	**Description:**
D_{50} (mm) 0.507	
D_{10} (mm) 0.212	

Figure E.11 Sediment analysis at Trimingham, location OW/S1, at a depth of 1m

W / S2 - 0.5m Lab. no. 18085

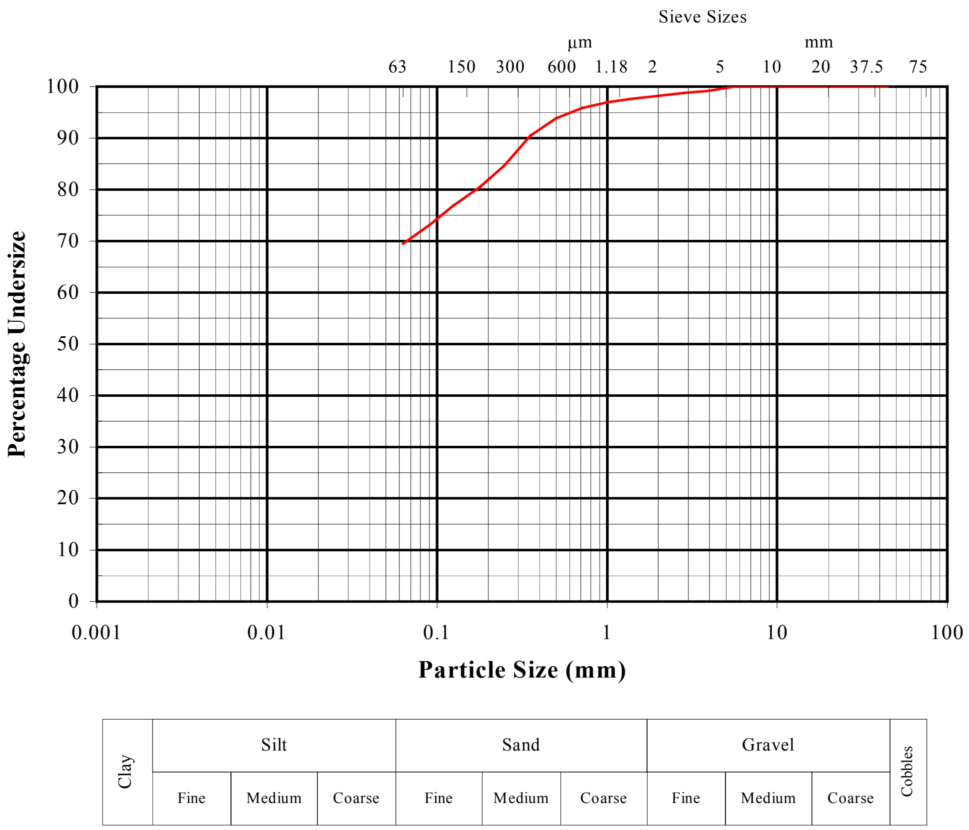


Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	82.463	0.125	1.590		
41.280	100.000	5.600	76.669	0.090	1.188		
38.100	100.000	4.000	72.683	0.063	1.008		
34.930	100.000	2.800	68.626				
31.750	100.000	2.000	65.716				
28.580	100.000	1.400	62.551				
25.400	100.000	1.000	58.787				
22.230	100.000	0.710	52.683				
19.050	96.146	0.500	42.803				
15.880	89.199	0.355	30.166				
12.700	88.020	0.250	13.396				
9.520	83.697	0.180	3.820				

D_{90} (mm) 16.245	**Description:**
D_{50} (mm) 0.653	
D_{10} (mm) 0.225	

Figure E.12 Sediment analysis at Trimingham at a depth of 0.5m

W / S2 - 1.9m   Lab. no. 18086

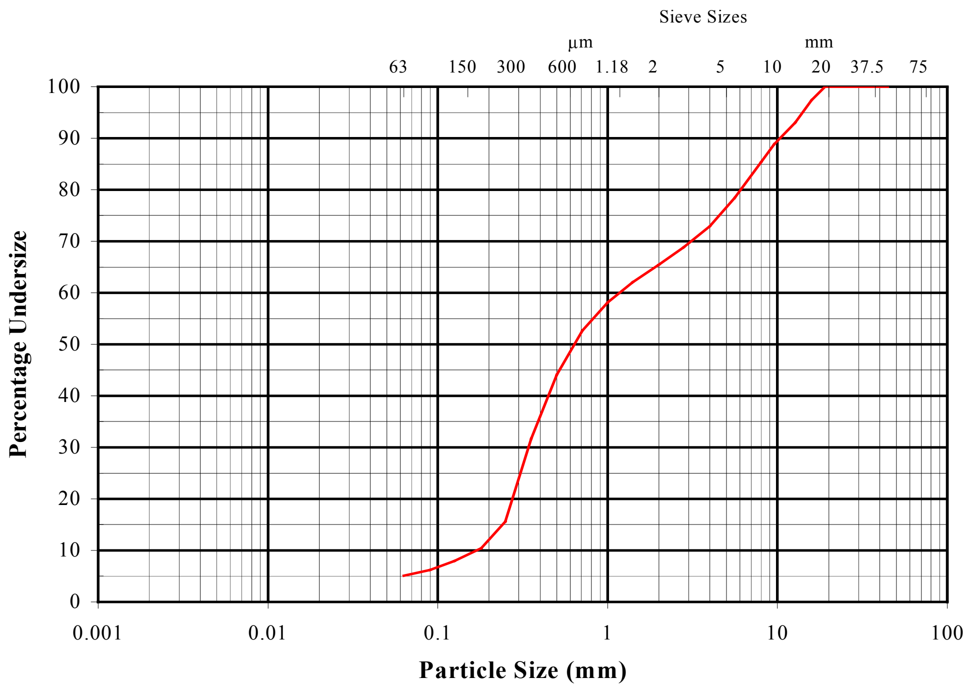


Sieve Size mm /µm	% Undersize	Sieve Size mm /µm	% Undersize	Sieve Size mm /µm	% Undersize	Sieve Size mm /µm	% Undersize
44.450	100.000	8.000	100.000	0.125	76.863		
41.280	100.000	5.600	100.000	0.090	73.063		
38.100	100.000	4.000	99.188	0.063	69.517		
34.930	100.000	2.800	98.719				
31.750	100.000	2.000	98.168				
28.580	100.000	1.400	97.658				
25.400	100.000	1.000	96.976				
22.230	100.000	0.710	95.814				
19.050	100.000	0.500	93.810				
15.880	100.000	0.355	90.525				
12.700	100.000	0.250	84.678				
9.520	100.000	0.180	80.492				

D_{90} (mm) 0.346	**Description:**
D_{50} (mm) 0.045	
D_{10} (mm) 0.009	

Figure E.13 Sediment analysis at Trimingham at a depth of 1.9m

W / S3 - 3.6m Lab. no. 18082



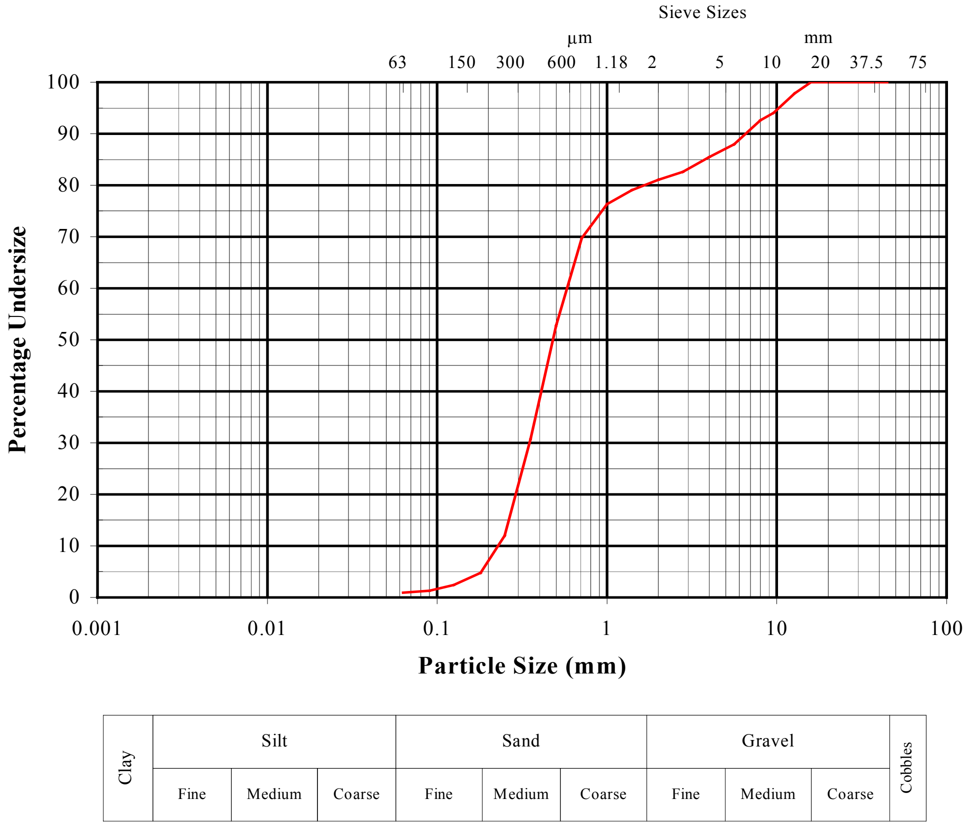
Clay	Silt			Sand			Gravel			Cobbles
	Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse	

Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	85.377	0.125	7.942		
41.280	100.000	5.600	78.449	0.090	6.229		
38.100	100.000	4.000	72.888	0.063	5.067		
34.930	100.000	2.800	68.841				
31.750	100.000	2.000	65.456				
28.580	100.000	1.400	62.045				
25.400	100.000	1.000	58.160				
22.230	100.000	0.710	52.689				
19.050	100.000	0.500	44.089				
15.880	97.393	0.355	31.716				
12.700	93.057	0.250	15.606				
9.520	88.794	0.180	10.418				

D_{90} (mm) 10.420	**Description:**
D_{50} (mm) 0.644	
D_{10} (mm) 0.171	

Figure E.14 Sediment analysis at Mundesley at a depth of 3.6m

W / S4 - 1.5m   Lab. no. 18083

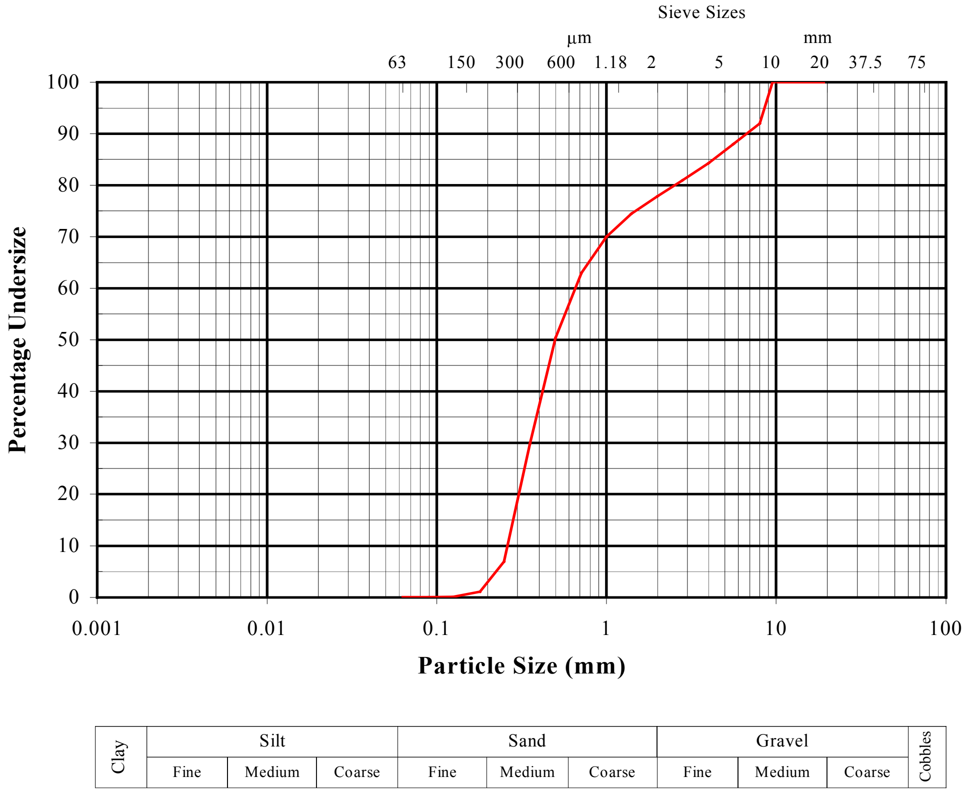


Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	92.638	0.125	2.429		
41.280	100.000	5.600	87.978	0.090	1.305		
38.100	100.000	4.000	85.481	0.063	0.938		
34.930	100.000	2.800	82.598				
31.750	100.000	2.000	81.057				
28.580	100.000	1.400	79.087				
25.400	100.000	1.000	76.329				
22.230	100.000	0.710	69.749				
19.050	100.000	0.500	52.832				
15.880	100.000	0.355	30.722				
12.700	97.809	0.250	11.998				
9.520	94.021	0.180	4.792				

D_{90} (mm) 6.641	**Description:**
D_{50} (mm) 0.481	
D_{10} (mm) 0.231	

Figure E.15 Sediment analysis at Mundesley at a depth of 1.5m

WS2 D1



Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
19.050		0.500	50.363				
15.880		0.355	29.778				
12.700		0.250	6.965				
9.520	100.000	0.180	1.082				
8.000	91.966	0.125	0.097				
5.600	88.046	0.090	0.065				
4.000	84.243	0.063	0.052				
2.800	80.971						
2.000	77.867						
1.400	74.465						
1.000	70.014						
0.710	62.997						

D_{90} (mm) 6.796

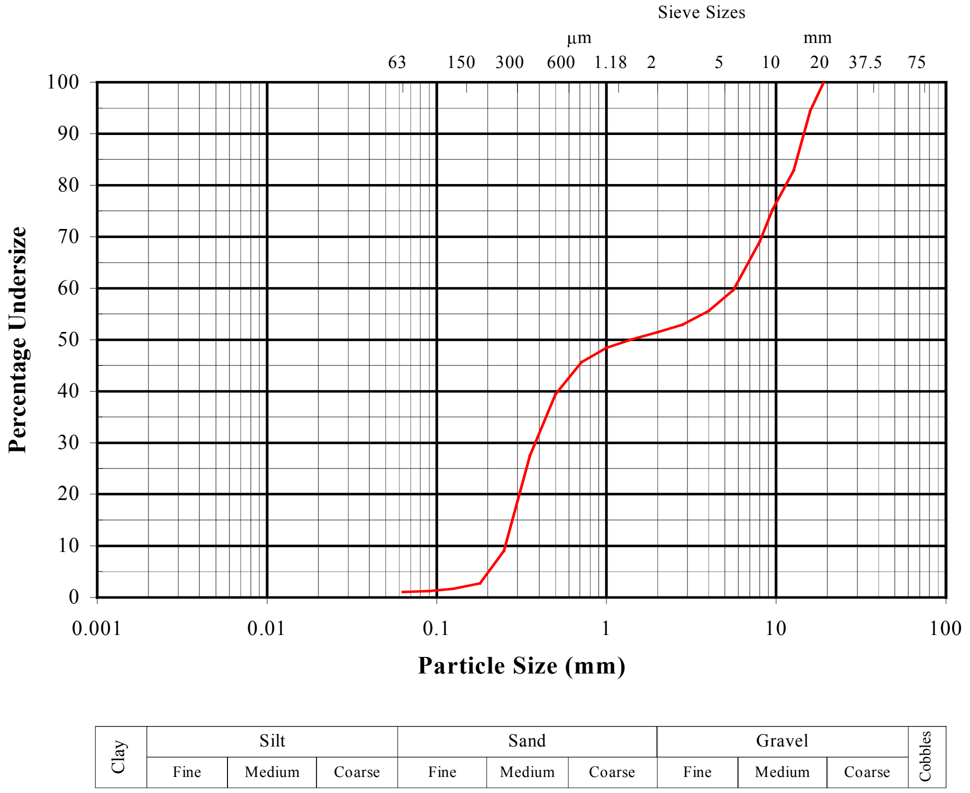
D_{50} (mm) 0.497

D_{10} (mm) 0.264

Description: Clean medium-coarse sand with gravel and small pebble up to ~10mm

Figure E.16 Sediment analysis at Trimingham, location WS2, at a depth of 0m

WS5 D1



Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
19.050	100.000	0.500	39.425				
15.880	94.478	0.355	27.474				
12.700	82.819	0.250	9.033				
9.520	75.257	0.180	2.746				
8.000	69.000	0.125	1.613				
5.600	59.629	0.090	1.215				
4.000	55.578	0.063	1.028				
2.800	52.870						
2.000	51.482						
1.400	50.019						
1.000	48.443						
0.710	45.615						

D_{90} (mm) 14.659

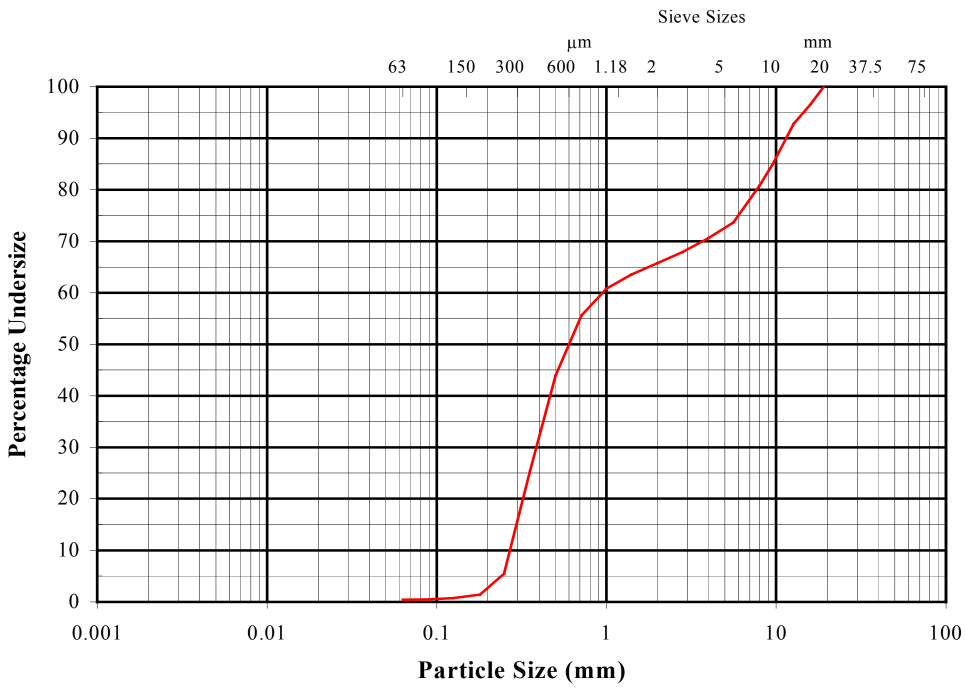
D_{50} (mm) 1.395

D_{10} (mm) 0.256

Description: Medium-coarse sand with gravel and pebble up to ~20mm with a small amount of fines.
Three large pebbles (35 - 45mm) not analysed.
Whole sample used.

Figure E.17 **Sediment analysis at Trimingham, location WS5, at a depth of 1.2m**

WS7 D1



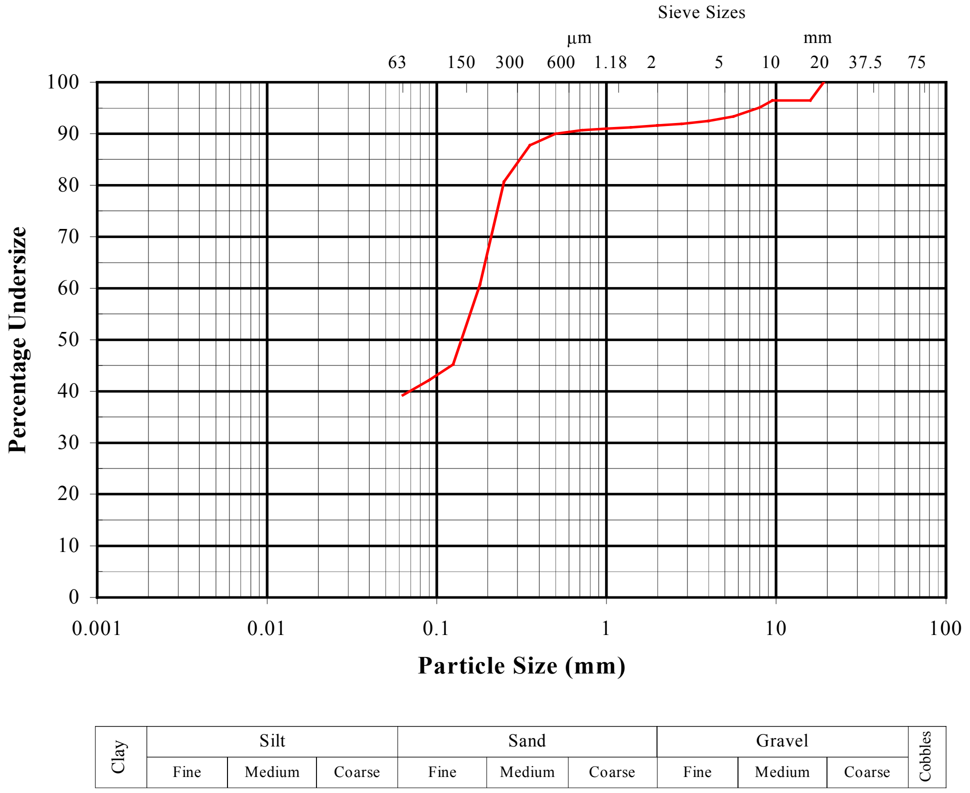
Clay	Silt			Sand			Gravel			Cobbles
	Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse	

Sieve Size mm /µm	% Undersize	Sieve Size mm /µm	% Undersize	Sieve Size mm /µm	% Undersize	Sieve Size mm /µm	% Undersize
19.050	100.000	0.500	43.950				
15.880	96.464	0.355	25.337				
12.700	92.816	0.250	5.456				
9.520	84.859	0.180	1.376				
8.000	80.897	0.125	0.709				
5.600	73.649	0.090	0.480				
4.000	70.583	0.063	0.400				
2.800	67.852						
2.000	65.740						
1.400	63.501						
1.000	60.791						
0.710	55.586						

D_{90} (mm) 11.574	**Description:** Medium-coarse sand with gravel and pebble up to ~20mm. Trace of fines.
D_{50} (mm) 0.609	
D_{10} (mm) 0.274	

Figure E.18 Sediment analysis at Trimingham, location WS7, at a depth of 2.0m

WS9 D2



Sieve Size mm /μm	% Undersize	Sieve Size mm /μm	% Undersize	Sieve Size mm /μm	% Undersize	Sieve Size mm /μm	% Undersize
19.050	100.000	0.500	90.005				
15.880	96.424	0.355	87.762				
12.700	96.424	0.250	80.729				
9.520	96.424	0.180	60.733				
8.000	95.104	0.125	45.193				
5.600	93.372	0.090	42.188				
4.000	92.492	0.063	39.255				
2.800	91.897						
2.000	91.581						
1.400	91.248						
1.000	90.980						
0.710	90.677						

D_{90} (mm)
0.500

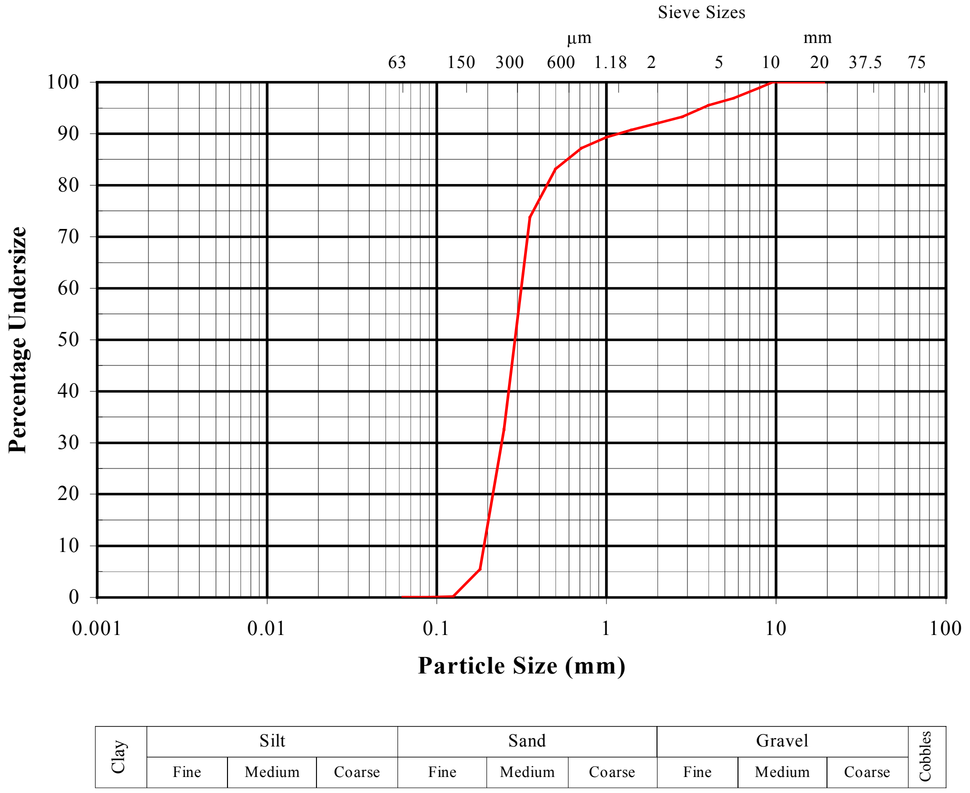
D_{50} (mm)
0.142

D_{10} (mm)
0.016

Description: Fine sand with blue clay. Gravel and pebble up to ~20mm.

Figure E.19 Sediment analysis at Trimingham, location WS9, at a depth of 1.8m

WS11 D1



Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
19.050		0.500	83.194				
15.880		0.355	73.775				
12.700		0.250	32.595				
9.520	100.000	0.180	5.446				
8.000	98.932	0.125	0.182				
5.600	96.932	0.090	0.072				
4.000	95.545						
2.800	93.265						
2.000	92.014						
1.400	90.737						
1.000	89.278						
0.710	87.168						

D_{90} (mm) 1.198

D_{50} (mm) 0.294

D_{10} (mm) 0.192

Description: Clean medium-coarse sand with gravel and pebble up to ~10mm.

Figure E.20 Sediment analysis at Trimingham, location WS11, at a depth of 0m

WS11 D2

Sieve Size mm /μm	% Undersize	Sieve Size mm /μm	% Undersize	Sieve Size mm /μm	% Undersize	Sieve Size mm /μm	% Undersize
19.050		0.500	91.955				
15.880		0.355	90.088				
12.700	100.000	0.250	87.629				
9.520	99.014	0.180	70.936				
8.000	98.198	0.125	42.251				
5.600	97.421	0.090	36.610				
4.000	96.747	0.063	33.959				
2.800	95.860						
2.000	95.334						
1.400	94.775						
1.000	94.266						
0.710	93.439						

D_{90} (mm)
0.351

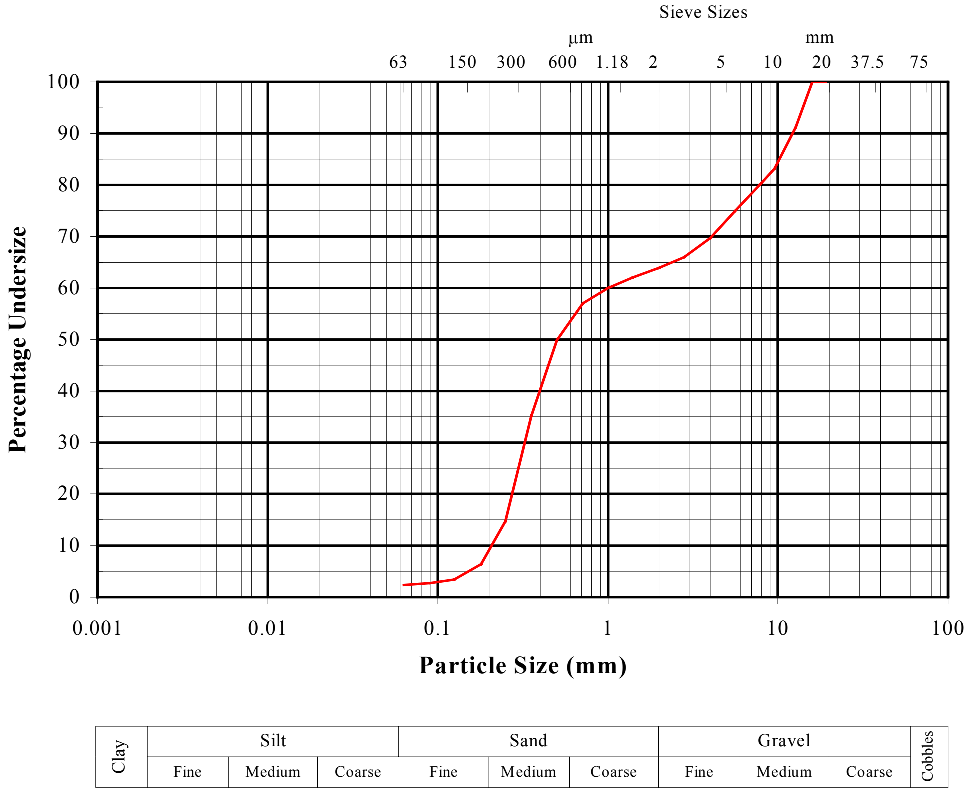
D_{50} (mm)
0.140

D_{10} (mm)
0.019

Description: Muddy fine-medium sand with coarse sand,gravel and pebble up to ~12mm.

Figure E.21 Sediment analysis at Trimingham, location WS11, at a depth of 1.4m

WS11 D3

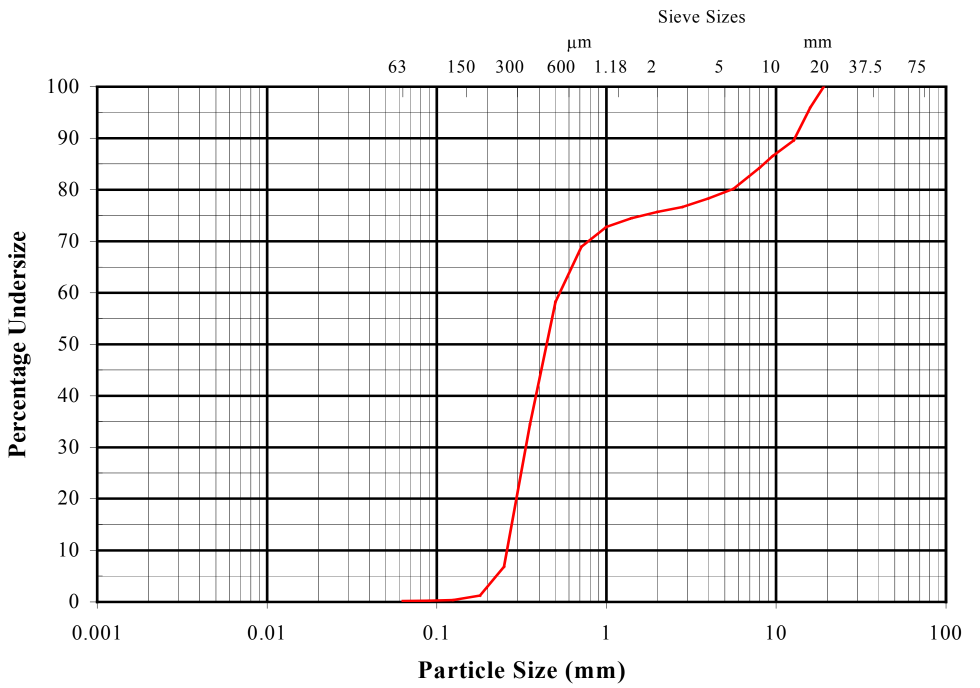


Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
19.050		0.500	49.856				
15.880	100.000	0.355	35.162				
12.700	91.167	0.250	14.726				
9.520	83.207	0.180	6.329				
8.000	80.330	0.125	3.378				
5.600	74.981	0.090	2.696				
4.000	69.696	0.063	2.376				
2.800	65.967						
2.000	63.868						
1.400	61.982						
1.000	60.032						
0.710	57.017						

D_{90} (mm) 12.234	**Description:** Medium-coarse sand with gravel and pebble up to ~15mm. Small amount of fines.
D_{50} (mm) 0.504	
D_{10} (mm) 0.211	

Figure E.22 Sediment analysis at Trimingham, location WS11, at a depth of 2.2m

U1 SS



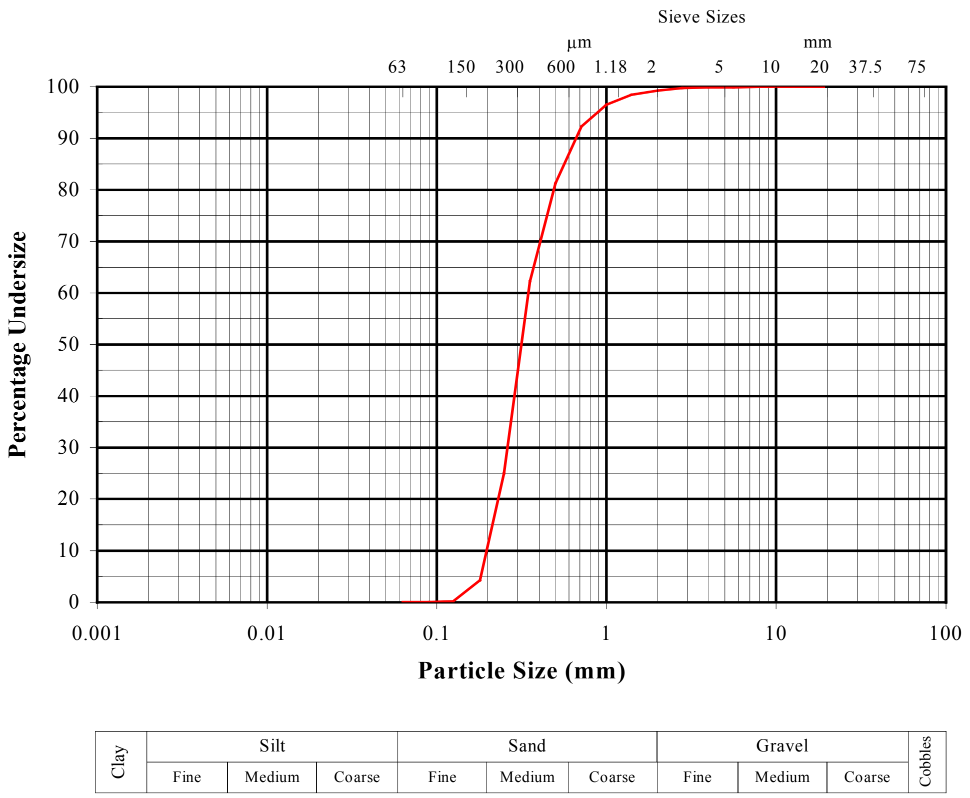
Clay	Silt			Sand			Gravel			Cobbles
	Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse	

Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
19.050	100.000	0.500	58.279				
15.880	95.960	0.355	34.427				
12.700	89.562	0.250	6.842				
9.520	86.511	0.180	1.221				
8.000	84.248	0.125	0.374				
5.600	80.134	0.090	0.245				
4.000	78.348	0.063	0.195				
2.800	76.646						
2.000	75.700						
1.400	74.479						
1.000	72.793						
0.710	68.895						

D_{90} (mm) 12.918	**Description:** Clean medium-coarse sand with gravel and pebble up to ~20 mm
D_{50} (mm) 0.450	
D_{10} (mm) 0.262	

Figure E.23 Sediment analysis at Trimingham, precise location unknown, surface sample

U2 SS



Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
19.050		0.500	81.331				
15.880		0.355	62.243				
12.700		0.250	24.962				
9.520		0.180	4.208				
8.000	100.000	0.125	0.164				
5.600	99.870	0.090	0.057				
4.000	99.870	0.063	0.034				
2.800	99.762						
2.000	99.269						
1.400	98.403						
1.000	96.500						
0.710	92.291						

D_{90} (mm) 0.666

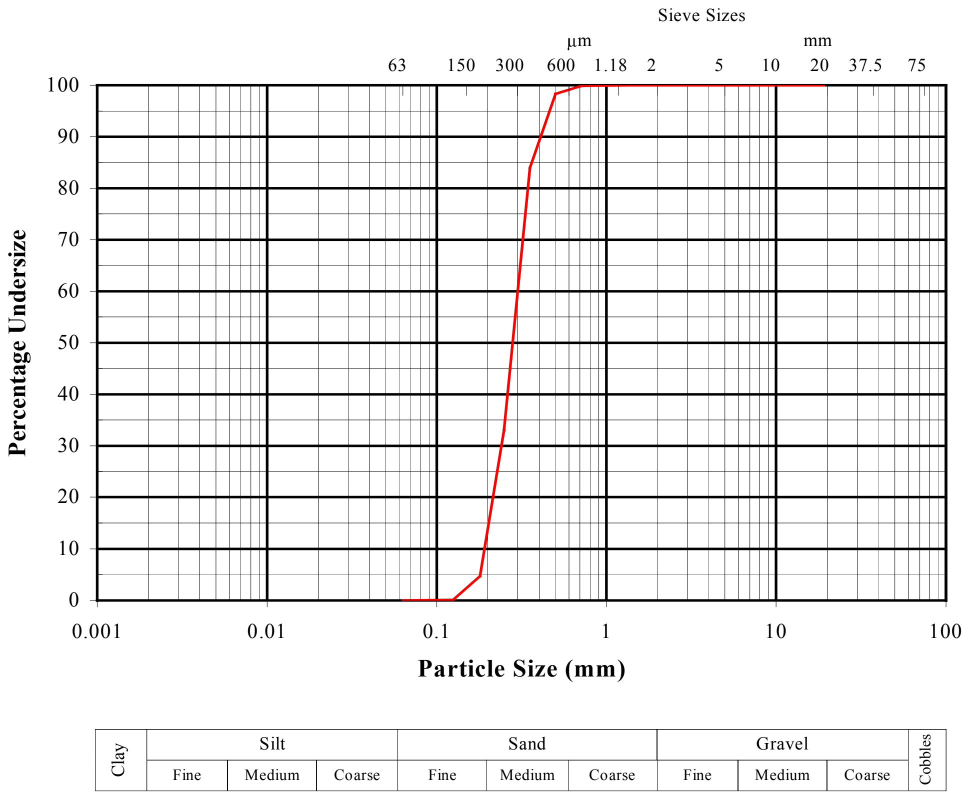
D_{50} (mm) 0.321

D_{10} (mm) 0.200

Description: Clean medium-coarse sand

Figure E.24 Sediment analysis at Trimingham, precise location unknown, surface sample

U3 SS



Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
19.050		0.500	98.324				
15.880		0.355	83.938				
12.700		0.250	33.014				
9.520		0.180	4.748				
8.000		0.125	0.121				
5.600		0.090	0.038				
4.000	100.000	0.063	0.030				
2.800	99.985						
2.000	99.985						
1.400	99.970						
1.000	99.962						
0.710	99.864						

D_{90} (mm) 0.416

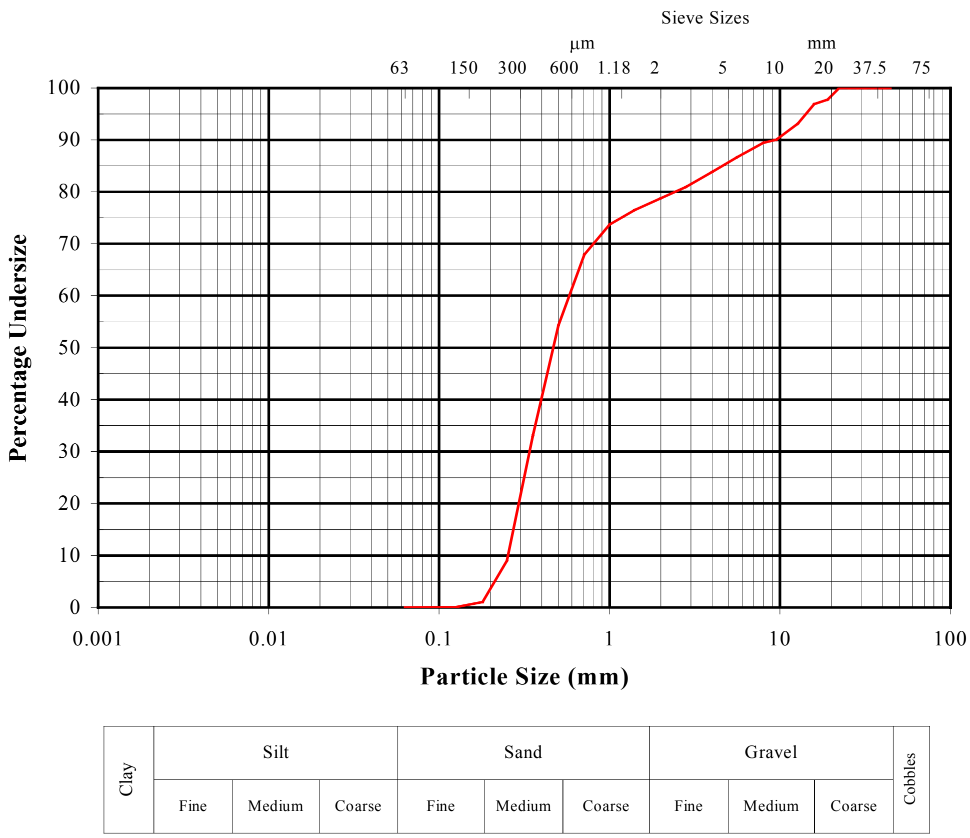
D_{50} (mm) 0.285

D_{10} (mm) 0.193

Description: Clean medium-coarse sand

Figure E.25 Sediment analysis at Trimingham, precise location unknown, surface sample

SS A Lab No 20494



Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	89.394	0.125	0.075		
41.280	100.000	5.600	86.602	0.090	0.034		
38.100	100.000	4.000	83.856	0.063	0.026		
34.930	100.000	2.800	80.935				
31.750	100.000	2.000	78.741				
28.580	100.000	1.400	76.463				
25.400	100.000	1.000	73.769				
22.230	100.000	0.710	67.923				
19.050	97.767	0.500	54.328				
15.880	96.924	0.355	33.020				
12.700	93.121	0.250	8.992				
9.520	90.088	0.180	1.061				

D_{90} (mm) 9.328

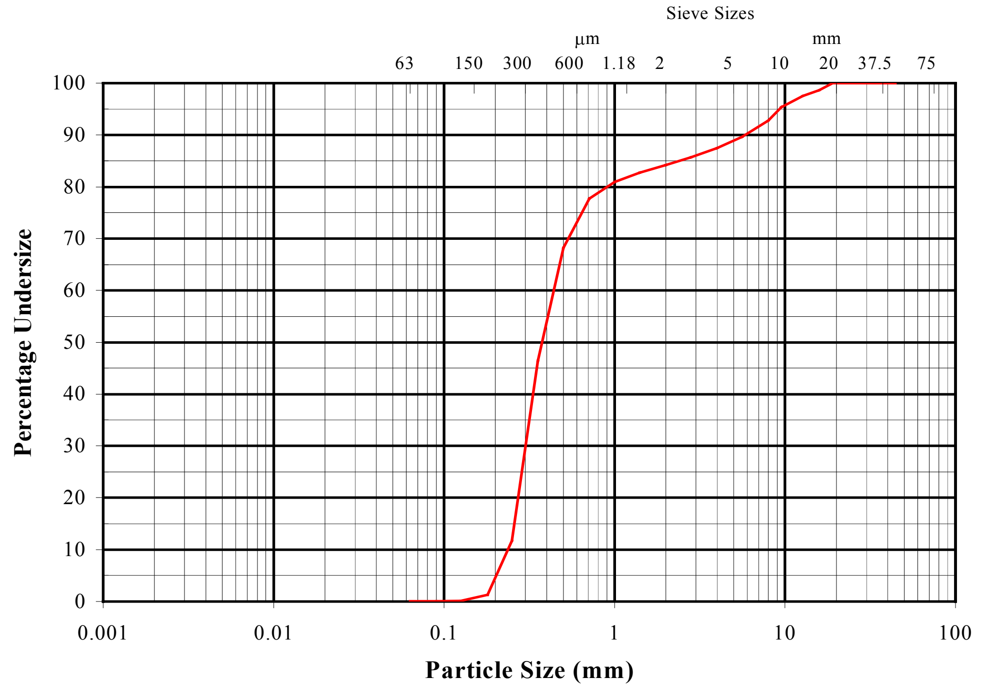
D_{50} (mm) 0.471

D_{10} (mm) 0.254

Description:
Clean medium/coarse sand with gravel and pebble to ~20mm

Figure E.26 Sediment analysis at Walcott, location SS A, surface sample

SS B Lab No 20495



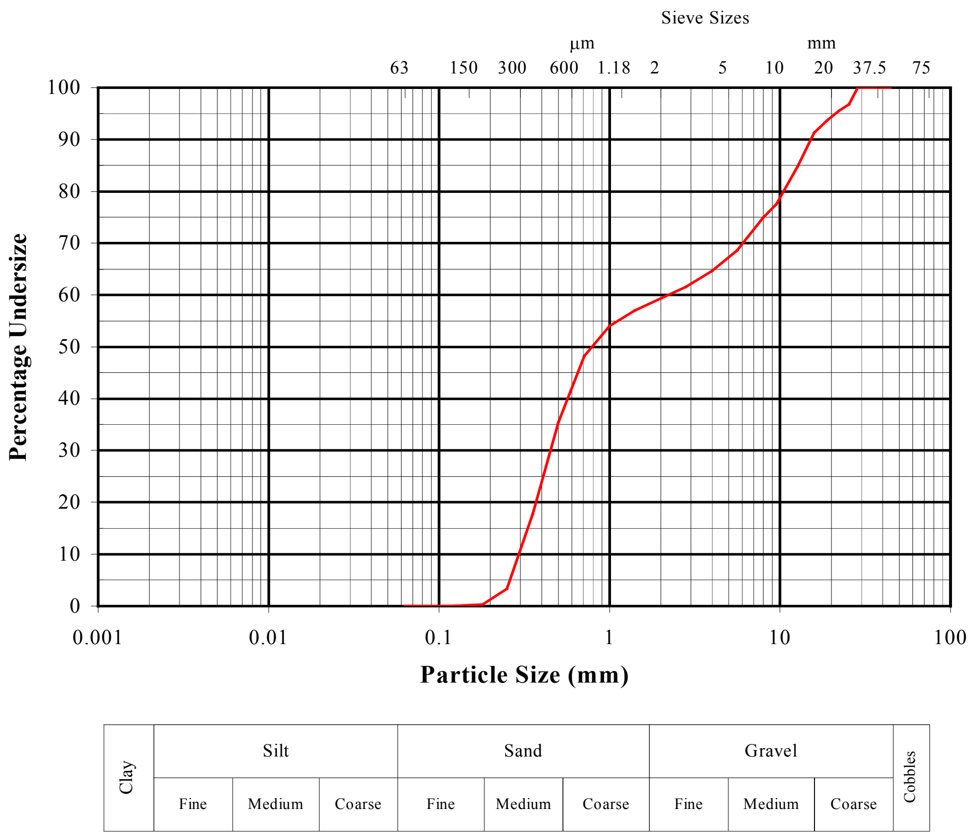
Clay	Silt			Sand			Gravel			Cobbles
	Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse	

Sieve Size mm /μm	% Undersize	Sieve Size mm /μm	% Undersize	Sieve Size mm /μm	% Undersize	Sieve Size mm /μm	% Undersize
44.450	100.000	8.000	92.812	0.125	0.111		
41.280	100.000	5.600	89.639	0.090	0.048		
38.100	100.000	4.000	87.465	0.063	0.041		
34.930	100.000	2.800	85.633				
31.750	100.000	2.000	84.193				
28.580	100.000	1.400	82.719				
25.400	100.000	1.000	80.931				
22.230	100.000	0.710	77.722				
19.050	100.000	0.500	68.213				
15.880	98.674	0.355	46.405				
12.700	97.506	0.250	11.760				
9.520	95.411	0.180	1.274				

D_{90} (mm) 5.873	**Description:** Clean medium/coarse sand with gravel and pebble to ~15mm
D_{50} (mm) 0.379	
D_{10} (mm) 0.238	

Figure E.27 Sediment analysis at Walcott, location SS B, surface sample

SS C Lab No 20496

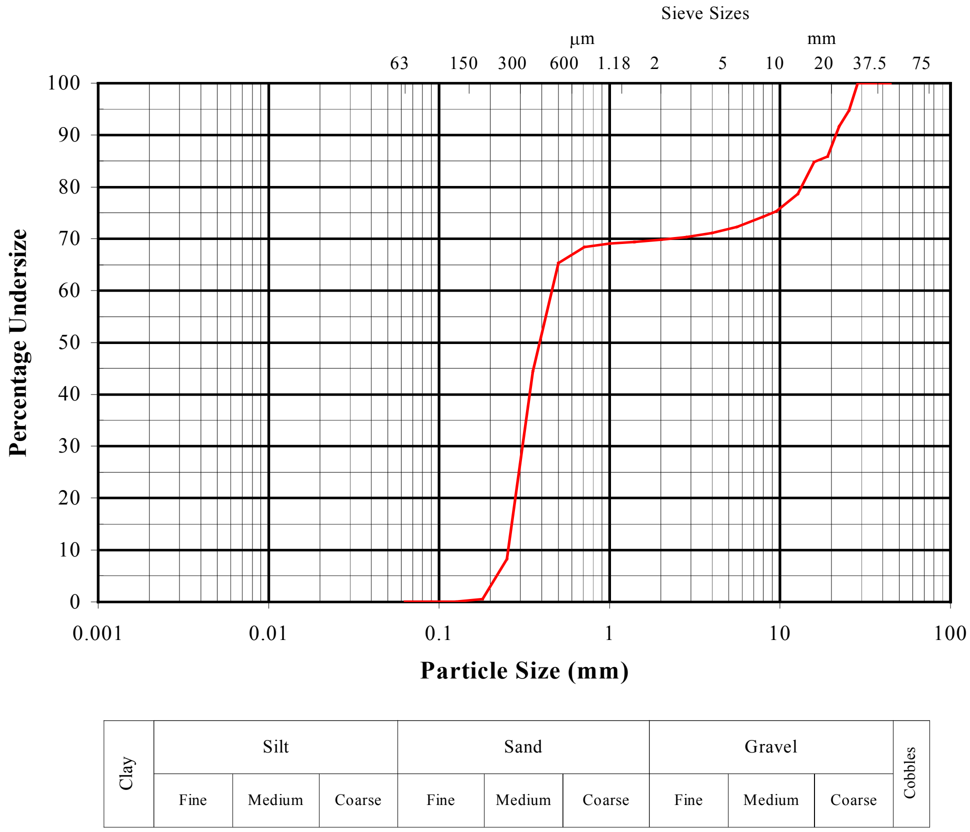


Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	74.968	0.125	0.044		
41.280	100.000	5.600	68.608	0.090	0.028		
38.100	100.000	4.000	64.646	0.063	0.022		
34.930	100.000	2.800	61.564				
31.750	100.000	2.000	59.348				
28.580	100.000	1.400	56.969				
25.400	96.796	1.000	54.018				
22.230	95.556	0.710	48.204				
19.050	93.789	0.500	35.424				
15.880	91.315	0.355	17.822				
12.700	84.850	0.250	3.311				
9.520	77.565	0.180	0.318				

D_{90} (mm) 15.233	**Description:** Clean medium/coarse sand with gravel and pebble to ~30mm
D_{50} (mm) 0.800	
D_{10} (mm) 0.298	

Figure E.28 Sediment analysis at Walcott, location SS C, surface sample

SS D Lab No 20497

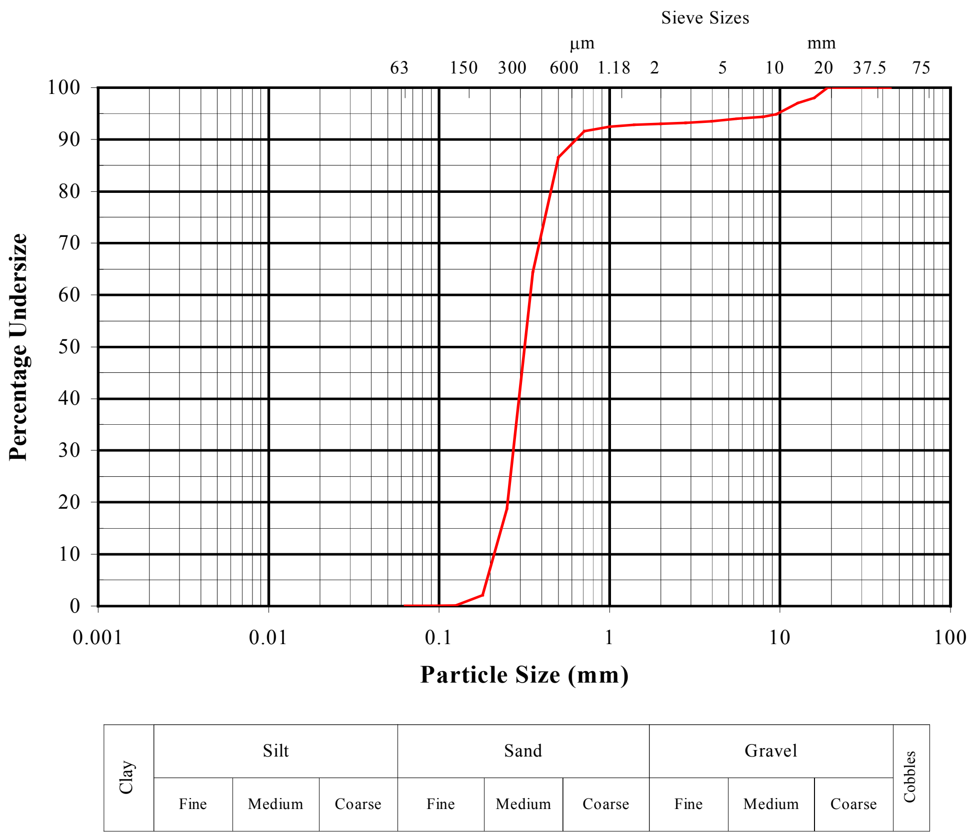


Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	74.313	0.125	0.056		
41.280	100.000	5.600	72.319	0.090	0.036		
38.100	100.000	4.000	71.169	0.063	0.032		
34.930	100.000	2.800	70.282				
31.750	100.000	2.000	69.798				
28.580	100.000	1.400	69.408				
25.400	94.707	1.000	69.057				
22.230	91.671	0.710	68.420				
19.050	85.873	0.500	65.329				
15.880	84.808	0.355	44.431				
12.700	78.653	0.250	8.282				
9.520	75.304	0.180	0.525				

D_{90} (mm) 21.314	**Description:** Clean medium/coarse sand with gravel and pebble to ~30mm
D_{50} (mm) 0.394	
D_{10} (mm) 0.255	

Figure E.29 Sediment analysis at Walcott, location SS D, surface sample

SS E Lab No 20498



Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	94.385	0.125	0.109		
41.280	100.000	5.600	93.998	0.090	0.053		
38.100	100.000	4.000	93.528	0.063	0.049		
34.930	100.000	2.800	93.253				
31.750	100.000	2.000	93.017				
28.580	100.000	1.400	92.835				
25.400	100.000	1.000	92.502				
22.230	100.000	0.710	91.619				
19.050	100.000	0.500	86.589				
15.880	98.022	0.355	64.452				
12.700	97.024	0.250	18.777				
9.520	94.873	0.180	2.137				

D_{90} (mm)
0.642

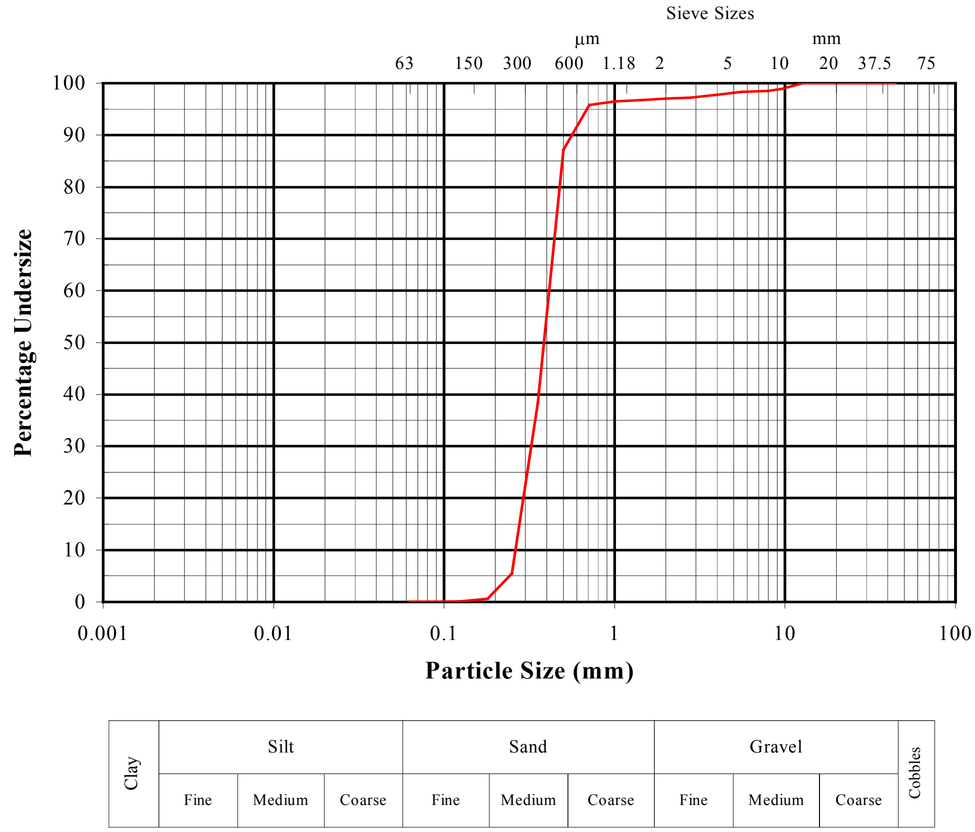
D_{50} (mm)
0.322

D_{10} (mm)
0.213

Description:
Clean medium sand with gravel and pebble to ~15mm

Figure E.30 Sediment analysis at Walcott, location SS E, surface sample

SS F Lab No 20499

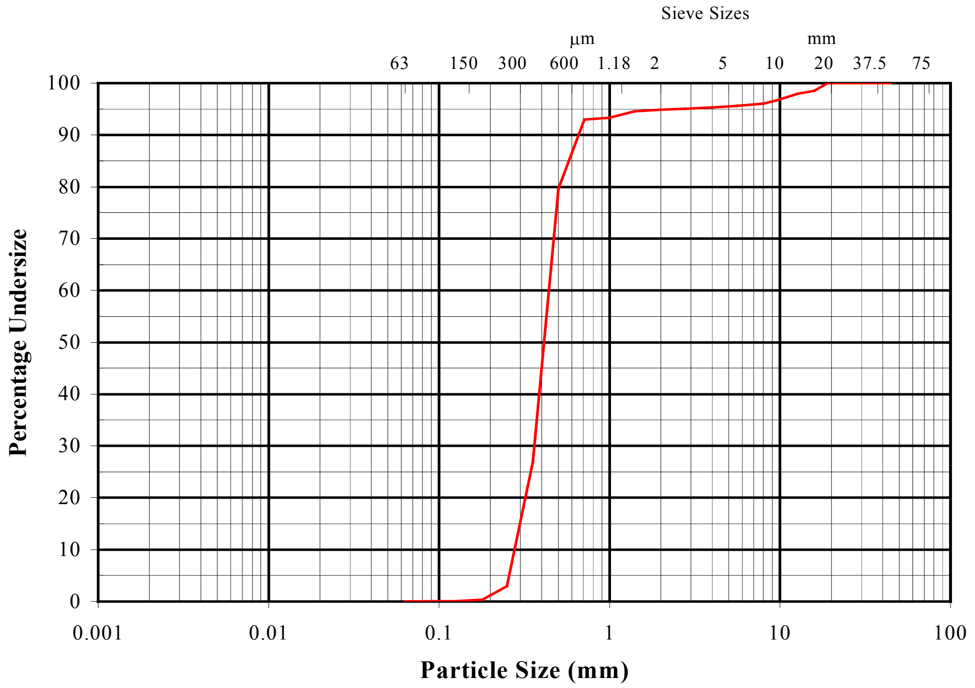


Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	98.573	0.125	0.126		
41.280	100.000	5.600	98.311	0.090	0.072		
38.100	100.000	4.000	97.745	0.063	0.054		
34.930	100.000	2.800	97.241				
31.750	100.000	2.000	97.051				
28.580	100.000	1.400	96.751				
25.400	100.000	1.000	96.489				
22.230	100.000	0.710	95.808				
19.050	100.000	0.500	87.177				
15.880	100.000	0.355	38.380				
12.700	100.000	0.250	5.531				
9.520	98.917	0.180	0.599				

D_{90} (mm) 0.569	**Description:** Clean medium sand with gravel to ~15mm
D_{50} (mm) 0.390	
D_{10} (mm) 0.264	

Figure E.31 Sediment analysis at Walcott, location SS F, surface sample

SS G Lab No 20500



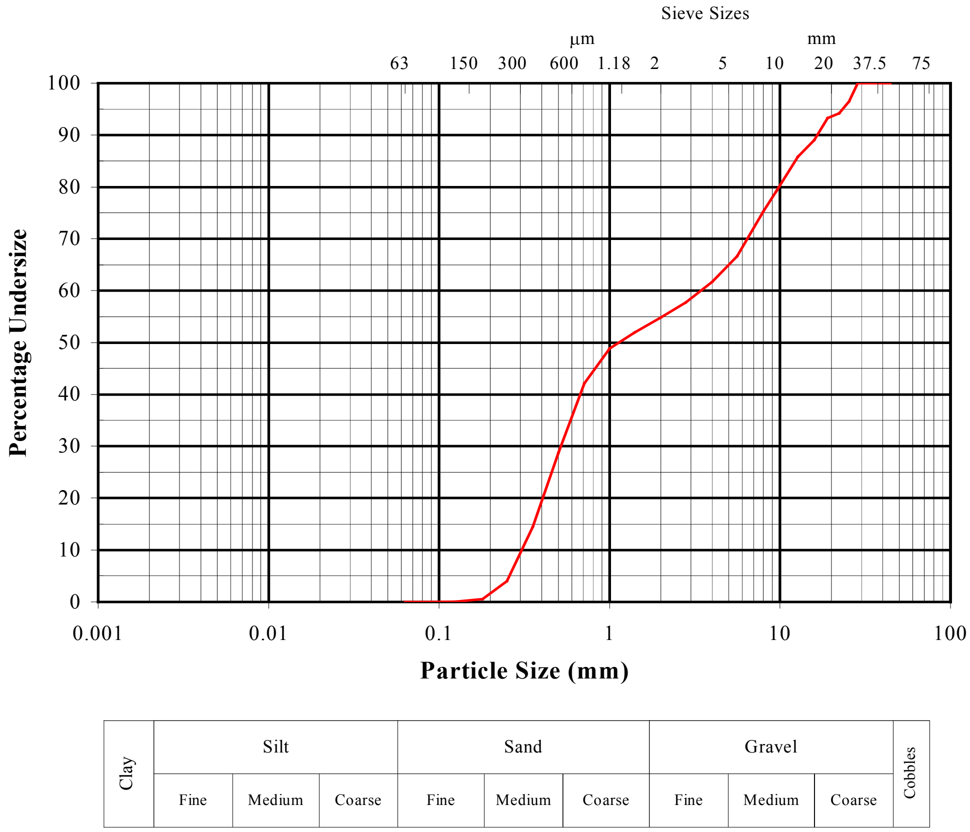
Clay	Silt			Sand			Gravel			Cobbles
	Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse	

Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	96.059	0.125	0.052		
41.280	100.000	5.600	95.628	0.090	0.033		
38.100	100.000	4.000	95.268	0.063	0.025		
34.930	100.000	2.800	95.061				
31.750	100.000	2.000	94.845				
28.580	100.000	1.400	94.584				
25.400	100.000	1.000	93.342				
22.230	100.000	0.710	92.981				
19.050	100.000	0.500	79.625				
15.880	98.521	0.355	26.919				
12.700	97.948	0.250	2.993				
9.520	96.643	0.180	0.379				

D_{90} (mm) 0.663	**Description:** Clean medium sand with gravel and pebble to ~15mm Two cobbles ~75mm not included in analysis.
D_{50} (mm) 0.418	
D_{10} (mm) 0.281	

Figure E.32 Sediment analysis at Bacton, location SS G, surface sample

SS H Lab No 20501

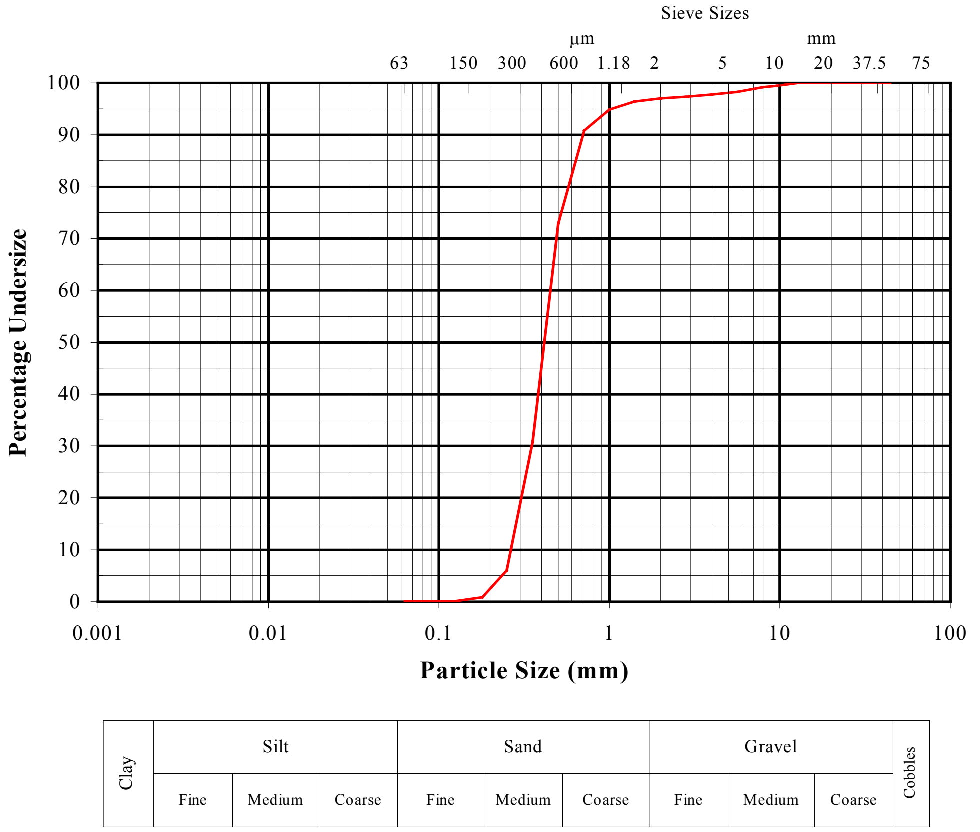


Sieve Size mm /μm	% Undersize	Sieve Size mm /μm	% Undersize	Sieve Size mm /μm	% Undersize	Sieve Size mm /μm	% Undersize
44.450	100.000	8.000	75.248	0.125	0.034		
41.280	100.000	5.600	66.586	0.090	0.021		
38.100	100.000	4.000	61.733	0.063	0.019		
34.930	100.000	2.800	57.739				
31.750	100.000	2.000	54.831				
28.580	100.000	1.400	51.975				
25.400	96.486	1.000	48.877				
22.230	94.196	0.710	42.132				
19.050	93.288	0.500	28.715				
15.880	88.959	0.355	14.512				
12.700	85.803	0.250	3.993				
9.520	79.203	0.180	0.535				

D_{90} (mm) 16.642	**Description:** Clean medium/coarse sand with gravel and pebble to ~25mm
D_{50} (mm) 1.145	
D_{10} (mm) 0.310	

Figure E.33 Sediment analysis at Bacton, location SS H, surface sample

SS I Lab No 20502



Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize	Sieve Size mm / μm	% Undersize
44.450	100.000	8.000	99.189	0.125	0.119		
41.280	100.000	5.600	98.259	0.090	0.090		
38.100	100.000	4.000	97.755	0.063	0.088		
34.930	100.000	2.800	97.310				
31.750	100.000	2.000	97.013				
28.580	100.000	1.400	96.415				
25.400	100.000	1.000	94.859				
22.230	100.000	0.710	90.811				
19.050	100.000	0.500	72.908				
15.880	100.000	0.355	30.830				
12.700	100.000	0.250	6.022				
9.520	99.467	0.180	0.828				

D_{90} (mm) 0.700	**Description:** Clean medium sand with gravel to ~10mm
D_{50} (mm) 0.421	
D_{10} (mm) 0.267	

Figure E.34 Sediment analysis at Bacton, location SS I, surface sample