



**Intertidal and Subtidal Benthic Studies
in Broadmeadow Estuary
August 2008**

Produced by

AQUAFACT International Services Ltd

On behalf of

PH McCarthy Consulting Engineers

AQUAFACT INTERNATIONAL SERVICES Ltd
12 KILKERRIN park
TUAM rd
GALWAY city
0H www.aquafact.ie

info@aquafact.ie

tel +353 (0) 91 756812
fax +353 (0) 91 756888

Table of Contents

1. Introduction	1
2. Methods.....	3
2.1. Subtidal Survey	3
2.1.1. Sampling Procedure & Sample Processing	3
2.1.2. Data Processing.....	6
2.1.2.1. Fauna	6
2.1.2.2. Sediment	8
2.1.3. Sediment Profile Imagery (SPI).....	9
2.2. Intertidal Survey	10
3. Results	13
3.1. Subtidal	13
3.1.1. Fauna	13
3.1.1.1. Univariate Analysis	13
3.1.1.2. Multivariate Analysis.....	14
3.1.2. Sediment	17
3.1.3. Sediment Profile Imagery.....	20
3.1.3.1. Sediment type	22
3.1.3.2. Mean prism penetration depth.....	22
3.1.3.3. Sediment surface boundary roughness.....	22
3.1.3.4. Apparent redox potential discontinuity (aRPD).....	23
3.1.3.5. Infaunal Successional stage & bioturbation depth.....	23
3.1.3.6. Additional biological information	24
3.2. Intertidal.....	25
3.2.1. Transect 1	25
3.2.2. Transect 2	32
3.2.3. Transect 3	39
4. Discussion	46
4.1. Subtidal	46
4.2. Intertidal.....	48

REFERENCES

List of Figures

Figure 1.1 Location of Broadmeadow Estuary, Co. Dublin	2
Figure 2.1: Locations of the 11 stations sampled in Broadmeadow Estuary on the 20 th and 21 st August 2008.....	4
Figure 2.2: Intertidal transects sampled in Broadmeadow Estuary on the 20 th and 21 st August 2008.	11
Figure 3.1: Dendrogram showing each station from the 11 stations sampled in Broadmeadow Estuary on the 20 th and 21 st August 2008.	15
Figure 3.2: MDS ordination showing each station from the 11 stations sampled in Broadmeadow Estuary on the 20 th and 21 st August 2008.	15
Figure 3.3: Sediment particle size distribution at each of the 11 stations sampled in Broadmeadow Estuary in August 2008.....	18
Figure 3.4: PCA ordination of the environmental data sampled at 11 stations in Broadmeadow Estuary in August 2008.....	20
Figure 3.5: Profile of the shore along Transect 1.....	25
Figure 3.6: View across Transect 2 with the slope profile superimposed.....	32
Figure 3.7: View across Transect 3 from the low tide station.....	39

List of Tables

Table 2.1: Coordinates of the 11 stations sampled in Broadmeadow Estuary on the 20 th and 21 st August 2008.....	4
Table 2.2: The classification of sediment particle size ranges into size classes.	5
Table 2.3: Intertidal station coordinates sampled in Broadmeadow Estuary on the 20 th and 21 st August 2008.....	12
Table 3.1: Diversity indices for the 11 stations sampled in Broadmeadow Estuary on the 20 th and 21 st August 2008.	14
Table 3.2: Granulometry results for the 11 stations sampled in Broadmeadow Estuary in August 2008.	18
Table 3.3: Organic carbon results for the 11 stations sampled in Broadmeadow Estuary on the 20 th and 21 st August 2008.....	19
Table 3.4. SPI parameters measured from images from the stations in Broadmeadow Estuary, August 2008	21

List Of Plates

Plate 3-1: Saltmarsh (LS.LMp.Sm) located in the strandline of Transect 1.....	26
Plate 3-2: Strandline station (LS.LSa.MoSa.OI.VS) along Transect 1.	27
Plate 3-3: View of the upper shore along Transect 1.....	28

Plate 3-4: Upper shore station (LS.LSa.MoSa.OI.VS) along Transect 1.....	28
Plate 3-5: View of the middle shore along Transect 1.	29
Plate 3-6: Middle shore station (LS.LMx.GvMu.HedMx.Cir) along Transect 1.....	30
Plate 3-7: View of the lower shore along Transect 1.....	31
Plate 3-8: Lower shore station (LS.LSa.MuSa.Lan) along Transect 1.....	31
Plate 3-9: Strandline and upper shore of Transect 2.	33
Plate 3-10: Bank of rock at the strandline along Transect 2 (LR.FLR.Lic.YG).	34
Plate 3-11: Strandline station, Transect 2 (T2S1).....	34
Plate 3-12: Upper shore station (LS.LMx.LMus.Myt.Sa/ LS.LSa.MoSa.OI.VS) along Transect 2.....	35
Plate 3-13: View of the middle shore along Transect 2.	36
Plate 3-14: Middle shore station (LS.LSa.MoSa.OI.VS) along Transect 2.....	37
Plate 3-15: View of the lower shore along Transect 2.....	38
Plate 3-16: Lower shore station (LR.LLR.FVS.FserVS) along Transect 2.....	38
Plate 3-17: Strandline and upper shore of Transect 3.	40
Plate 3-18: Strandline station along Transect 3 (LS.LSa.MoSa.OI.VS).	40
Plate 3-19: View of the upper shore along Transect 3.	41
Plate 3-20: Upper shore station (LS.LSa.MoSa.OI.VS) along Transect 3.....	42
Plate 3-21: View of the middle shore along Transect 3.	43
Plate 3-22: Middle shore station (LS.LSa.MoSa.OI.VS) along Transect 3.....	43
Plate 3-23: View of the lower shore along Transect 3.....	44
Plate 3-24: Lower shore station (LS.LSa.MoSa.OI.VS) along Transect 3.....	45

List of Appendices

Appendix A	Subtidal Species List
Appendix B	SIMPER Results
Appendix C	Sediment Profile Imagery (SPI) Results, Apparatus and Data Analysis
Appendix D	Intertidal Sediment Results
Appendix E	Intertidal Species List
Appendix F	cSAC Site Synopsis

1. Introduction

Broadmeadow Estuary is situated immediately north of Malahide and east of Swords, Co Dublin (Figure 1.1). The estuary is divided by a railway viaduct built in the 1800s. The outer part of the estuary, which is mostly cut off from the sea by a large sand spit, known as "the island", drains almost completely at low tide, exposing sand and mud flats. The inner part of the estuary does not drain due to a weir located under the railway viaduct and is essentially a shallow, artificial lagoon.

The main freshwater input is from the Broadmeadow River and the outfall that flows into it (see Figure 2.1) but there are also contributions from streams at Barrack Hill and Newport House and a few smaller inflows from streams and drainage pipes on the south bank (Healy *et al*, 1993).

Broadmeadow Estuary is an important site for wintering waterfowl providing both feeding and roosting areas for a range of species. It is designated as a RAMSAR site (Broadmeadow Estuary; 833), a Special Protection Area (Broadmeadow/Swords Estuary SPA; 004025) and an Important Bird Area (Malahide/Broadmeadow Estuary; IE113). In addition, Broadmeadow Estuary is a Special Area of Conservation (SAC) (Rogerstown Estuary; 000205) and a proposed Natural Heritage Area (pNHA) (Rogerstown Estuary; 000205). Broadmeadow Estuary is a fine example of an estuarine system and includes the following habitats: saltmarsh, salt meadows, rocky shores, sand dunes, *Zostera* beds, sand flats and mud flats.

Fingal County Council would like to increase the capacity of the Swords wastewater treatment works located at the top of the estuary (see Figure 2.1). Given the importance of Broadmeadow estuary, an appropriate assessment of the impact of any increase in input to the water body needed to be carried out. However, there has been few surveys detailing the faunal communities within the estuary. In 1998 AQUAFACT carried out a broadscale survey of the estuary outlining the habitats within the estuary (Aquafact, 1998). Prior to that, Healey *et al.*(1993) carried out an environmental impact study of the Inner Estuary in relation to construction of a motorway bridge at the head of the estuary. A more recent description of the faunal communities was required and consequently, AQUAFACT International Services Ltd

was commissioned to carry out intertidal and subtidal benthic studies in the Broadmeadow Estuary as specified in the invitation to tender document issued by P. H. McCarthy Consulting Engineers on behalf of Fingal County Council. The following report details the results of this study.

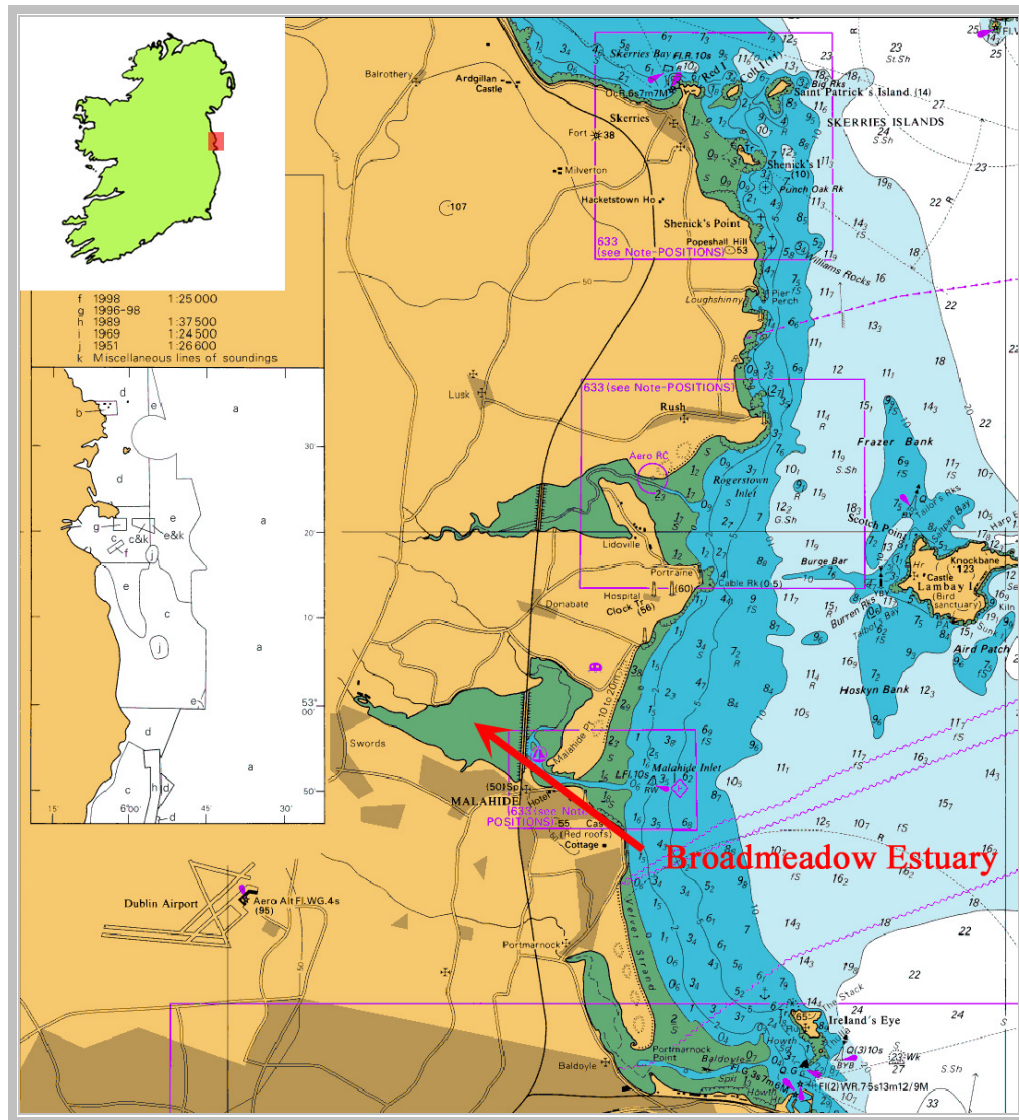


Figure 1.1 Location of Broadmeadow Estuary, Co. Dublin

2. Methods

2.1. Subtidal Survey

2.1.1. Sampling Procedure & Sample Processing

Eleven subtidal stations were sampled in the Broadmeadow Estuary on the 20th and 21st August 2008. The locations of the stations are shown in Figure 2.1 while station coordinates are given in Table 2.1. Station positions were recorded by means of a Trimble GeoXT, which is capable of sub-meter horizontal accuracy using real time corrections from the integrated EGNOS (European Geostationary Navigation Overlay System) receiver. A 0.025m² van Veen was used to collect three replicate benthic samples at each of the 11 stations. Data on each sample, e.g. station number, date, time, depth of sediment, surface features and visible macrofauna were logged in a field notebook. The faunal returns were sieved on a 1 mm mesh sieve, stained with Rhodamine dye, fixed with 10% buffered formalin and preserved in 70% alcohol. Samples were then sorted under a microscope (x 10 magnification), into four main groups: Polychaeta, Mollusca, Crustacea and others. The 'others' group consisted of nematodes, insects and other lesser phyla. The taxa were then identified to species level where possible.

An additional sample was taken at each station and used for sediment analyses. The sediment samples were taken through the opening on the top of the grab. Two sub samples were collected from each sample, one for organic carbon analysis and a second for granulometric analysis. Both sub-samples were collected using a plastic spoon and placed in labelled plastic bags. All samples were stored immediately in a cold box on board the vessel and were frozen on return to the lab.



Figure 2.1: Locations of the 11 stations sampled in Broadmeadow Estuary on the 20th and 21st August 2008.

Station	Latitude	Longitude
1	53° 27.15340'	-6° 8.75376'
2	53° 27.21219'	-6° 9.01024'
3	53° 27.31060'	-6° 9.73837'
4	53° 27.54931'	-6° 9.64697'
5	53° 27.75262'	-6° 9.60976'
6	53° 27.89775'	-6° 9.77308'
7	53° 27.95848'	-6° 10.37788'
8	53° 27.70428'	-6° 10.44028'
9	53° 27.55572'	-6° 10.71642'
10	53° 27.77796'	-6° 10.99608'
11	53° 27.78122'	-6° 11.51523'

Table 2.1: Coordinates of the 11 stations sampled in Broadmeadow Estuary on the 20th and 21st August 2008.

Granulometric analysis was carried out on one aliquot of each sediment sample as described by Folk (1974). A 30-ml solution of aqueous sodium hexametaphosphate (6.2 g/l) was added to 100 g of oven-dried (100°C) sediment; the mixture was made up to 1 litre with distilled water, stirred mechanically for 15 min and allowed to stand overnight. This mixture was then re-stirred and washed through a 63-µm sieve. The material that passed through the sieve was regarded as the silt–clay fraction. The remaining contents were regarded as the sand fraction. This fraction was oven-dried at 100°C and weighed, and the silt–clay fraction determined by subtraction. The sand fraction was graded through a nest of sieves of 4, 2, 1 mm and 500-, 250-, 125-, and 63-µm mesh. Each grade was weighed and the value expressed as a percentage of the total dry weight of the sample. Material passing through the 63 µm mesh was added to the silt–clay fraction. Table 2.2 shows the classification of sediment particle ranges into size classes.

Range of Particle Size	Classification	Phi Unit
<63 µm	Silt/Clay	4.5 Ø-8 Ø
63-125 µm	Very Fine Sand	3.5 Ø, 4 Ø
125-250 µm	Fine Sand	3 Ø, 2.5 Ø
250-500 µm	Medium Sand	2 Ø, 1.5 Ø
500-1000 µm	Coarse Sand	1 Ø, 0.5 Ø
1000-2000 µm	Very Coarse Sand	0 Ø, -0.5 Ø
>2000 µm	Gravel	-1 Ø, -1.5 Ø, -2 Ø, -3 Ø, -4 Ø

Table 2.2: The classification of sediment particle size ranges into size classes.

Organic carbon analysis was carried out by OMAC Labs, using an Eltra Carbon and Sulphur Analyzer. This involved weighing 0.2g of the sample into a filtering crucible and treating it with dilute hydrochloric acid to decompose carbonate materials. The crucible and treated sample is then dried at 105°C and the carbon concentration is measured using the Eltra Carbon and Sulphur Analyzer. The concentration measured represents carbon present in non-carbonate (organic) form.

2.1.2. Data Processing

2.1.2.1. Fauna

All faunal replicates were combined for each station for univariate analyses and averaged for each station for multivariate analyses. Data matrices of all the faunal data were compiled and later used for statistical analyses using the Primer ® (Plymouth Routines in Multivariate Ecological Research) programme.

Univariate statistics in the form of diversity indices were calculated. The following diversity indices were calculated:

- 1) Margalef's species richness index (D), (Margalef, 1958).

$$D = \frac{S-1}{\log_2 N}$$

where: N is the number of individuals

S is the number of species

- 2) Pielou's Evenness index (J), (Pielou, 1977).

$$J = \frac{H'(\text{observed})}{H'_{\max}}$$

where: H'_{\max} is the maximum possible diversity, which could be achieved if all species were equally abundant ($= \log_2 S$)

- 3) Shannon-Wiener diversity index (H'), (Pielou, 1977).

$$H' = - \sum_{i=1}^S p_i (\log_2 p_i)$$

where: p_i is the proportion of the total count accounted for by the i^{th} taxa

Species richness is a measure of the total number of species present for a given number of individuals. Evenness is a measure of how evenly the individuals are distributed among different species. The diversity index incorporates both of these parameters. Richness ranges from 0 (low richness) to 12 (high richness), evenness ranges from 0 (low evenness) to 1 (high evenness), diversity ranges from 0 (low diversity) to 5 (high diversity).

The PRIMER ® programme (Clarke & Warwick, 2001) was used to carry out multivariate analyses on the station-by-station faunal data. This was done for all surveys individually and on the combined survey data. All species/abundance data were fourth root transformed and used to prepare a Bray-Curtis similarity matrix in PRIMER ®. The fourth root transformation was used in order to down-weight the importance of the highly abundant species and to allow the mid-range and rarer species to play a part in the similarity calculation. The similarity matrix was then used in classification/cluster analysis. This aim of this analysis was to find “natural groupings” of samples, i.e. samples within a group that are more similar to each other, than they are similar to samples in different groups (Clarke & Warwick, *loc. cit.*). The PRIMER ® programme CLUSTER carried out this analysis by successively fusing the samples into groups and the groups into larger clusters, beginning with the highest mutual similarities then gradually reducing the similarity level at which groups are formed. The result is represented graphically in a dendrogram, the x-axis representing the full set of samples and the y-axis representing similarity levels at which two samples/groups are said to have fused.

The Bray-Curtis similarity matrix was also subjected to a non-metric multi-dimensional scaling (MDS) algorithm (Kruskal & Wish, 1978), using the PRIMER ® programme MDS. This programme produces an ordination, which is a map of the samples in two- or three-dimensions, whereby the placement of samples reflects the similarity of their biological communities, rather than their simple geographical location (Clarke & Warwick, 2001). With regard to stress values, they give an indication of how well the multi-dimensional similarity matrix is represented by the two-dimensional plot. They are calculated by comparing the interpoint distances in the similarity matrix with the corresponding interpoint distances on the 2-d plot. Perfect or near perfect matches are rare in field data, especially in the absence of a single overriding forcing factor such as an organic enrichment gradient. Stress values increase, not only with the reducing dimensionality (lack of clear forcing structure), but also with increasing quantity of data (it is a sum of the squares type regression coefficient). Clarke and Warwick (*loc. cit.*) have provided a classification of the reliability of MDS plots based on stress values, having compiled simulation studies of stress value behaviour and archived empirical data. This classification generally holds well for 2-d ordinations of the type used in this study. Their classification is given below:

- Stress value < 0.05: Excellent representation of the data with no prospect of misinterpretation.
- Stress value < 0.10: Good representation, no real prospect of misinterpretation of overall structure, but very fine detail may be misleading in compact subgroups.
- Stress value < 0.20: This provides a useful 2-d picture, but detail may be misinterpreted particularly nearing 0.20.
- Stress value 0.20 to 0.30: This should be viewed with scepticism, particularly in the upper part of the range, and discarded for a small to moderate number of points such as < 50.
- Stress values > 0.30: The data points are close to being randomly distributed in the 2-d ordination and not representative of the underlying similarity matrix.

Each stress value must be interpreted both in terms of its absolute value and the number of data points. In the case of this study, the moderate number of data points indicates that the stress value can be interpreted more or less directly. While the above classification is arbitrary, it does provide a framework that has proved effective in this type of analysis.

The species, which were responsible for the grouping of samples in cluster and ordination analyses, were identified using the PRIMER® programme SIMPER (Clarke & Warwick, 1994). This programme determined the percentage contribution of each species to the dissimilarity/similarity within and between each sample group. Only two groups of samples were compared at a time and the influential species were identified for each specific comparison.

2.1.2.2. *Sediment*

A procedure similar to multi-dimensional scaling (MDS) was carried out on the sediment data. The procedure is known as principal component analysis (PCA) and it is a 2D/3D ordination. Like MDS, it is based on an underlying (dis)similarity matrix; however in this case it is a Euclidean distance dissimilarity matrix not a Bray-Curtis similarity matrix. The data matrix used for PCA included all of the environmental parameters, i.e. sediment particle size percentage distributions (% sand, %silt-clay

etc) and sediment organic carbon concentrations. This dataset was transformed to prevent any outliers having a disproportionate influence on the results. The organic carbon values were \log_{10} transformed. The sediment particle size percentage distributions were Arcsin transformed. If any significant (pairwise correlation >0.95) correlations existed between variables, only one variable from that correlated group was included in the analysis, to prevent the correlation being exaggerated in the analysis. Following the transformations, the data were normalised to equalise the variance and standardise the contributory importance of each variable. The resulting data matrix was subjected to a correlation based PCA using the PRIMER® program PCA (Clarke & Warwick, 1994), to identify the parameters that accounted for a large proportion of the variance in the original data set. The variances of the principal components (eigen values), the proportion and cumulative proportion of the total variance, explained by each principal component, and the coefficients for each principal component (eigen vectors) were calculated. A two-dimensional PCA ordination of the data was constructed. The PCA plot defined the positions of samples in relation to each axes, which represented the full set of variables. Each station acquired a place on this graph and the location depended on a number of variables significant to that station and which set it apart from all the rest.

2.1.3. Sediment Profile Imagery (SPI)

In order to examine the nature of the seafloor, Sediment Profile Imagery (SPI) was employed. Using SPI, one can deduce the dynamics of biological and physical seafloor processes from imaged structures. The SPI camera differs from other underwater cameras in that it effects a vertical profile of the sediment water interface and obtains a photographic image of that profile. Since the SPI camera obtains images of the undisturbed sediment *in situ*, it delivers information on benthic processes that is not readily available using many conventional sampling tools. Furthermore, as the object being photographed is directly against the faceplate of the camera assembly, water turbidity is never a limiting factor.

Sediment Profile Imaging (SPI) can remotely identify the successional status of the seafloor and also has the potential to document its maintenance, development and/or destruction over time. With experience, both the physical and biological forces responsible for maintaining or driving a succession (e.g. bottom erosion or deposition, changes in substratum type, relative changes in levels of dissolved

oxygen, organic decomposition processes, etc.) can also be detected with confidence. This also applies to chemical driving forces where sensing probes are used in conjunction with the SPI instrument. A great deal of information about benthic processes is available from sediment profile images and while certain features (e.g. deep-living infaunal forms) may escape direct observation on the SPI images, their presence can typically be inferred from their impacts on the sediment structure.

Sediment parameters that can be measured from each image include:

1. sediment type (generally measured from the upper 5 cm sediment layer);
2. prism penetration depth which gives an indication of relative sediment compaction, softness and/or coarseness;
3. sediment boundary roughness which indicates the degree of physical disturbance or biotic activity at the sediment water boundary;
4. sediment apparent redox potential discontinuity depth (aRPD), allows the apparent depth of oxygen into bottom sediments to be determined;
5. infaunal successional status which qualifies the type of animals living in the bottom;
6. additional parameters such as the presence of mud clasts, epifauna (surface living animals), infaunal burrows and tubes, gas pockets and outgassing of sediments (due to production of hydrogen sulphide and ammonia as by-products of anaerobic metabolism) etc.;

A full description of the SPI camera and SPI data analysis is provided in Appendix C.

2.2. Intertidal Survey

Three intertidal transects were sampled in the Broadmeadow Estuary on the 20th and 21st August 2008 during low water spring tide. Figure 2.2 shows the locations of the sampling stations and Table 2.3 gives the station coordinates along each transect.

Each transect was surveyed from extreme high water down the shore to the low water mark. Determination of the shore zones (strand line, upper/mid/lower shore) were based on slope, differences in the substrata and biological communities. Within each zone identified, a 0.25m² quadrat was placed in an area representative of the

zone. Within this quadrat, a record was made of species present, their abundance and the substrata. Abundance was recorded as percentage cover where possible. Photographs were taken within each zone and a photograph of the overall view of the transect line was also taken. Where substrata allowed, five 20cm diameter cores were taken for species analysis. The faunal returns were sieved on a 1 mm mesh sieve, stained with Rhodamine dye, fixed with 10% buffered formalin and preserved in 70% alcohol. Samples were then sorted under a microscope (x 10 magnification), into four main groups: polychaeta, mollusca, crustacea and others. The 'others' group consisted of nematodes, insects and other lesser phyla. The taxa were then identified to species level where possible.

In addition to the cores, four 1 m² areas were dug to a depth of circa 20 cm at each station and sieved through a 5 mm sieve in order to quantify the large deeper-dwelling species in the area. Species abundance was recorded from these digs. A sample of sediment from each dig over was retained for granulometric and organic carbon analysis.



Figure 2.2: Intertidal transects sampled in Broadmeadow Estuary on the 20th and 21st August 2008.

Station	Latitude	Longitude
T1S1	53° 27.33556'	-6° 8.85891'
T1S2	53° 27.31577'	-6° 8.89322'
T1S3	53° 27.29418'	-6° 8.93057'
T1S4	53° 27.26991'	-6° 8.97135'
T2S1	53° 27.89309'	-6° 9.25485'
T2S2	53° 27.88990'	-6° 9.23736'
T2S3	53° 27.82901'	-6° 9.07113'
T2S4	53° 27.78147'	-6° 9.02803'
T3S1	53° 27.89884'	-6° 11.9224'
T3S2	53° 27.89761'	-6° 11.9084'
T3S3	53° 27.88653'	-6° 11.8773'
T3S4	53° 27.86861'	-6° 11.8315'

Table 2.3: Intertidal station coordinates sampled in Broadmeadow Estuary on the 20th and 21st August 2008.

An engineer's level (LevelMark 75055) and staff was used to calculate vertical intervals of approximately 10% of the mean range of the spring tide to determine the slope along each transect. Horizontal distance was estimated from DGPS positions.

3. Results

3.1. *Subtidal*

3.1.1. **Fauna**

The taxonomic identification of the benthic infauna across all 11 stations sampled in the Broadmeadow Estuary survey yielded a total count of 62 species, ascribed to 10 phyla. A complete listing of these species abundance is provided in Appendix A. Of the 62 species enumerated, 40 were polychaetes (segmented worms), 3 were crustaceans (crabs, shrimps, prawns), 7 were molluscs (mussels, cockles, snails etc.), 2 species were echinoderms (star fish, brittle stars), 1 species was a porifera (sponge), 1 species was a tunicate (sea squirts), 2 species were cnidarians (jelly fish, coral), 1 species was a nematode (roundworm) and 1 species was a hexapod (seashore insects). The sponge present was *Haliclona* sp. and given their colonial nature, this species abundance was given on a present/absence scale and therefore this species was excluded from the faunal analyses.

3.1.1.1. *Univariate Analysis*

Univariate statistical analyses were carried out on the combined replicate station-by-station faunal data. The following parameters were calculated and can be seen in Table 3.1; species numbers, number of individuals, richness, evenness and diversity. Species numbers ranged from 2 (Station 4) to 36 (Station 2). Number of individuals ranged from 9 (Station 4) to 405 (Station 10). Richness ranged from 0.46 (Station 4) to 5.91 (Station 2). Evenness ranged from 0.52 (Station 11) to 0.99 (Station 4). Diversity ranged from 0.99 (Station 4) to 3.36 (Station 1).

Station	Species Numbers	Number of Individuals	Richness	Evenness	Diversity
1	33	391	5.36	0.67	3.36
2	36	372	5.91	0.55	2.83
3	4	12	1.21	0.71	1.42
4	2	9	0.46	0.99	0.99
5	9	24	2.52	0.91	2.88
6	7	83	1.36	0.79	2.23
7	10	288	1.59	0.62	2.07
8	13	256	2.16	0.62	2.31
9	11	366	1.69	0.64	2.20
10	8	405	1.17	0.76	2.28
11	7	374	1.01	0.52	1.45

Table 3.1: Diversity indices for the 11 stations sampled in Broadmeadow Estuary on the 20th and 21st August 2008.

3.1.1.2. *Multivariate Analysis*

Figures 3.1 and 3.2 present a station similarity dendrogram and the MDS plot, respectively. Stations 1 and 2, which form a group at a similarity level of 53.58% (Group I), can be isolated from the remaining stations at a similarity level of 19.31%. The remaining stations all form a broad grouping at a similarity level of 31.96%. Within this broad grouping, Stations 6, 7, 8, 9 and 10 form a group at a similarity level of 71.21% (Group II). Station 11 joins Group II at a similarity of 57.23% and station 5 joins Group II at a similarity level of 44.33. However, as Station 5 is more dissimilar to Group II than it is similar; it was not included as part of this Group. Stations 3 and 4 form a group at a similarity level of 69.01% (Group III). Group II and Group III are 31.96% similar to each other.

These delineations were also preserved in the MDS plot. The stress value of the MDS ordination is 0.04; therefore this ordination provides an excellent representation of the data with no prospect of misinterpretation.

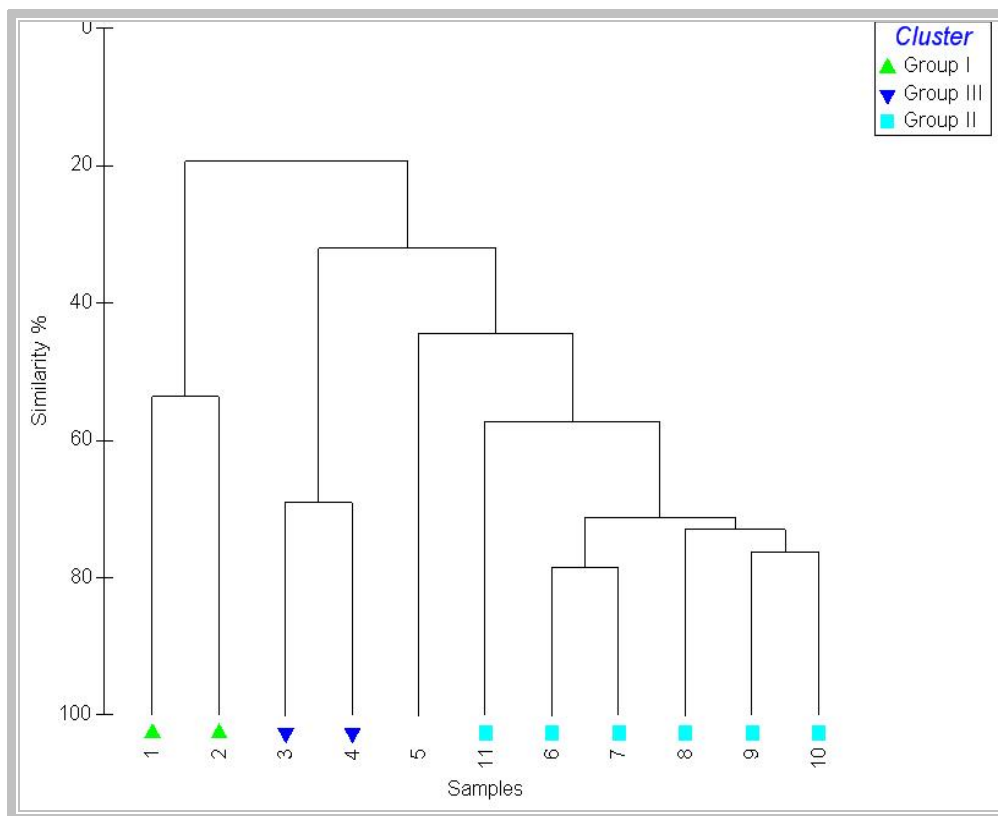


Figure 3.1: Dendrogram showing each station from the 11 stations sampled in Broadmeadow Estuary on the 20th and 21st August 2008.

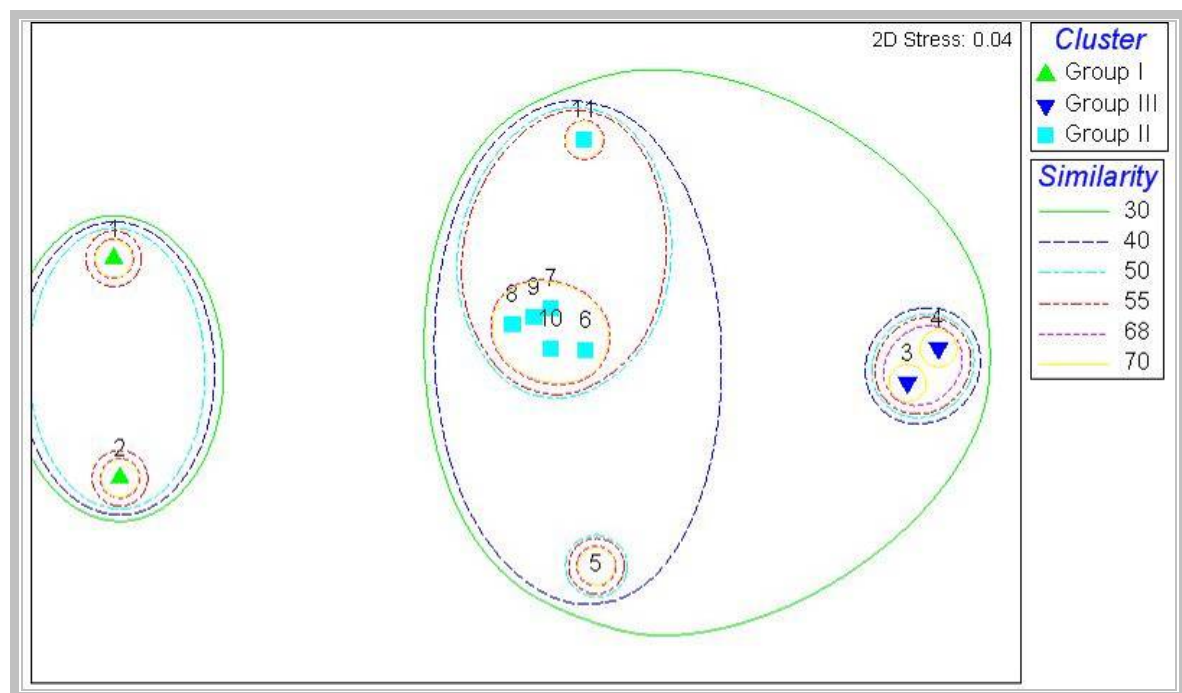


Figure 3.2: MDS ordination showing each station from the 11 stations sampled in Broadmeadow Estuary on the 20th and 21st August 2008.

SIMPER analysis revealed the species responsible for the similarities and dissimilarities seen in the dendrogram and MDS plot above. SIMPER analysis could only be carried out on the stations which were assigned to groups. The results of the SIMPER analysis can be seen in Appendix B.

Station 5 was more dissimilar to the other stations than it was similar. This station contained 5 species comprising 7 individuals. All seven species were present twice or less. The polychaete *Tharyx killariensis* was the dominant species at this station (2 individuals). The following 4 species were only present once (the cnidarian *Sagartia* sp., the polychaete *Heteromastus filiformis*, the cnidarian *Actinia* sp. and the oligochaete *Tubificoides pseudofaster*). This station was so species poor, the assignment of a biotope was not possible.

Group I (Stations 1 and 2) contained 39 species comprising 251 individuals. Twenty-four of the species were present twice or less. The dominant species was the cnidarian *Cereus pedunculatus*. (77 individuals), which accounted for 31% of the total abundance at this station. Other species present included the oligochaete *Tubificoides benedii* (59 individuals), the polychaetes *Sabella pavonina* (24 individuals) and *Eumida bahusiensis* (10 individuals) and the oligochaete *T. pseudogaster* (10 individuals). These five species accounted for 71% of the total abundance within this group. SIMPER analysis for this group revealed that of the 53.58% similarity between Stations 1 and 2, nine species were responsible for just over 50% of the similarity between these two stations: *Tubificoides benedii* (8.64%), *Cereus pedunculatus* (7.51%), *T. pseudogaster* (7.13%), *Eumida bahusiensis* (6.5%), *Eumida* sp. (5.88%), *Sthenelais boa* (4.47%), *Nereis* sp. (4.47%), *Nephtys* sp (4.47%). and *Caulleriella zetlandica* (4.47%). This group shows characteristics of the SS.SMx.IMx.SpavSpAn *Sabella pavonina* with sponges and anemones on infralittoral mixed sediment biotope (Connor *et al*, 2004).

Group II (Stations 6, 7, 8, 9, 10 and 11) contained 12 species comprising 651 individuals. Four of the species were present twice or less. The dominant species was the oligochaete *Tubificoides pseudogaster* (233 individuals) which accounted for 36% of the total abundance within this group. Other species present include the oligochaete *T. benedii* (131 individuals), the cnidarian *Sagartia* sp. (112 individuals),

the polychaetes *Heteromastus filiformis* (109 individuals), *Tharyx killariensis* (29 individuals) and *Streblospio benedicti* (25 individuals). These 6 species accounted for 98% of the total abundance. SIMPER analysis for this group revealed that of the 67.4% similarity between Stations 6, 7, 8, 9, 10 and 11, the following three species were responsible for 50% of the similarity: *Tubificoides pseudogaster* (22.04%), *T. benedii* (17.85%) and *Heteromastus filiformis* (16.84%). This group shows characteristics of the SS.SMU.SMuVS.CapTubi in variable salinity infralittoral muddy sediment biotope (Connor *et al*, 2004).

Group III (Stations 3 and 4) contained 2 species comprising 6 individuals. One of the species was present twice or less. The two species in this group were the oligochaetes *Tubificoides benedii* (4 individuals) and *T. pseudogaster* (2 individuals). SIMPER analysis for this group revealed that of the 69.01% similarity between Stations 3 and 4, *T. benedii* and *T. pseudogaster* were responsible for 100% of it. This group is representative of the SS.SMU.SMuVS.OIVS Oligochaetes in variable or reduced salinity infralittoral muddy sediment biotope (Connor *et al*, 2004).

3.1.2. Sediment

Results from the granulometric analysis on the sublittoral sediments are presented in Table 3.2. The sediment sampled in Broadmeadow Estuary was dominated by silt-clay and fine sands. The majority of stations were dominated by slit-clay (Stations 3 to 11). The remaining two stations were dominated by fine sand (Stations 1 and 2). Station 9 contained the highest percentage of gravel (5.8%), very coarse sand (6.2%) and coarse sand (6%). Station 2 contained the highest percentage of medium sand (11.4%). Station 1 contained the highest percentage of fine sand (74.4). Station 11 contained the highest percentage of very fine sand (32.8%) and Station 7 contained the highest proportion of silt-clay (95.8%). Figure 3.3 shows the sediment particle size distribution at each station.

Station	Gravel (%)	Very Coarse Sand (%)	Coarse Sand (%)	Medium Sand (%)	Fine Sand (%)	Very Fine Sand (%)	Silt-Clay (%)
1	1.6	0.7	1.2	5.1	74.4	6.4	10.6
2	2.4	1	1.3	11.4	66.8	7.6	9.4
3	1.1	1.2	1.2	4.3	24	7.2	61
4	2.4	2.5	1.2	0.7	6.9	4.8	81.3
5	0.2	0.3	0.2	0.4	37.7	6.9	54.3
6	0.9	1.8	1	0.8	14.2	8.3	73
7	0.4	0.1	0.1	0.3	1.3	2	95.8 </td
8	0.9	1.2	1.1	1.4	12.6	8.6	74.1
9	5.8	6.2	6	7.9	14.3	8.1	51.7
10	0	0.5	0.5	0.5	1.2	3.3	94.1
11	0.4	0.3	0.5	1.4	15	32.8	49.6

Table 3.2: Granulometry results for the 11 stations sampled in Broadmeadow Estuary in August 2008.

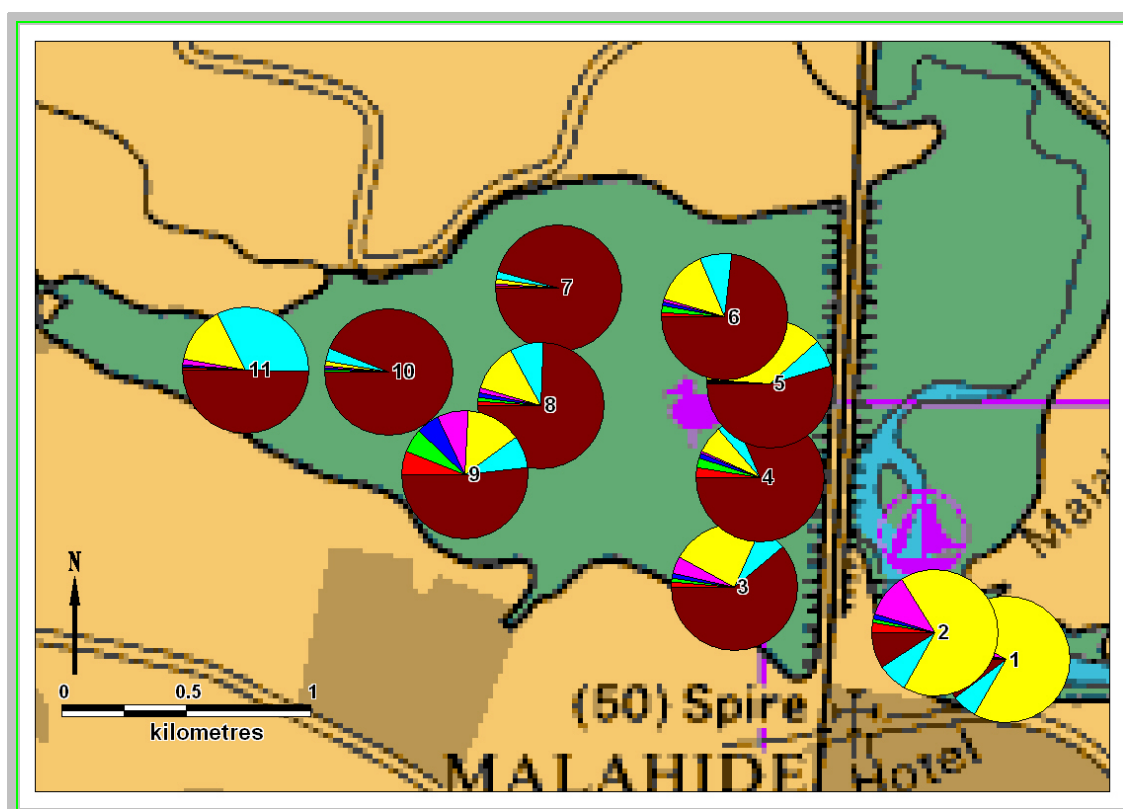


Figure 3.3: Sediment particle size distribution at each of the 11 stations sampled in Broadmeadow Estuary in August 2008.

The results from the organic carbon analysis can be seen in Table 5. Organic carbon values in Broadmeadow Estuary ranged from 0.28% (Station 1) to 2.32% (Station 10).

Station	1	2	3	4	5	6	7	8	9	10	11
O C (%)	0.28	0.36	1.76	1.73	1.17	1.69	2.21	1.78	1.51	2.32	1.58

Table 3.3: Organic carbon results for the 11 stations sampled in Broadmeadow Estuary on the 20th and 21st August 2008.

Figure 3.4 presents the PCA ordination of the sediment data analysed from Broadmeadow Estuary. The variation seen in this 2-D ordination accounted for 82.5% of the overall variation, PC1 accounted for 53.4% of the variation, whereas PC2 accounted for 29.1% of the variation. The stations in Broadmeadow Estuary were dominated by silt-clay and fine sand as identified by the granulometric analysis. Stations 1 and 2 (Faunal Group I) grouped separately from the other stations due to their high fine sand content and low organic carbon content. Station 3 (Faunal Group III) was located in the centre of the plot due to its high silt-clay content and its relatively high medium sand content. Station 4 (Faunal Group III) grouped away from Station 3, due to its higher silt-clay fraction and lower fine sand fraction. Station 9 (Faunal Group II) grouped away from the other stations due to the higher coarse fraction and lower silt-clay fraction found at this station. Stations 7 and 10 (Faunal Group II) grouped together due to the high silt-clay and organic carbon content at these stations. Stations 8 and 6 (Faunal Group II) grouped more to the centre of the plot due to their fine sand fraction. Stations 5 and 11 (Faunal Group II – Station 11 only) grouped towards the top of the plot due to their relatively high fine sand and medium sand contents respectively.

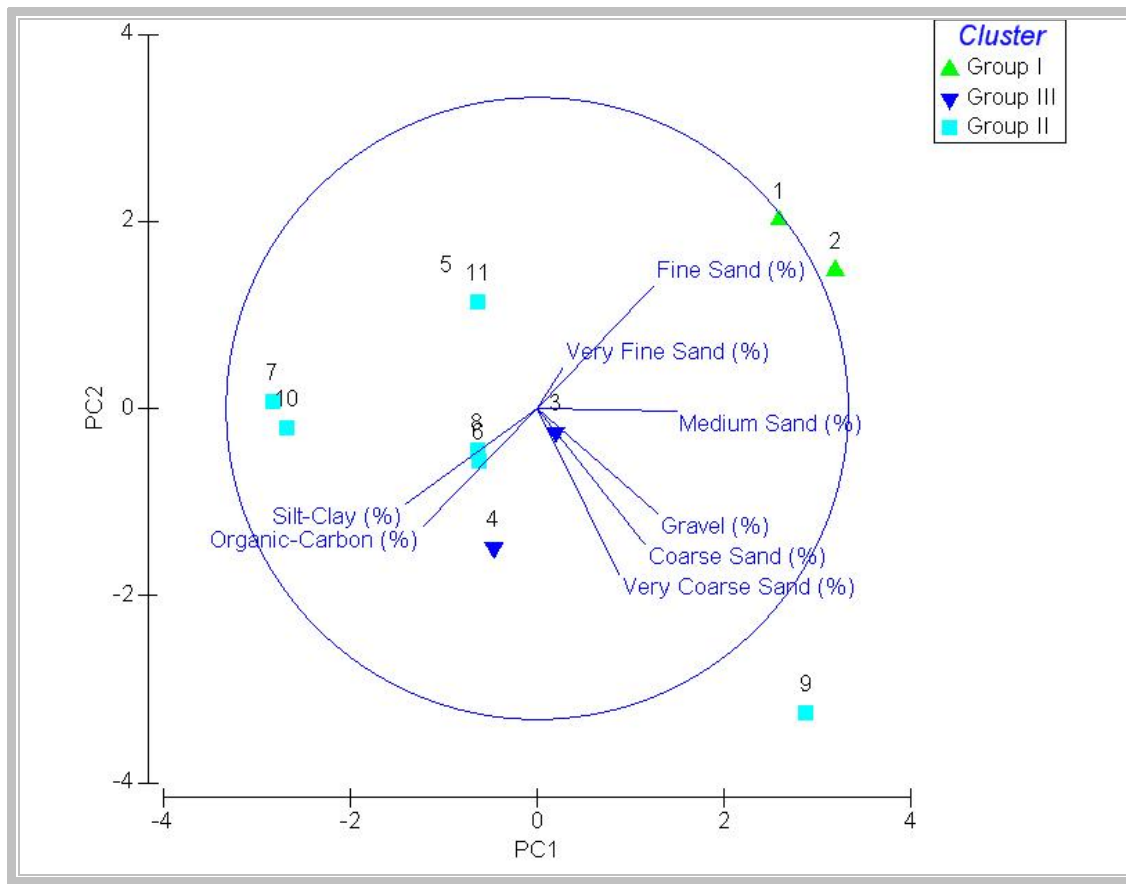


Figure 3.4: PCA ordination of the environmental data sampled at 11 stations in Broadmeadow Estuary in August 2008.

3.1.3. Sediment Profile Imagery

Sediment profile images for each of the sublittoral stations sampled are presented in Appendix C, along with a description of the SPI apparatus and data. Measured data for each of the images analysed are presented in Table 3.4 and superimposed on the provided images.

Station Image	Penetration		Sediment	aRPD		Stage	Comment
	Max (cm)	Min (cm)		Max (cm)	Min (cm)		
S1i	-	-	FS	-	-	-	<i>Cereus pedunculatus</i> & <i>Lanice conchilega</i> at sediment surface
S1ii	3.47	2.73	FS	-	-	II-III	Shell fragments & small pebbles on muddy fine sand. Seaweed (<i>F. lumbricalis</i>) in shot
S1iii	5.77	1.97	FS	-	-	II-III	Shell fragments on MFS. <i>L. conchilega</i> . Ox & red sed at sed surface around a burrow
S2i	2	0	FS	-	-	II-III	Low pen. Sabellid tube in background. Shelly fine sand
S2ii	9.64	4.03	FS	5.72	1.11	II-III	Variable aRPD. Sabellid tubes. <i>A. aspersa</i>
S2iii	2.26	0.75	FS			II-III	Low pen. <i>Lanice</i> and Sabellid tubes
S3i	16.16	15.31	Silt/Clay/FS	1.99	0	I	Mud/FS mix. Streaks of reduced sediment. Superficial oxidation
S3ii	11.82	10.64	Silt/Clay/FS	1.36	0	I	Mud. Resuspended sed in water column
S3iii	13.91	13.35	Silt/Clay/FS	4.24	0.37	I	Mud/FS mix.
S4i	18.69	18.25	Silt/Clay	-	-	O	Mud/VFS/FS mix. Reduced sed with superficial oxidation
S4ii	18.37	17.15	Silt/Clay	-	-	O	Mud/VFS/FS mix. Reduced sed with superficial oxidation
S5i	15.47	13.73	Silt/Clay/FS	4.09	1.48	I	Mud/FS mix. Superficial oxidation
S5ii	18.23	15.02	Silt/Clay/FS	4.19	0	I	Mud/FS mix. Uneven sed surface
S6i	16.41	14.98	Silt/Clay/FS	4.34	0	I	Mud/FS mix. Streaky aRPD.
S6ii	18.01	17.16	Silt/Clay/FS	4.61	1.48	I	Mud/FS mix. Variable aRPD
S7i	19.02	18.25	Silt/Clay	2.25	0.44	II	Mud. Layer of benthic diatoms at SWI. Anemones at surface.
S7ii	20.62	19.66	Silt/Clay	1.66	0.5	II	Mud. Layer of benthic diatoms at SWI. Superficial oxidation.
S8i	16.41	15.09	Silt/Clay	2.25	0.44	I	Mud/FS/VFS mix. Layer of benthic diatoms.
S8ii	16.16	15.53	Silt/Clay	2.8	0.81	I	Mud/FS/VFS mix. Layer of benthic diatoms.
S9i	13.25	10.41	Silt/Clay	11.55	0.61	II	Mud/FS mix. Layer of benthic diatoms.
S9ii	14.55	12.55	Silt/Clay	5.57	1.04	II	Mud/FS mix. Evidence of surface bioturbation.
S10i	20.2	18.76	Silt/Clay	5.24	0	II	Mud. Variable aRPD, anemone at surface.
S10ii	20.34	19.82	Silt/Clay	2.73	0	II	Mud. Variable aRPD. Oxidised surface.
S11i	15.48	14.56	Silt/Clay/VFS	7.97	2.1	II	Mud/VFS/FS mix. Amphipod at surface. Tube at surface.
S11ii	15.63	14.89	Silt/Clay/VFS	5.2	0.81	II	Mud/VFS/FS mix. Small tubes at surface.
S11iii	17.59	16.6	Silt/Clay/VFS	4.94	0	II	Mud/VFS/FS mix. Small patches of reduced sediment at surface.

Table 3.4. SPI parameters measured from images from the stations in Broadmeadow Estuary, August 2008

3.1.3.1. *Sediment type*

The sediment major mode is assessed from the top 5cm of the sediment. Stations 1 and 2 were characterised by the presence of fine sand. The remaining stations were characterised by the predominance of silt/clay sediment with a variable proportion of fine and very fine sand. Sediments were slightly coarser at Station 11 with a high proportion of very fine sand present.

3.1.3.2. *Mean prism penetration depth*

The maximum prism penetration depths (in centimetres) achieved on each deployment is presented in the table 3.4 and superimposed on the photo sets presented in Appendix C. These figures reflect both the grain size composition and compactness of the bottom deposits.

Penetration depths were good throughout the inner estuary. Low penetration at Stations 1 and 2 were due to boulders/bedrock under the layer of sediment at these stations.

3.1.3.3. *Sediment surface boundary roughness*

Surface boundary roughness is an indication of the unevenness of the sediment surface resulting from either bioturbation (animals in the sediment) or from physical disturbance. In the case of the current survey, sediment relief (high SBR values) is due to a combination of bioturbation and physical disturbance. The images presented in Appendix C show a seafloor where SBR is modified to a large degree only at Stations 1 and 2. The profile images are characteristic of a seafloor with a well-developed faunal community – with numerous tubes and burrow features. SBR values throughout the remaining stations examined were quite low, apart from one image at Station 9 (see Appendix C) where an increase in SBR is associated with the presence of anemones.

3.1.3.4. *Apparent redox potential discontinuity (aRPD)*

The apparent redox potential discontinuity (aRPD) depth is the visible line between oxygenated and reduced sediment in a profile image. Oxygen penetration varied from 0cm to 11.55cm. The deepest oxygenated sediment recorded was associated with a subsurface burrow feature at Station 9. The lowest penetration recorded was at Station 4, where oxygen had diffused from the water column to a depth of 1-2mm into the sediment surface. The presence of a layer of benthic diatoms at the sediment surface at several of the stations (e.g Stations 7 and 8 Appendix C) contributes to the diffusion of oxygen beyond the sediment water interface and into the surface of the sediment.

3.1.3.5. *Infaunal Successional stage & bioturbation depth*

Infaunal successional stages calculated for the stations surveyed are presented on the SPI shots in Appendix C. Stage III environments (mature, healthy conditions) are typically characterised by deep redox boundary depths and the presence of certain fauna or faunally-related features. All stations were assigned a Benthic Habitat Quality Index following the methodology proposed by Nilsson and Rosenberg (1997) (see data analysis Appendix C). Successional stages were then assigned to each sediment profile image based on this calculated value. At the other end of the scale, stage 0 and Stage I environments are characterised by shallow redox depths and by a general absence or low level of faunal activity.

The outermost stations surveyed (Stations 1 and 2) were allocated a Stage II-III Successional status. This was largely due to the presence of characteristically variable moderate depth ARPDs, substantial faunal activity and prominent biogenic features such as burrows and tubes. Sediments at Stations 7, 9, 10 & 11 were allocated Stage II Successional status due to rather shallow aRPD depths and limited faunal activity. Stations 3, 5, 6 & 8 were allocated a Stage I successional status due to the presence of reduced sediments in the profile images and a lack of biogenic features such as burrows/feeding casts. Sediments at Station 4 were awarded a Stage 0 successional status due the presence of strongly reduced sediments and the absence of any obvious faunal activity.

3.1.3.6. *Additional biological information*

Many of the stations surveyed showed signs of faunal activity. Additional biological information recorded by SPI is detailed below:

- Station 1 – Terebellid polychaete *Lanice conchilega* (the Sand Mason) and *Cereus pedunculatus* (Daisy Anemone) recorded at the sediment surface. Seaweed (probably *Furcellaria lumbricalis*) recorded in one of the images.
- Station 2 – Quite a dense aggregation of *L. conchilega* and Sabellid tubes (fanworms) at sediment surface. A specimen of the tunicate *Ascidella aspersa* (a sea squirt) was visible in one of the profile images.
- Station 7 – Layer of benthic diatoms at the sediment surface. Small anemones at the sediment water interface (SWI).
- Station 8 – Layer of benthic diatoms at the SWI.
- Station 9 – Layer of benthic diatoms at the SWI.
- Station 10 – Anemone at SWI.
- Station 11 – Amphipod at SWI. Small and medium sized tubes (1mm diameter and 4mm diameter respectively).

3.2. *Intertidal*

Results of the granulometric and organic carbon analysis from the sediments collected along each of the transects are presented in Appendix D while Appendix E details the species returns from each of the cores.

3.2.1. Transect 1

Transect 1 was located along a sheltered area of coastline (see Figure 2.2) to the north of the outer estuary. The upper shoreline consisted of gravelly sand with saltmarsh dominating the area beyond the strandline. The transect began at the high tide mark and continued along the shore in a south westerly direction to the low tide mark. The total length of the transect was 185.4m across a generally muddy sand substrate. A view from the upper to low shore along this transect is shown in Figure 3.5 with a representation of the slope profile overlaying this image.

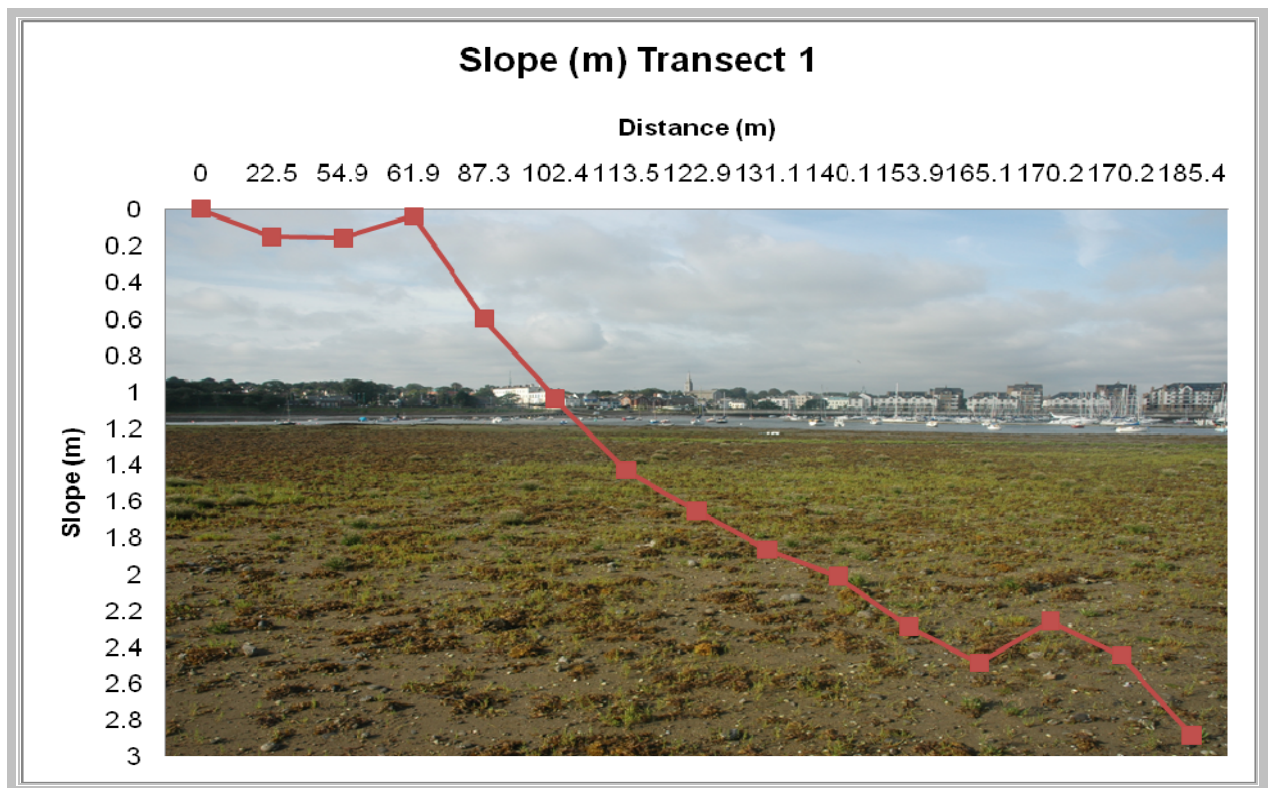


Figure 3.5: Profile of the shore along Transect 1.

Strandline

The area above the standline consisted of a well-developed saltmarsh (Plate 3-1). It was characterised by species such as sea purslane (*Halimolobos portulacoides*), sea aster (*Aster tripolium*), thrift (*Armeria maritima*), sea arrowgrass (*Triglochin maritima*) and common saltmarsh grass (*Puccinellia maritima*). The biotope classification for this habitat is LS.LMp.Sm Saltmarsh (Connor *et al*, 2004).



Plate 3-1: Saltmarsh (LS.LMp.Sm) located in the strandline of Transect 1.

An area typical of the strandline on Transect 1 is shown in Plate 3-2. The substrate within the 0.25 m² quadrat had approximately 25% sea purslane cover over gravel, empty shells and sand. From the replicate cores taken at this site, 7 species were recorded (See Table 1 Appendix E). Oligochaete sp. were the dominant fauna at this location. From the granulometric analyses, this site consisted of 34.6% fine sand and 33.2% gravel. Organic carbon levels at this site were 0.95%. No fauna were encountered during the dig over at this site. In addition to this, patches of spiral wrack (*Fucus spiralis*) and channelled wrack (*Pelvetia canaliculata*) were present scattered throughout the strandline. The biotope classification for this habitat is LS.LSa.MoSa.Ol.VS, Oligochaetes in variable salinity littoral mobile sand (Connor *et al*, 2004).



Plate 3-2: Strandline station (LS.LSa.MoSa.OI.VS) along Transect 1.

Upper Shore

The upper shore consisted of sand and gravel with a light cover of gut weed (*Enteromorpha* spp.) (Plate 3-3). There was a light scatter of dead *Cerastoderma edule* shells with patches of spiral wrack (*F. spiralis*). The substratum in the upper shore quadrat consisted of 100% gravel overlying sand (Plate 3-4). Spiral wrack (*Fucus spiralis*) occupied approximately 40% of the quadrat, gut weed (*Enteromorpha* spp.) 25% and the remainder was occupied by exposed gravel and shell. From the replicate cores taken at this site, 12 species were recorded (See Table 2 Appendix E). Enchytraeidae sp. and Oligochaete sp. were the dominant species at this location. From the granulometric analyses, this site consisted of 42.4% fine sand and 18.9% gravel. Organic carbon levels at this site were 0.47%. The dig over revealed 6 common cockles (*Cerastoderma edule*). The biotope classification for this habitat is LS.LSa.MoSa.OI.VS Oligochaetes in variable salinity littoral mobile sand (Connor *et al*, 2004).



Plate 3-3: View of the upper shore along Transect 1.



Plate 3-4: Upper shore station (LS.LSa.MoSa.OI.VS) along Transect 1.

Middle Shore

The middle shore consisted of gravelly sand with *Cerastoderma* shells. Some large rocks protruded from the sand (Plate 3-5). Patches of bladder wrack (*Fucus vesiculosus*) and gut weed (*Enteromorpha* spp.) were scattered around the exposed sandflat with mussel clumps in places. The substratum at the middle shore station consisted of 90% gravel and sand with approximately 10% shell (Plate 3-6). No flora or fauna were observed within the quadrat. From the replicate cores taken at this site, 29 species were recorded (See Table 3 Appendix E). The polychaete *Thayrx* sp. was the dominant species at this location. From the granulometric analyses, the substrate at this station consisted of 56.5% fine sand and 15.6% gravel. The organic carbon content of the sediment at this site was 0.15%. The dig over revealed 7 common cockles (*Cerastoderma edule*), 5 lugworms (*Arenicola marina*) and 7 catworms (*Nephtys* sp.). The biotope classification for this habitat is LS.LMx.GvMu.HedMx.Cir *Hediste diversicolor*, Cirratulids and *Tubificoides* spp. in littoral gravelly sandy mud (Connor *et al*, 2004).



Plate 3-5: View of the middle shore along Transect 1.

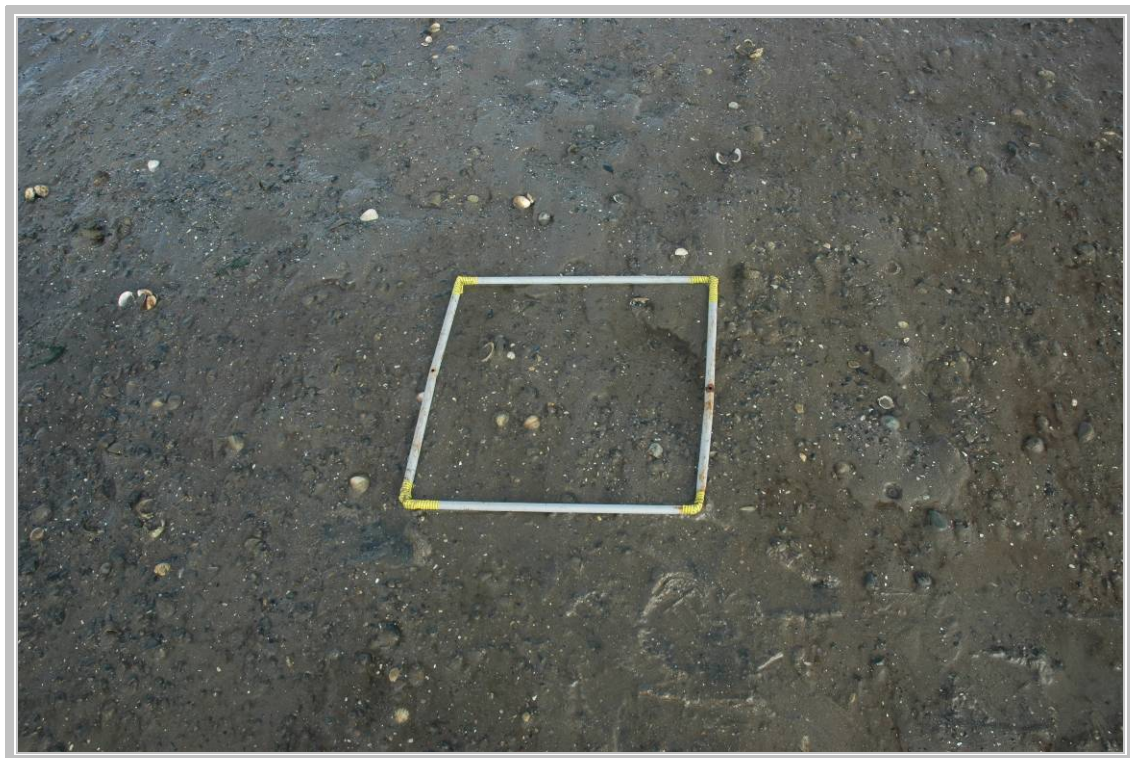


Plate 3-6: Middle shore station (LS.LMx.GvMu.HedMx.Cir) along Transect 1.

Lower Shore

The lower shore consisted of a mixture of gravel, sand and mud (Plate 3-7). The sediment had a grey colour with a shallow redox layer. The lower shore was characterised by sand mason (*Lanice concheliga*) beds, common mussels (*Mytilus edulis*), common cockles (*Cerastoderma edule*), sea lettuce (*Ulva lactuca*), gut weed (*Enteromorpha* spp.) and some sponges. Sea lettuce (*Ulva lactuca*) (5%), and sand mason (*L. concheliga*) (5%) were the main cover within the quadrat (Plate 3-8). From the replicate cores taken at this site, 32 species were recorded (See Table 4 Appendix E). The oligochaete *Tubificoides benedii* and the polychaete *Thayrx* sp. were the dominant species at this location. From the granulometric analyses, this site consisted of 33.7% fine sand and 29.3% gravel. The organic carbon content of the sediment at this site was 0.36%. The dig over revealed 26 sand masons (*L. concheliga*) and 6 catworms (*Nephtys* sp.). The biotope classification for this habitat is LS.LSa.MuSa.Lan *Lanice conchilega* in littoral sand (Connor *et al*, 2004).



Plate 3-7: View of the lower shore along Transect 1.

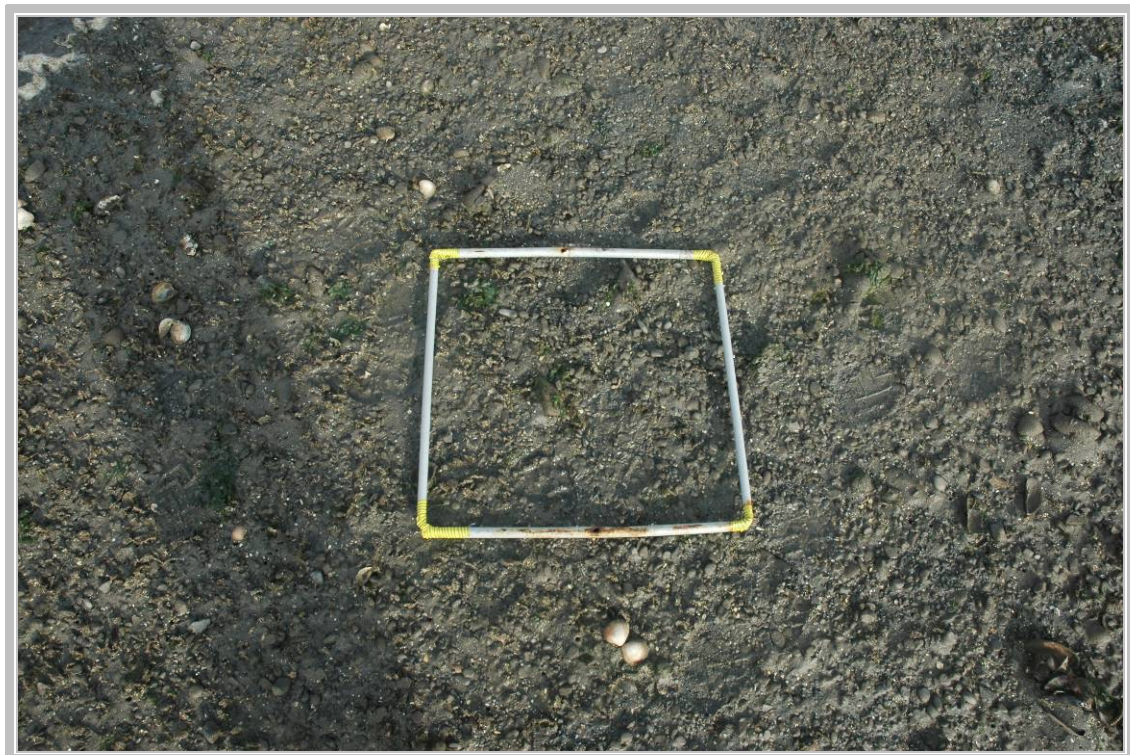


Plate 3-8: Lower shore station (LS.LSa.MuSa.Lan) along Transect 1.

3.2.2. Transect 2

Transect 2 was located across a large sheltered mudflat to the north of the outer estuary (see Figure 2.1). The shoreline can be described as a gravelly sandy shore that quickly changed to a sand/mud flat that continued to the water line.

The transect began at the high tide mark, which was located at the base of the rock embankment that supported the railway track that bisects the estuary, and continued in a south easterly direction to the low tide mark. The total length of the transect was 444.2m. A view from the upper to low shore along this transect is shown in Figure 3.6 with a representation of the slope profile overlaying this image.

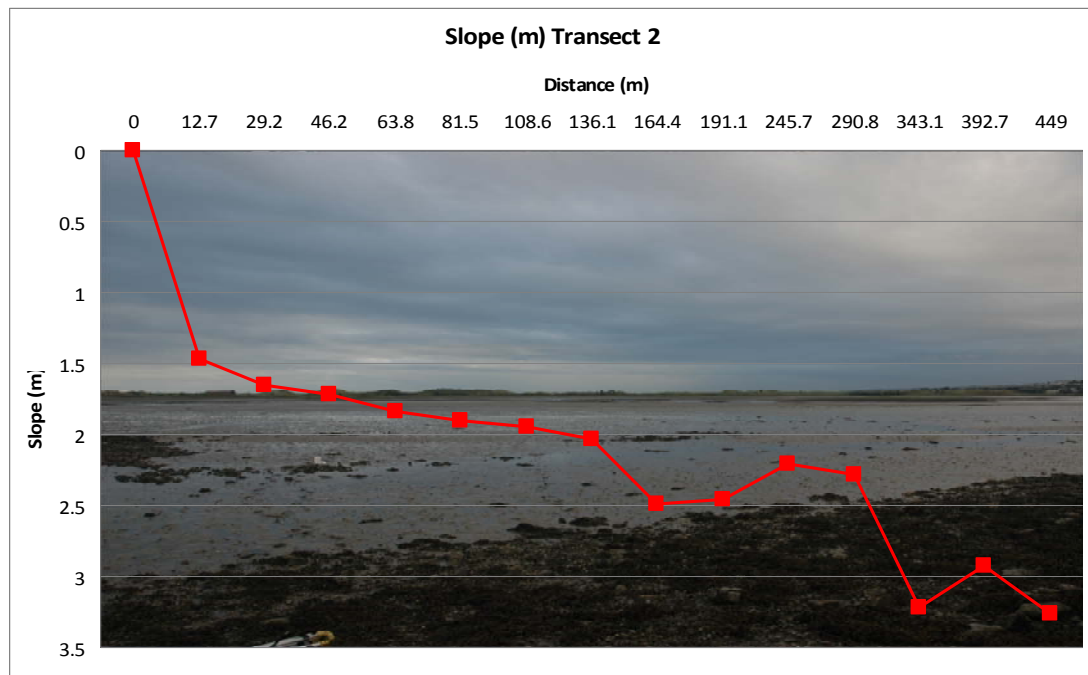


Figure 3.6: View across Transect 2 with the slope profile superimposed.

Strandline

The standline was located at the foot of a man-made embankment (Plate 3-9). The rock at the base of the embankment was encrusted with the lichens including: 80% black-tar lichen (*Verrucaria* spp.), 10% black shields lichen (*Lecanora atra*) and 5% orange lichen (*Caloplaca marina*) (Plate 3-10). This represented the LR.FLR.Lic.YG

Yellow and grey lichens on supralittoral rock biotope (Connor *et al*, 2004). The strandline station was located just below this band of encrusted rock (Plate 3-11). The substrate consisted of gravelly sediments overlying mud. *Mytilus* and *Cerastoderma* shells were scattered throughout this area. Channelled wrack (*Pelvetia canaliculata*), knotted wrack (*Ascophyllum nodosum*) and spiral wrack (*Fucus spiralis*) were present in this area. The area within the sample quadrat had a cover of 60% *F. spiralis* and 20% *A. nodosum*. From the replicate cores taken at this site, 29 species were recorded (See Table 5 Appendix E). The oligochaete *Tubificoides benedii* and the polychaete *Thayrx* sp. were the dominant species at this location. From the granulometric analyses, this site consisted of 31.3% fine sand and 23.3% gravel. Organic carbon levels at this site were 1.03%. The dig overs revealed 57 common mussels (*Mytilus edulis*), 7 common cockles (*Cerastoderma edulis*) and 8 topshells (*Littorina littorea*). This site represents the LR.LLR.F.Fspi *Fucus spiralis* on moderately exposed to very sheltered upper eulittoral rock biotope with characteristics of a *Mytilus edulis* biotope found lower on the shore (Connor *et al*, 2004).



Plate 3-9: Strandline and upper shore of Transect 2.



Plate 3-10: Bank of rock at the strandline along Transect 2 (LR.FLR.Lic.YG).

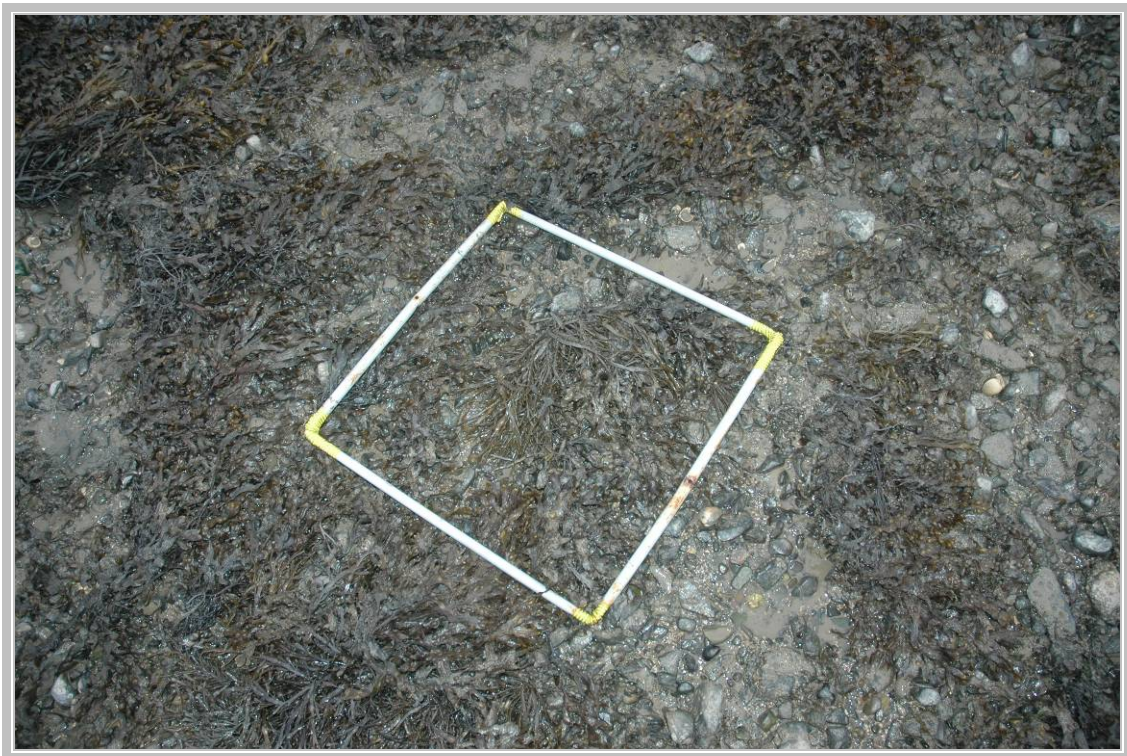


Plate 3-11: Strandline station, Transect 2 (T2S1).

Upper Shore

The upper shore was characterised by a muddy substrate with some *Mytilus edulis* clumps, lugworm (*Arenicola marina*) casts (approximately 6/m²) and gut weed (*Enteromorpha* spp.) (see Plate 3-9). The upper shore station consisted of fine muddy sand with circa 50% cover of *Mytilus* clumps and *F. spiralis* (Plate 3-12). From the replicate cores taken at this site, 24 species were recorded (See Table 6 Appendix E). The oligochaetes *Tubificoides benedii*, *Heterochaeta costata* and the polychaete *Tharyx* sp. were the dominant species at this location. From the granulometric analyses, this site consisted of 74.3% fine sand. Organic carbon levels at this site were 0.38%. The dig over revealed no species. The biotope classification for this habitat is an a mixture of the LS.LMx.LMus.Myt.Sa *Mytilus edulis* beds on littoral sand biotope and the LS.LSa.MoSa.Ol.VS Oligochaetes in variable salinity littoral mobile sand biotope (Connor *et al*, 2004).

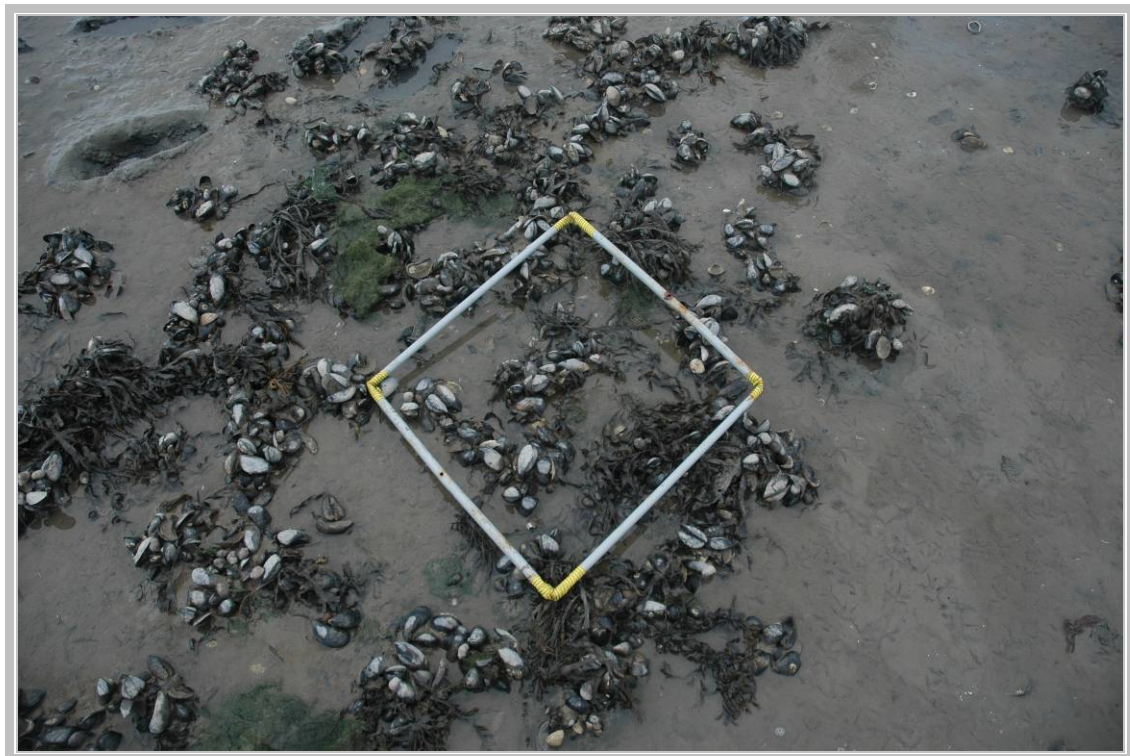


Plate 3-12: Upper shore station (LS.LMx.LMus.Myt.Sa/ LS.LSa.MoSa.Ol.VS) along Transect 2.

Middle Shore

The middle shore consisted of sandy mud with Lug worm (*A. marina*) casts (3/m²) and bioturbatory depressions giving the substrate a pocked appearance (Plate 3-13).

The sediment within the middle shore quadrat consisted of 100% sandy mud with a single lugworm cast present (Plate 3-14). From the replicate cores taken at this site, 16 species were recorded (See Table 7 Appendix E). The oligochaete *T. benedii* was the dominant species at this location. From the granulometric analyses, this site consisted of 89.2% fine sand. Organic carbon levels at this site were 0.15%. The dig over revealed 1 common cockle (*Cerastoderma edule*) and 4 catworms (*Nephtys* sp.). The biotope classification for this habitat is LS.LSa.MoSa.OI.VS Oligochaetes in variable salinity littoral mobile sand (Connor *et al*, 2004).



Plate 3-13: View of the middle shore along Transect 2.

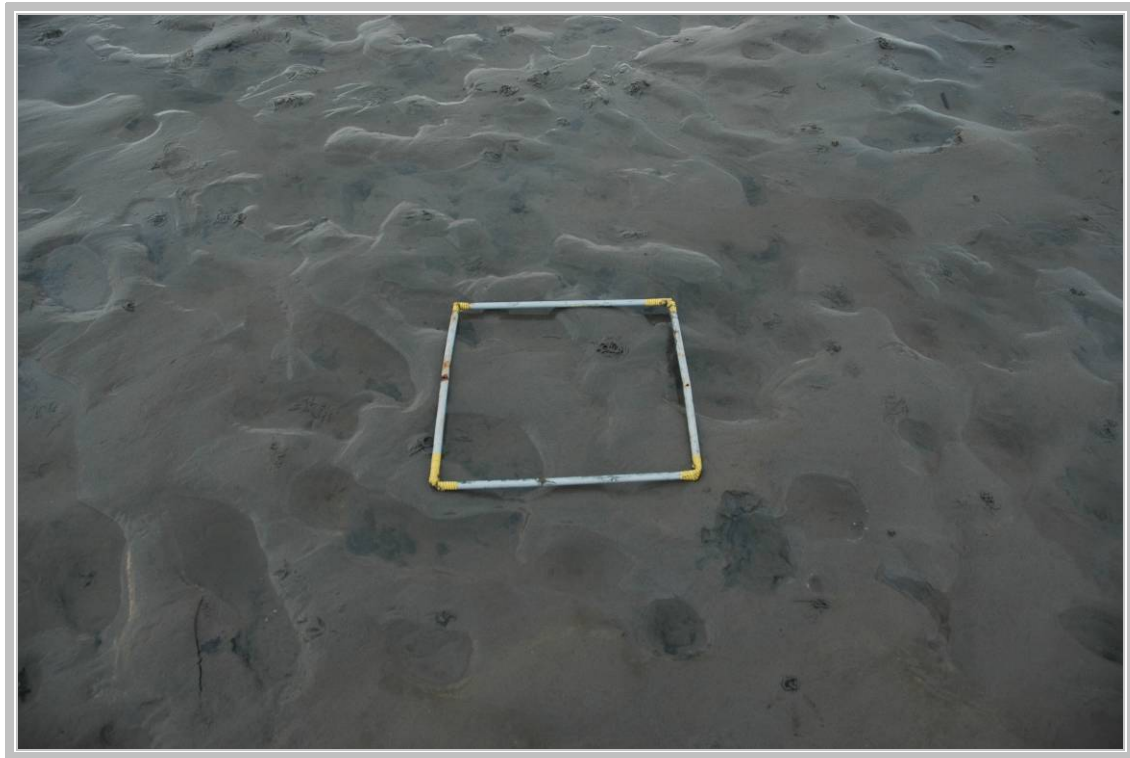


Plate 3-14: Middle shore station (LS.LSa.MoSa.OI.VS) along Transect 2.

Lower Shore

The lower shore station was located in the vicinity of an old cockle bed. Sea lettuce (*Ulva lactuca*), serrated wrack (*Fucus serratus*), gut weed (*Enteromorpha* spp.), sand mason (*Lanice conchilega*) and some *Mytilus* clumps were present (Plate 3-15). The lower shore station had a substrate consisting of fine sand with *Cerastoderma edule* shells and some gravel (Plate 3-16). Sea lettuce occupied 20% of the quadrat and gut weed 30%. From the replicate cores taken at this site, 22 species were recorded (See Table 8 Appendix E). The polychaete *Thayrx* sp. was the dominant species at this location. From the granulometric analyses, this site consisted of 53.8% fine sand and 15.4% gravel. Organic carbon levels at this site were 0.19%. The dig over revealed 11 sand masons (*L. conchilega*), 12 common cockles (*C. edule*) and 9 common mussels (*M. edulis*). The biotope classification for this habitat is LR.LLR.FVS.FserVS *Fucus serratus* and large *Mytilus edulis* on variable salinity lower eulittoral rock (Connor *et al*, 2004).



Plate 3-15: View of the lower shore along Transect 2.



Plate 3-16: Lower shore station (LR.LLR.FVS.FserVS) along Transect 2.

3.2.3. Transect 3

Transect 3 was located at the top of the inner estuary close to the M1 motorway bridge (see Figure 2.2) and mouth of the River Broadmeadow. The transect began at the high tide mark and continued in a south easterly direction to the low tide mark. The total length of the transect was 124.76m. A view across the transect from the low water station is presented in Figure 3.7 along with a profile of the slope from the strandline to the low tide mark.

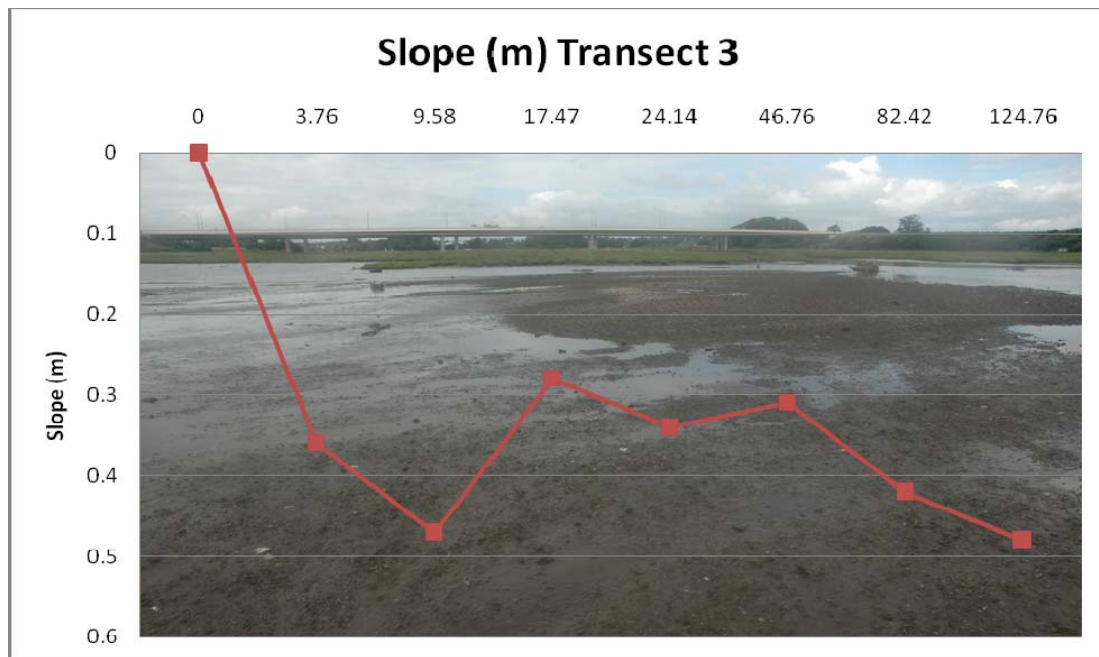


Figure 3.7: View across Transect 3 from the low tide station.

Strandline

The strandline substrate consisted of a mud, sand and gravel mix which approached onto a grass verge (Plate 3-17). The substrate at the strandline station consisted of gravelly sandy mud with approximately 20% grass cover within the quadrat (Plate 3-18). From the replicate cores taken at this site, 13 species were recorded (See Table 9 Appendix D). The oligochaetes *Heterochaeta costata* and Enchytraeidae sp. were the dominant species at this location. From the granulometric analyses, this site consisted of 27.2% fine sand and 16.9% gravel. Organic carbon levels at this site were 1.48%. The dig over did not reveal any faunal life. The biotope at this station represented the LS.LSa.MoSa.OI.VS Oligochaetes in variable salinity littoral mobile sand biotope (Connor *et al*, 2004).



Plate 3-17: Strandline and upper shore of Transect 3.



Plate 3-18: Strandline station along Transect 3 (LS.LSa.MoSa.OI.VS).

Upper Shore

The upper shore consisted of gravel on mixed sands (Plate 3-19). No faunal life was observed in the quadrat from the upper shore station (Plate 3-20). From the replicate cores taken at this site, 11 species were recorded (See Table 10 Appendix E). The oligochaetes *Heterochaeta costata*, *Enchytraeidae* sp. and *Tubificoides pseudogaster* were the dominant species at this location. From the granulometric analyses, this site consisted of 58.6% gravel. Organic carbon levels at this site were 1.72%. The dig over revealed no species. The biotope at this station represented the LS.LSa.MoSa.Ol.VS Oligochaetes in variable salinity littoral mobile sand biotope (Connor *et al*, 2004).



Plate 3-19: View of the upper shore along Transect 3.



Plate 3-20: Upper shore station (LS.LSa.MoSa.OI.VS) along Transect 3.

Middle Shore

The middle shore consisted of a mixture of gravel and sand with a light gut weed (*Enteromorpha* spp.) cover (Plate 3-21). No faunal species were observed in the quadrat (Plate 3-22). From the replicate cores taken at this site, 12 species were recorded (See Table 11 Appendix E). The oligochaetes Enchytraeidae sp. and Oligochaeta sp. were the dominant species at this location. From the granulometric analyses, this site consisted of 31.5% medium sand, 26.1% fine sand and 17% gravel. Organic carbon levels at this site were 1.01%. The dig over revealed no fauna. The biotope at this station represented the LS.LSa.MoSa.OI.VS Oligochaetes in variable salinity littoral mobile sand biotope (Connor *et al*, 2004).



Plate 3-21: View of the middle shore along Transect 3.



Plate 3-22: Middle shore station (LS.LSa.MoS.a.OI.VS) along Transect 3.

Lower Shore

The lower shore consisted of medium soft sand formed into small ripples (Plate 3-23). There was a lot of debris present i.e. tyres, trollies, traffic cones etc. The substrate at the lower shore station consisted of 100% medium sand in ripples (Plate 3-24). No faunal life was observed within the quadrat. From the replicate cores taken at this site, 13 species were recorded (See Table 12 Appendix E). The oligochaetes *Heterochaeta costata* and *Tubificoides pseudogaster* were the dominant species at this location. From the granulometric analyses, this site consisted of 35.4% medium sand and 24.4% coarse sand. The percentage organic carbon within the substrate at this site was 1.26%. The dig over did not reveal any faunal species. The biotope classification for this habitat is LS.LSa.MoSa.Ol.VS Oligochaetes in variable salinity littoral mobile sand (Connor *et al*, 2004).



Plate 3-23: View of the lower shore along Transect 3.

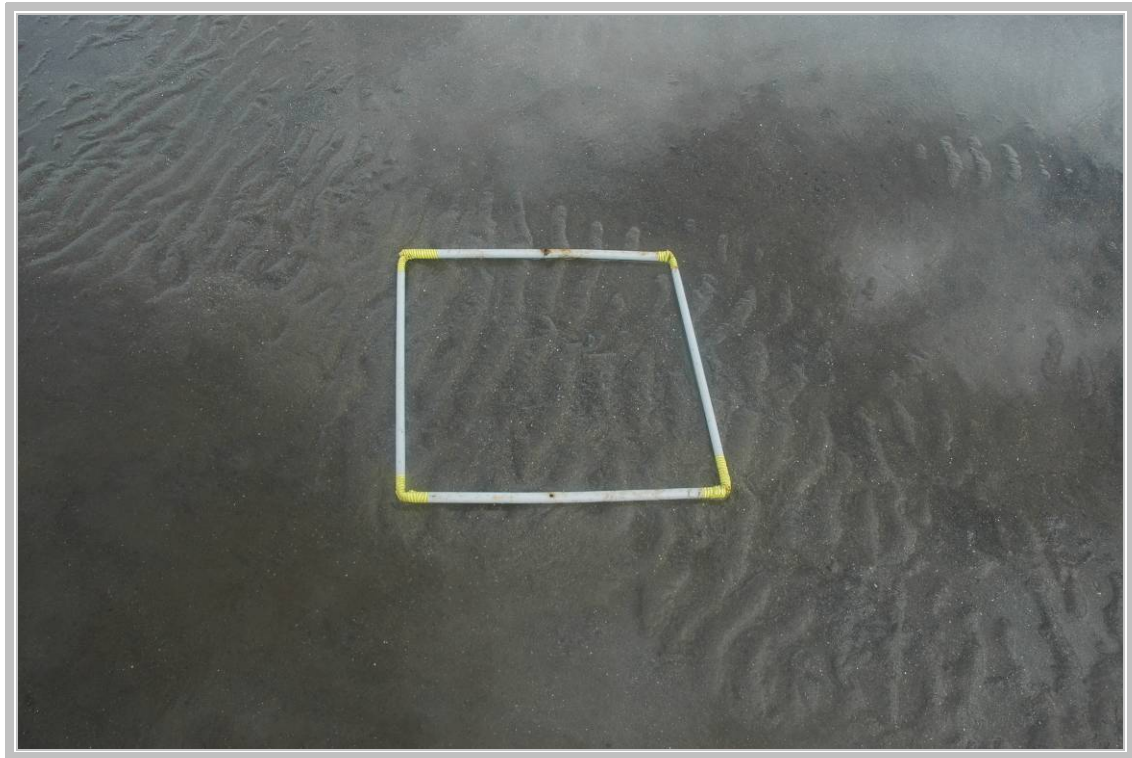


Plate 3-24: Lower shore station (LS.LSa.MoSa.OI.VS) along Transect 3.

4. Discussion

4.1. Subtidal

The 11 subtidal stations sampled in the Broadmeadow Estuary were for the most part dominated by the oligochaetes *Tubificoides* spp. These oligochaetes are pollution tolerant opportunistic species, which are representative of stressed conditions. However, there was a noticeable difference in species composition and sediment type in those stations located in the inner estuary compared to the outer. Species richness was low at all stations sampled in the inner estuary with benthic communities typical of those influenced by variable or reduced salinity conditions. In general, the inner stations were dominated by one or two small opportunistic pollution tolerant species, which is usually indicative of organically or nutrient enriched sediments. Multivariate analysis grouped the inner stations together in a biotope that showed characteristics of the SS.SMU.SMuVS.CapTubi or SS.SMU.SMuVS.OVIS biotopes (Connor *et al*, 2004). These biotopes are typical of reduced or variable salinity muddy sediment characterised by the *Capitella capitata* species complex with relatively low species richness. Large numbers of the oligochaetes *Tubificoides* spp. may be found in conjunction with *C. capitata*, along with other species. This biotope usually has a moderate organic content, and is found away from tidal channels in estuaries. The biotope has classically been associated with organically enriched and physically disturbed habitats in the marine environment.

Although *Tubificoides* spp. was also a major component of the fauna recovered from the stations located in the outer estuary (Stations 1 & 2), the overall species list was more diverse with an established *Lanice conchilegal/Sabella pavonina* community that is characterised by SS.SMx.IMx.SpavSpAn *Sabella pavonina* with sponges and anemones on infralittoral mixed sediment biotope (Connor *et al* 2004). This biotope is known to occur in strong to moderate tidal currents on muddy gravelly sand off shallow, sheltered or moderately exposed coasts or embayments and may support dense populations of the peacock worm *Sabella pavonina*. This biotope may have an extremely diverse epifaunal community. Less is known about its infaunal component, although it is likely to include polychaetes such as *Nephtys* spp., *Harmothoe* spp., *Glycera* spp., syllid and cirratulid polychaetes, bivalves such as *Abra* spp., Aoridae

amphipods and brittlestars such as *Amphipholis squamata*.

In addition to oligochaetes, other typical species found in appreciable numbers in the estuary were the anemones *Sagartia* sp. and *Cereus pedunculatus*, the polychaetes *Sabella pavonina*, *Eumida bahusiensis*, *Tharyx killariensis*, *Heteromastus filiformis*, *Streblospio benedicti* and *Hediste diversicolor*. These species are typical of an estuarine environment subjected to varying salinity conditions and enrichment.

Sediment Profile Imagery gave a clear visual profile of the benthic environment at each of the stations and results were in keeping with the statistical designation of the stations into groupings based mainly on sediment type and faunal composition. The two outer stations had a predominant fine sand component over rock with a stable faunal community dominated by *Sabella pavonina*, *Lanice conchilega* and *Cereus pedunculatus*. The inner estuary stations had a sediment composition dominated by silt/clay with no obvious fauna being imaged.

The sediment composition at each of the stations indicate that the weir across the mouth of the inner estuary under the railway viaduct has an important part to play in sedimentation within the inner estuary. While there is a strong tidal current in the outer estuary for the duration of the tide, water exchange to the inner estuary is restricted by the weir with limited water movement once the water level falls below the top of the weir on the ebbing tide and doesn't flow again until this elevation is again reached on the flooding tide. As a consequence, fine material suspended in the water column in the inner estuary will settle to the seafloor and the bottom will have a progressively higher silt/clay composition on moving down the inner estuary towards the weir. This is also confirmed by the biotopes identified in the inner estuary as they are those typically found towards the edges of tidal channels in estuaries where current velocities allow deposition of silt and the establishment of an infaunal community. Organic loading and poor water-exchange within the sediment lead to anoxic conditions which may explain the low species richness within these biotopes, the stations with the lowest values located at the lower end of the inner estuary.

Faunal composition of the samples from the inner estuary are very much in keeping with the results of the survey carried out in the inner estuary by the Marine Research

Unit, UCD, in 1993 (Healey *et al*, 1993). Healey *et al* (1993) reported the sublittoral fauna of the Inner Estuary to be poor in terms of both species diversity and density with only two species, *Sagartia ornata* and a species of capitellid, being widespread and occurring in relatively high numbers at some stations. In comparing the results of that survey to the present it would seem that the ecological status of the inner estuary has changed little in the intervening years between surveys. A similar conclusion was made in 1998 when the 1993 survey results were compared to a broadscale survey of the estuary, which was carried out by Aquafact (1998). However, it must be remembered that although there has been little change in the ecological status of the estuary, the faunal communities and biotopes identified from the inner estuaries are typical of those from a system under stress from organic and nutrient enrichment.

4.2. Intertidal

Transect 1 was located in the outer estuary and consisted of a typical saltmarsh community at the strandline. The shore was characterised by gravelly sand. The seaweeds, *Pelvetia canaliculata*, *Enteromorpha* and *Fucus spiralis* were present in the upper shore, with the gravelly sand component dominated by oligochaetes. The polychaete *Tharyx* sp. dominated the middle shore species composition and lugworms, catworms and common cockles were present. The lower shore was characterised by sand mason beds, common mussels, common cockles, sea lettuce, gut weed and some sponges. Oligochaetes and *Tharyx* sp. dominated the lower shore.

Transect 2 was located on the mudflat in the northern part of the outer estuary. The standline consisted of a man-made embankment encrusted with typically littoral lichen species. The shore was characterised by gravelly sand to fine sand. Mussel and cockle shells were scattered throughout this area. *Pelvetia canaliculata*, *Ascophyllum nodosum* and *Fucus spiralis* were present close to the strandline. Oligochaetes and *Tharyx* sp. dominated the sediment. The upper shore consisted of mud with some mussel clumps, lugworm casts and *Enteromorpha* spp. Oligochaetes dominated the upper shore sediment matrix. The middle shore consisted of fine sand with cockle shells and lugworm casts. Oligochaetes dominated the sediment matrix. Cockles and catworms were also present. The lower shore consisted of an old cockle

bed. Present in the lower shore was *Ulva lactuca*, *Fucus serratus*, *Enteromorpha* spp., sand masons, mussel and cockles. The polychaete *Thayrx* sp. dominated the sediment matrix

Transect 3 was located in the inner reaches of the inner estuary. A grass verge was located at the strandline. Oligochaetes dominated the sandy gravel matrix. Oligochaetes dominated the upper shore also. The middle shore consisted of a mixture of gravel and sand with a light *Enteromorpha* spp. cover. Again, oligochaetes dominated the sediment matrix. The lower shore consisted of medium soft sand in ripples. There was a lot of debris present along the lower shore i.e. tyres, trollies, traffic cones etc. Oligochaetes dominated the sediment matrix.

The dominant biotope found in the intertidal zone of the Broadmeadow Estuary was characterised by oligochaete species. These are opportunistic pollution tolerant species which are usually indicative of organically or nutrient enriched sediments. This biotope consists of a species-poor community of oligochaetes, which typically occurs in estuarine conditions where sands and gravel are associated with the lower shore river channel in estuaries. The sediment is relatively coarse and mobile due to strong river flow and subject to variable salinity. There is usually very little mud in the sediment. Oligochaetes, including enchytraeid oligochaetes, constitute the infaunal assemblage. The saltmarsh biotope located in the strandline area of Transect 1 is a protected habitat and is noted in the SAC site synopsis (See Appendix F).

References

Aquafact International Services Ltd. 1998. Broadmeadow Estuary Survey, April 1998. Report to Tobin Environmental Services.

Clarke K.R. & Warwick RM (1994) Similarity-based testing for community pattern: the 2-way layout with no replication. *Mar Biol* 118, 167-176

Connor, D.W., Allen, J.H., Golding, N., Howell, K.L., Lieberknecht, L.M., Northern, K.O. & J.B. Reker. 2004. The Marine Habitat Classification for Britain and Ireland. Version 04.05. Littoral Sediment Section. JNCC, Peterborough. ISBN 1 861 07561 8 (internet version). www.jncc.gov.uk/MarineHabitatClassification

Folk, R.L. 1974. Petrology of Sedimentary Rocks. Hemphill Publishing Co., Austin, Texas, 182pp.

Healy, B, Galvin, P & Lyons, J. 1993. Environmental Impact Study of the Aquatic Fauna of the Inner Manlaide Estuary, Co. Dublin. Marine Research Group, UCD for Dublin City Council.

Kruskal, J.B. and Wish, M. (1978), *Multidimensional Scaling*, Sage University Paper series on Quantitative Applications in the Social Sciences, 07-011. Beverly Hills and London: Sage Publications

Margalef, R. (1958). Temporal succession and spatial heterogeneity in phytoplankton. In: Buzzti-Traverso, A. A. (ed.) *Perspectives in marine biology*. University of California Press, Berkeley, p. 323–349

Nilsson, H. & R. Rosenberg, 1997. Benthic habitat quality assessment of an oxygen stressed fjord by surface and sediment profile images. *J. Mar. Syst.* 11: 249-264..

Pielou, E.C. 1977. *Mathematical Ecology*. Wiley, New York, 385pp.

Appendix A
Subtidal Species List

[illegible]

[illegible]

[illegible]

Station			6a	6b	6c	7a	7b	7c	8a	8b	8c	9a	9b	9c	10a	10b	10c
PORIFERA	C	1															
HALICHONDRIA	C	525															
Halichondria sp.	C	632															
CNIDARIA	D	1															
ACTINIARIA	D	662															
Cerus pedunculatus	D	662															
Sagartia sp.	D	674	6	6	5	13	12	26	18	22	18	54	45	58	28	15	9
NEMATODA	HD	1															
Nematoda sp.	HD	1											1				
ANNELIDA	P	1															
PHYLLODOCIDA	P	3															
Polynoidae	P	25															
Harmothoe sp.	P	50															
Lepidonotus squamatus	P	83							1								
Pholoidae	P	90															
Pholoe inornata	P	92															
Sigalionidae	P	96															
Sthenelais boa	P	107															
Phyllodocidae	P	114															
Eteone longa	P	118															
Anaitides mucosa	P	145															
Eumida sp.	P	163															
Eumida bahusiensis	P	164															
Eumida sanguinea	P	167															
Sphaerodoridae	P	277															
Ephesiella abyssorum	P	282															
Nereididae	P	458															
Kefersteinia cirrata	P	305															
Hediste diversicolor	P	462	1			1	1		1	2		1	4	2			1
Nereis sp.	P	473			1			1			3						

[illegible]

Station			11a	11b	11c	Station			11a	11b	11c
PORIFERA	C	1				Nephtyiidae	P	490			
HALICHONDRIA	C	525				Nephtys sp.	P	494			
Halichondria sp.	C	632				Nephtys hombergii	P	499			
CNIDARIA	D	1				Nephtys incisa	P	501			
ACTINIARIA	D	662				SPIONIDA	P	707			
Cerus pedunculatus	D	662				Spionidae	P	720			
Sagartia sp.	D	674				Aonides oxycephala	P	722			
NEMATODA	HD	1				Polydora sp.	P	748			
Nematoda sp.	HD	1				Polydora ciliata	P	752			
ANNELIDA	P	1				Prionospio sp.	P	763			
PHYLLODOCIDA	P	3				Pygospio elegans	P	776			
Polynoidae	P	25				Streblospio benedicti	P		14	22	14
Harmothoe sp.	P	50				Cirratulidae	P	822			
Lepidonotus squamatus	P	83				Cirratulidae sp.	P	822			
Pholoidae	P	90				Caulleriella alata	P	829			
Pholoe inornata	P	92				Caulleriella zetlandica	P	831			
Sigalionidae	P	96				Chaetozone sp.	P	832			
Sthenelais boa	P	107				Chaetozone gibber	P	833			
Phyllodocidae	P	114				Cirriformia tentaculata	P	839			
Eteone longa	P	118				Tharyx killariensis	P	846			
Anaitides mucosa	P	145				CAPITELLIDA	P	902			
Eumida sp.	P	163				Capitella sp.	P	906			
Eumida bahusiensis	P	164				Heteromastus filiformis	P	917	1	3	2
Eumida sanguinea	P	167				Notomastus latericeus	P	921			
Sphaerodoridae	P	277				OWENIIDA	P	1089			
Ephesiella abyssorum	P	282				Oweniidae	P	1090			
Nereididae	P	458				Galathowenia oculata	P	1093			
Kefersteinia cirrata	P	305				TEREBELLIDA	P	1099			
Hediste diversicolor	P	462	1	1	1	Ampharetidae	P	1118			
Nereis sp.	P	473	1	1		Melinna palmata	P	1124			

[illegible]

Appendix B

SIMPER Results

Group I

Average similarity: 53.58%

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Tubificoides benedii	2.2	4.63	#####	8.64	8.64
Cerus pedunculatus	2.21	4.02	#####	7.51	16.15
Tubificoides pseudogaster	1.49	3.82	#####	7.13	23.28
Eumida bahusiensis	1.47	3.48	#####	6.5	29.78
Eumida sp.	1.29	3.15	#####	5.88	35.66
Sthenelais boa	1.07	2.39	#####	4.47	40.12
Nereis sp.	0.95	2.39	#####	4.47	44.59
Nephtys sp.	1.05	2.39	#####	4.47	49.05
Caulleriella zetlandica	0.95	2.39	#####	4.47	53.52
Cirriformia tentaculata	0.95	2.39	#####	4.47	57.99
Modiolula phaseolina	0.95	2.39	#####	4.47	62.45
Lepidonotus squamatus	0.83	2.01	#####	3.75	66.21
Pholoe inornata	0.83	2.01	#####	3.75	69.96
Eteone longa	0.83	2.01	#####	3.75	73.72
Anaitides mucosa	1.07	2.01	#####	3.75	77.47
Eumida sanguinea	0.88	2.01	#####	3.75	81.23
Cirratulidae sp.	0.88	2.01	#####	3.75	84.98
Sabella sp.	0.76	2.01	#####	3.75	88.74
Achelia echinata	0.92	2.01	#####	3.75	92.49

NOTE: Sim/SD could not be calculated for this group because there was only 2 stations in this group.

Group II

Average similarity: 67.6%

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Tubificoides pseudogaster	2.33	14.9	6.62	22.04	22.04
Tubificoides benedii	1.96	12.07	3.48	17.85	39.89
Heteromastus filiformis	1.89	11.38	4.68	16.84	56.73
Sagartia sp.	1.73	8.91	1.36	13.18	69.91
Hediste diversicolor	0.94	6.23	8.77	9.22	79.13
Tharyx killariensis	1.18	5.72	1.34	8.46	87.59
Streblospio benedicti	1.14	5.28	1.29	7.81	95.4

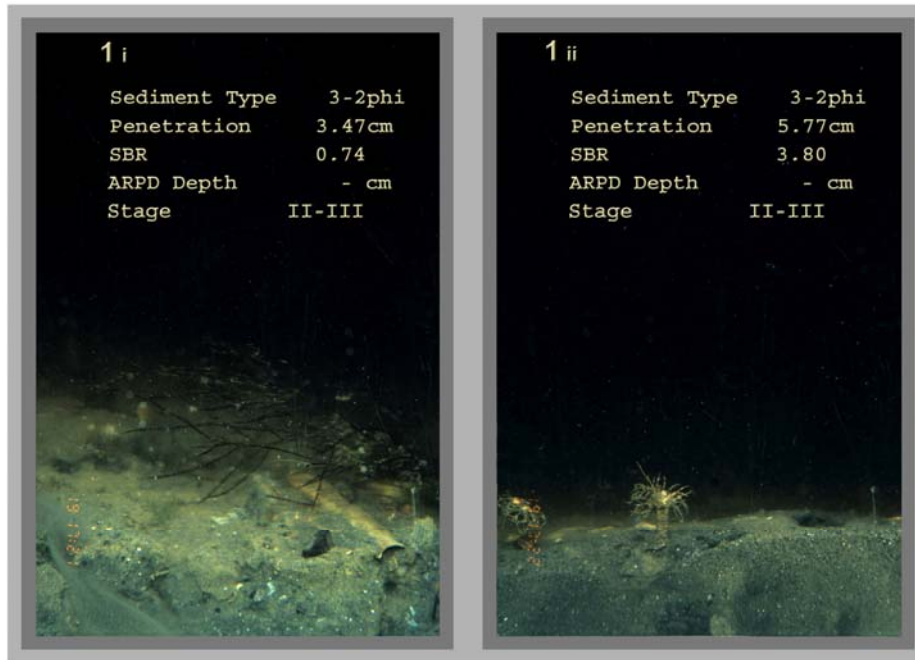
Group III

Average similarity: 69.01%

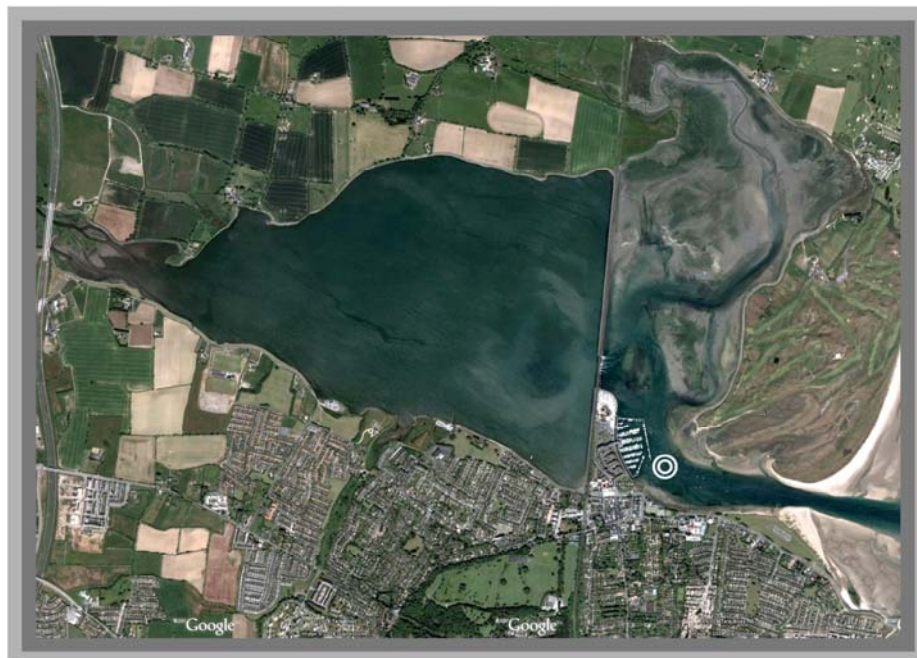
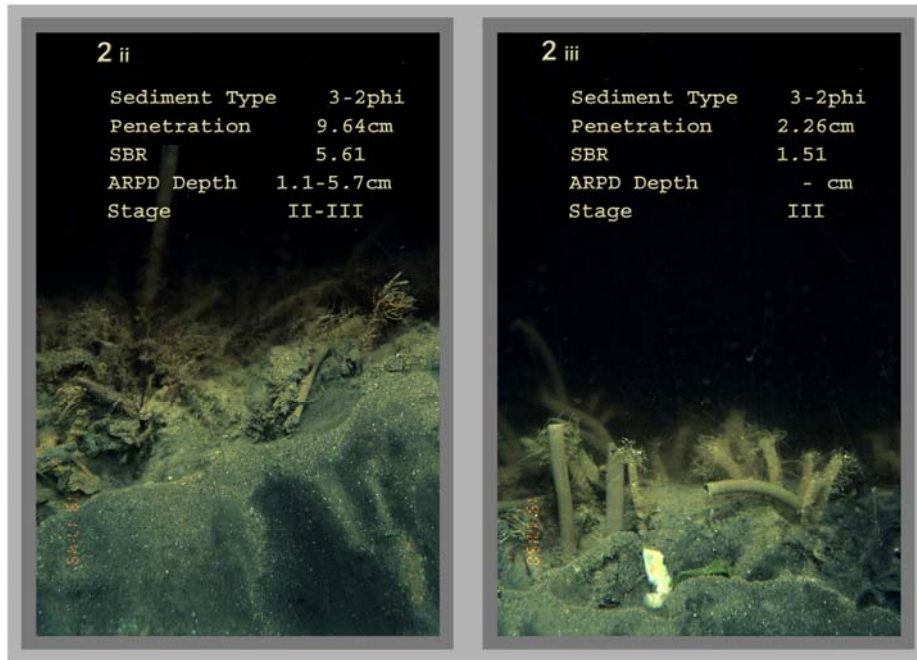
Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Tubificoides benedii	1.21	38.44	#####	55.7	55.7
Tubificoides pseudogaster	0.99	30.57	#####	44.3	100

NOTE: Sim/SD could not be calculated for this group because there was only 2 stations in this group.

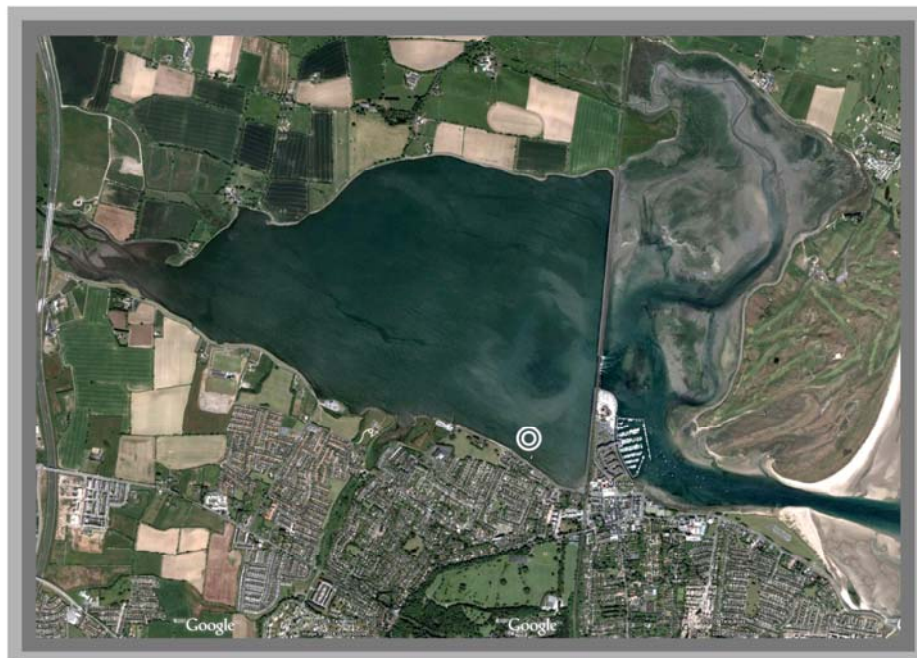
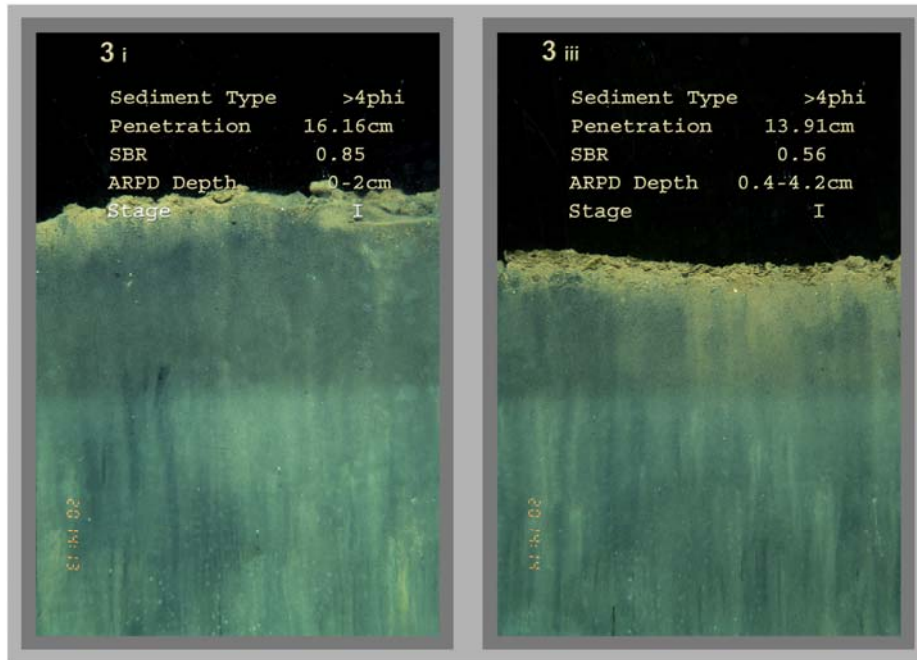
Appendix C
Sediment Profile Imagery (SPI) Results,
Apparatus and Data Analysis



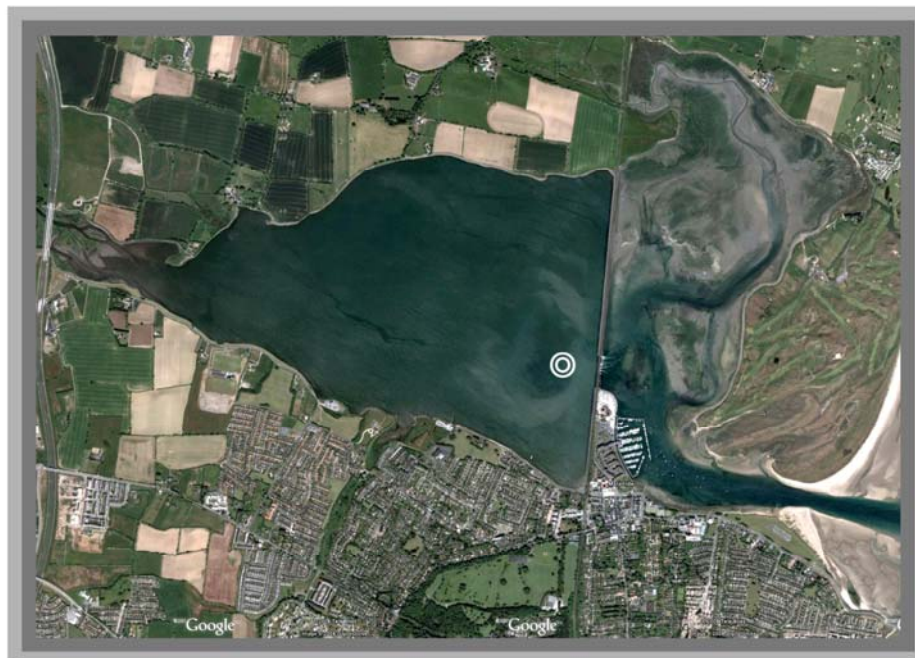
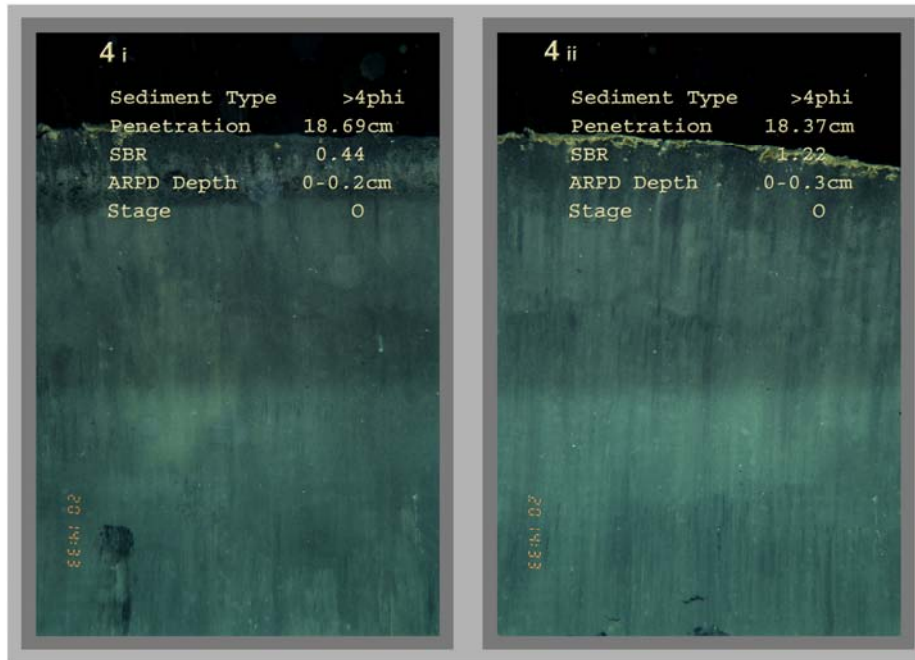
Station 1: Sediment profile images and location aerial view (© Google).



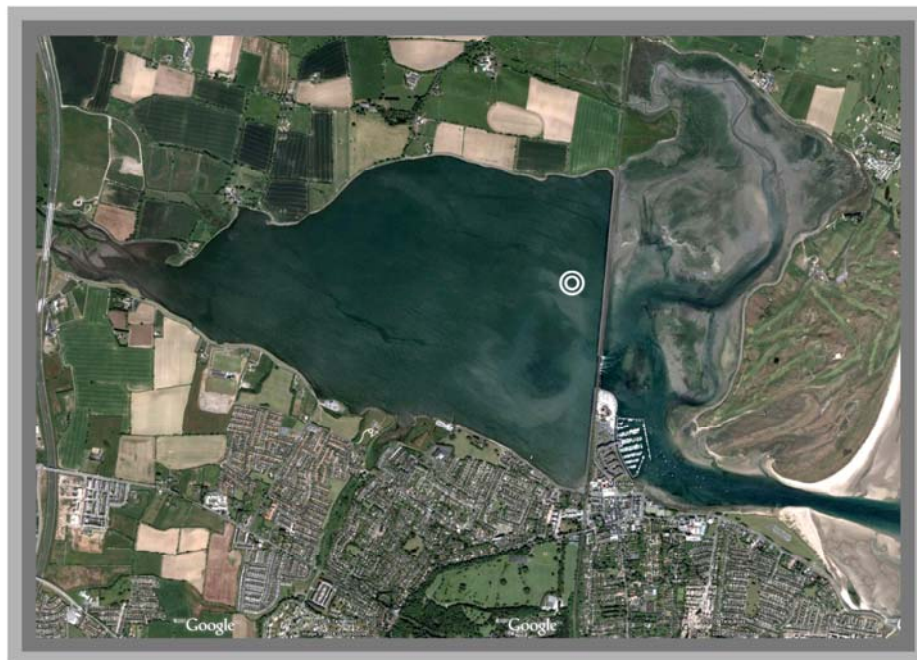
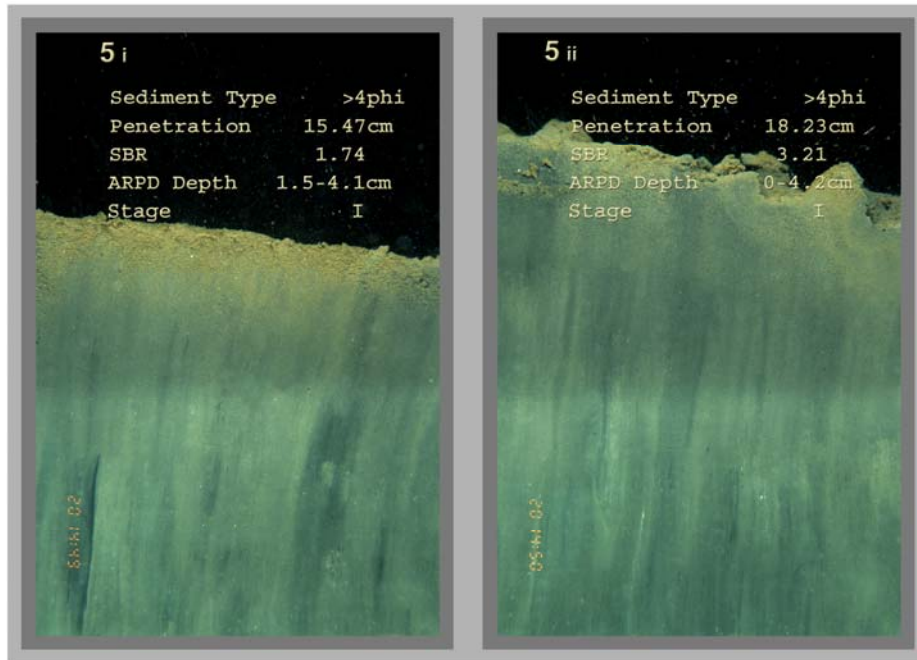
Station 2: Sediment profile images and location aerial view (© Google).



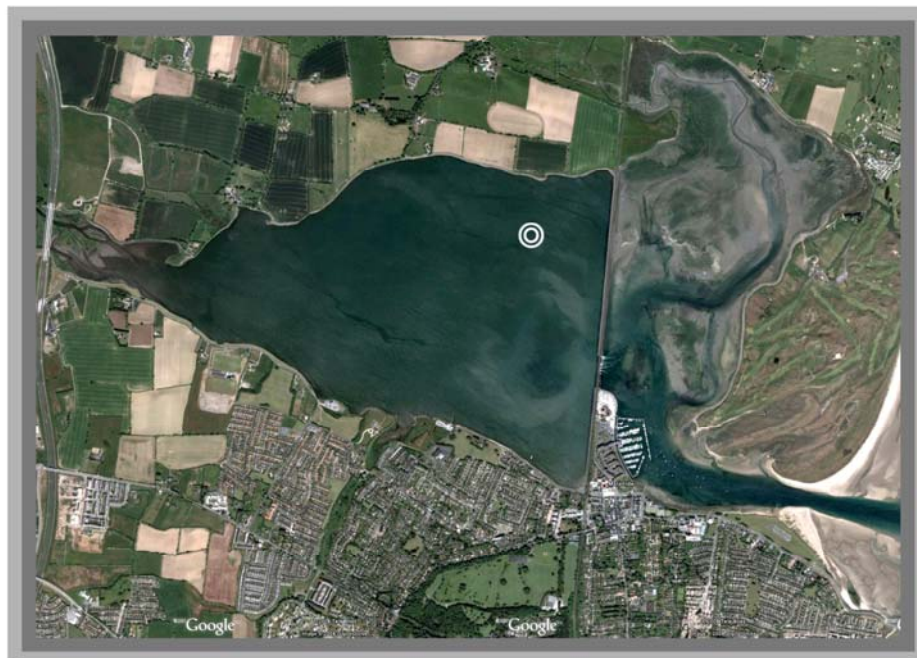
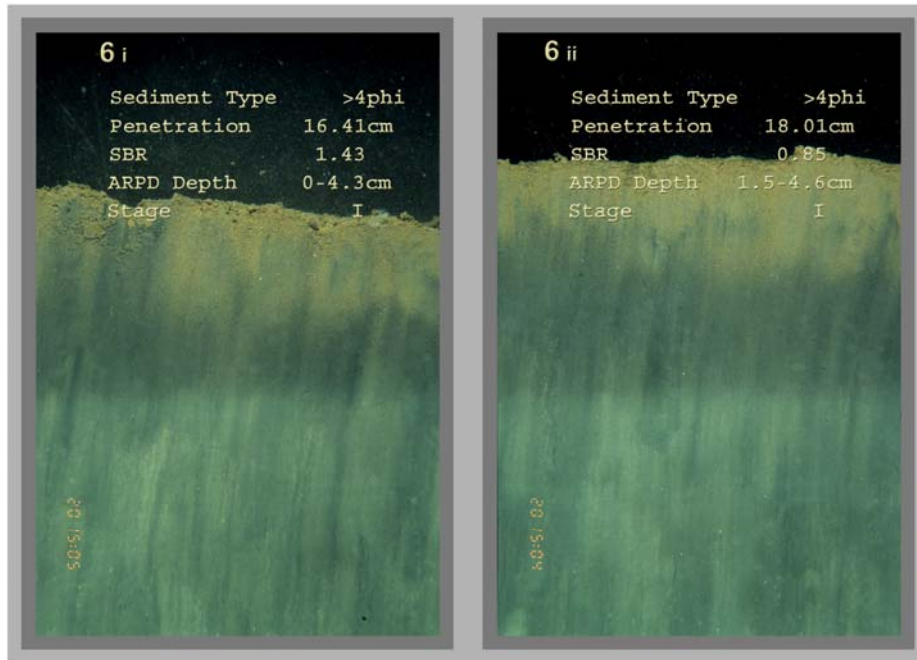
Station 3: Sediment profile images and location aerial view (© Google).



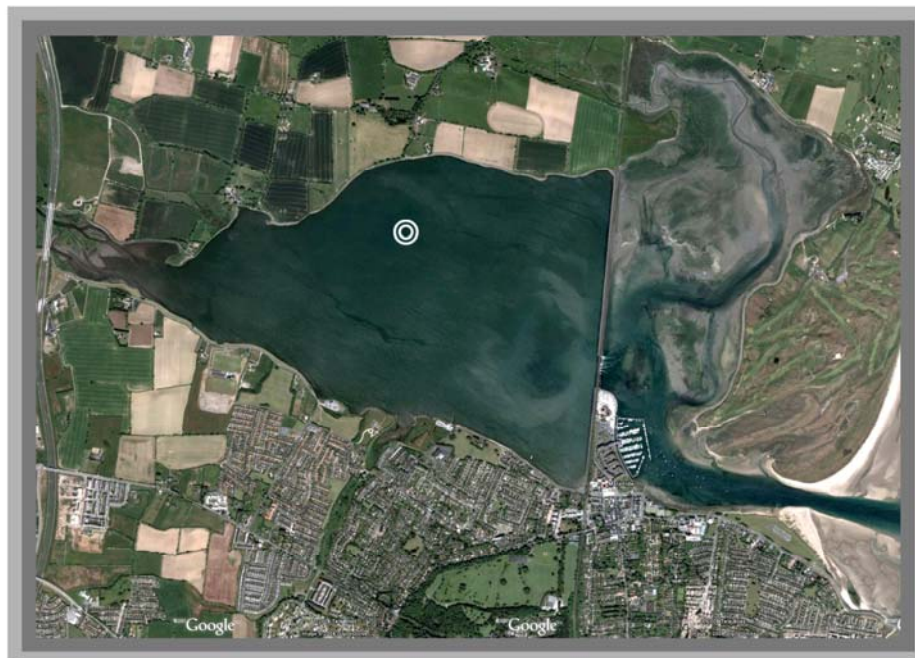
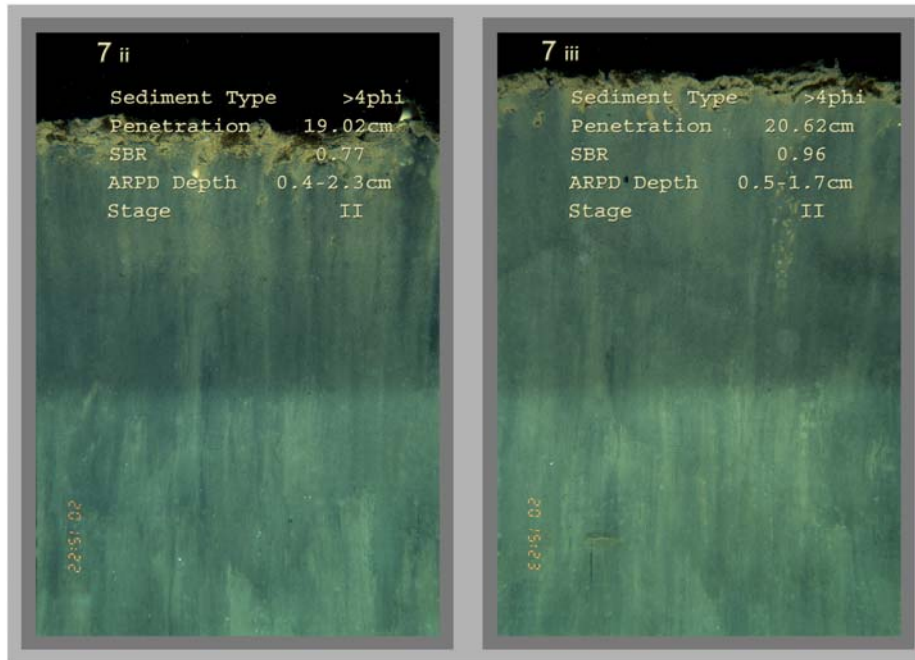
Station 4: Sediment profile images and location aerial view (© Google).



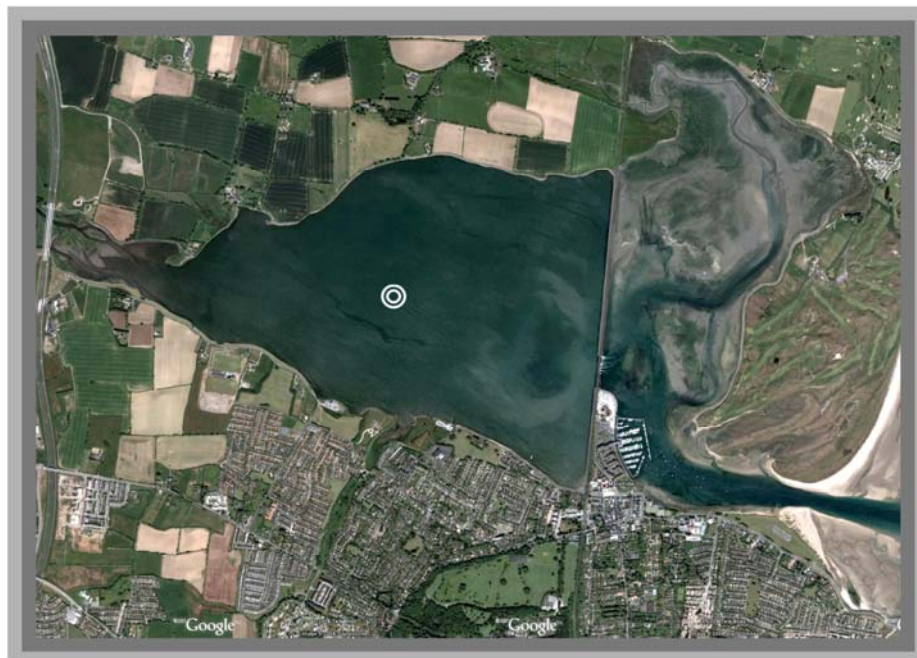
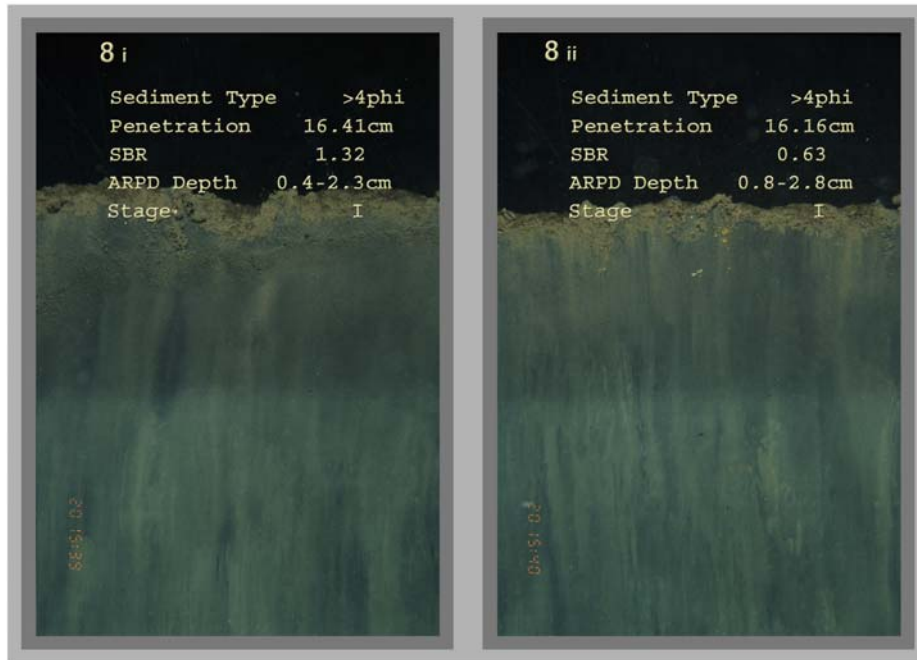
Station 5: Sediment profile images and location aerial view (© Google).



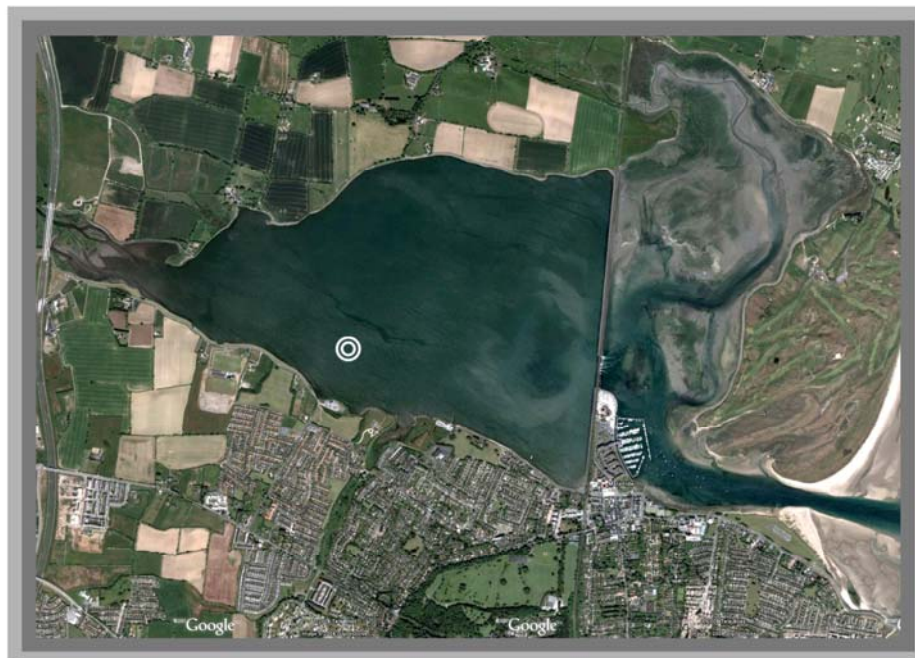
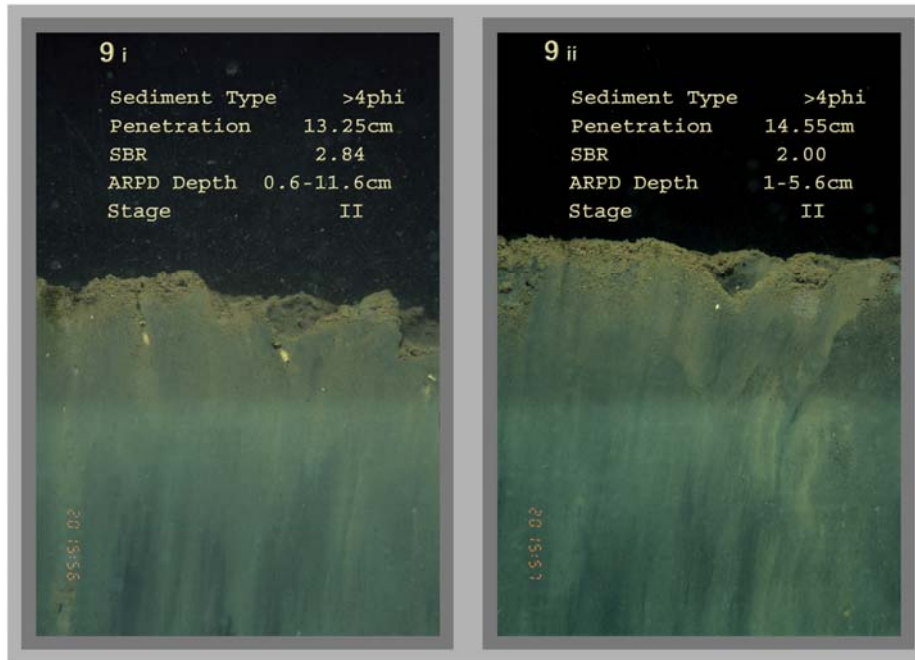
Station 6: Sediment profile images and location aerial view (© Google).



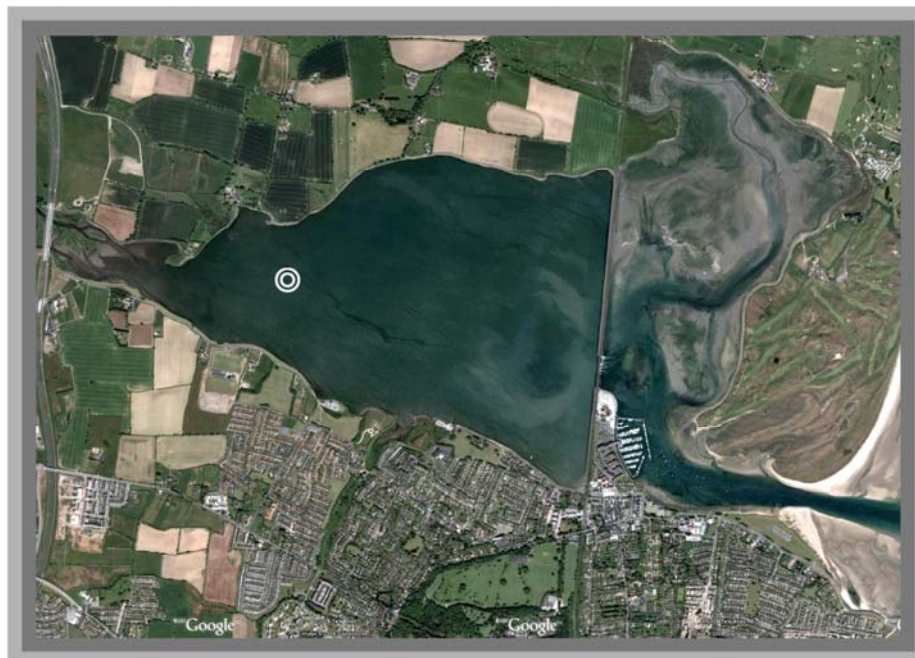
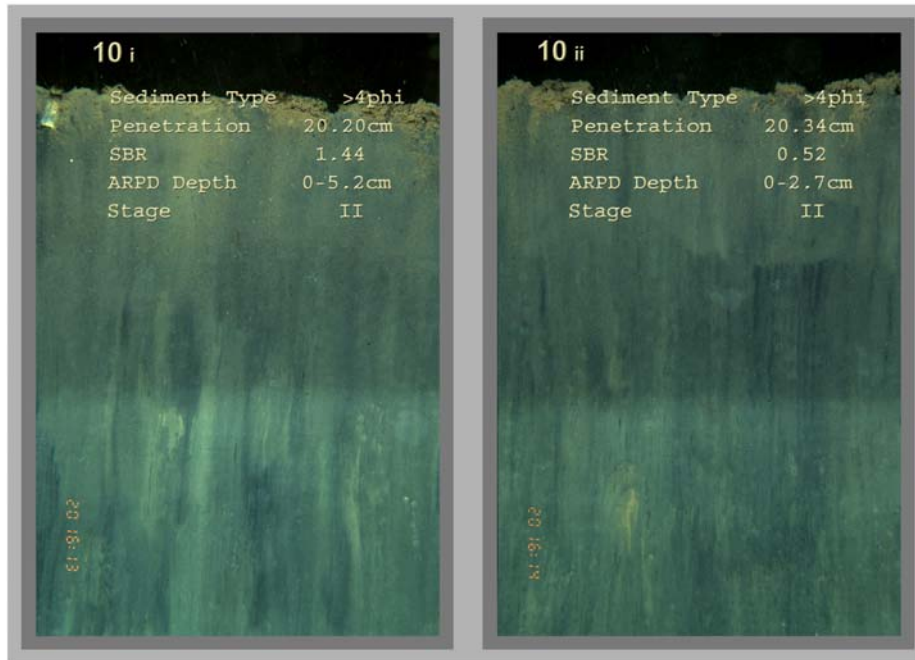
Station 7: Sediment profile images and location aerial view (© Google).



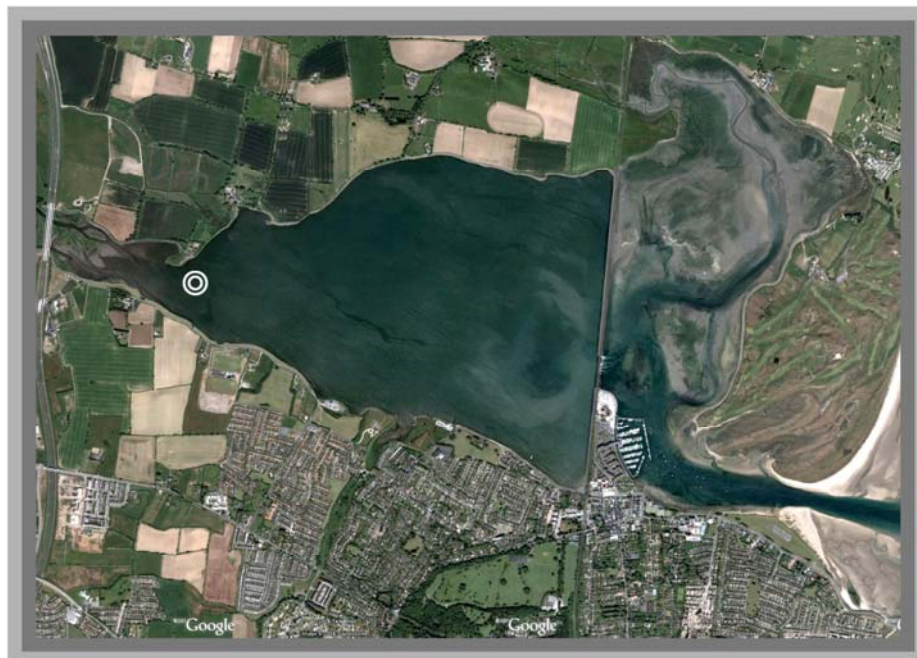
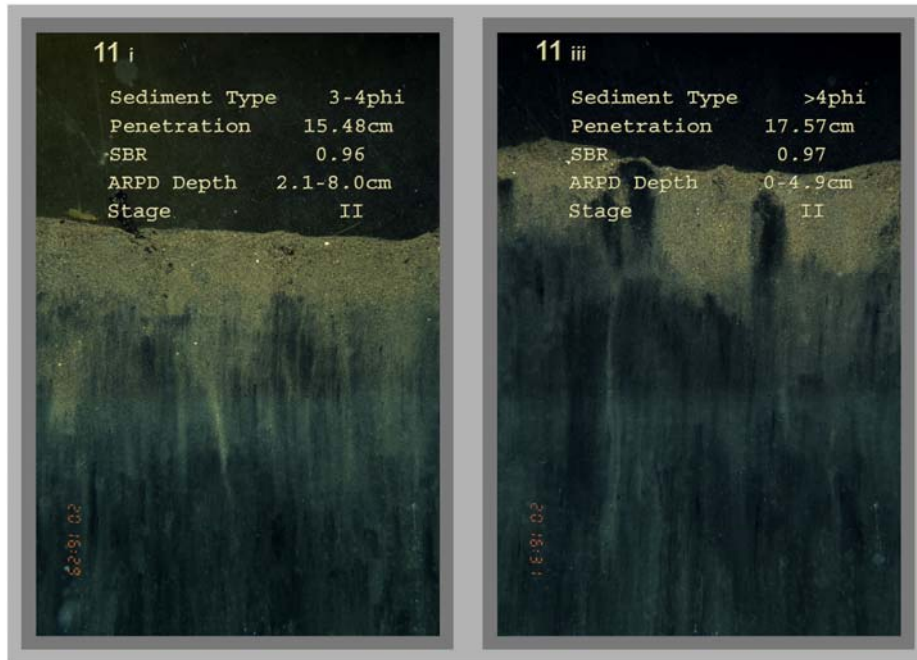
Station 8: Sediment profile images and location aerial view (© Google).



Station 9: Sediment profile images and location aerial view (© Google).



Station 10: Sediment profile images and location aerial view (© Google).



Station 11: Sediment profile images and location aerial view (© Google).

Sediment Profile Imagery (SPI) – apparatus and data analysis



APPARATUS AND DEPLOYMENT

A remotely operated sediment profile camera is used to obtain *in situ* digital profile images of up to 20 cm of the top layers of sediment on the seafloor. It differs from other underwater cameras in that it vertically slices through the sediment-water interface and images the sediment section in profile. Functioning like an inverted periscope, it consists of a wedge-shaped prism with a plexiglass face plate. Light is provided internally by a flash strobe and the back of the prism has a mirror mounted at a 45° angle. This reflects the image of the sediment-water interface at the face plate up to the camera, which is housed on top of the prism. The camera - prism assembly is supported by an inner frame or cradle which can move relative to an outer supporting frame under control of a 'passive' hydraulic piston (see Figure 1).

The camera prism assembly cradle can be moved up and down by producing tension or slack on the winch wire. As the camera is lowered to the seafloor, tension on the winch wire keeps the prism in the up position. The supporting frame lands on the bottom first, leaving the area directly under the prism undisturbed. As the winch wire is slackened, the prism cradle descends toward the bottom at a controlled rate of fall (Figure 2). The wedge-shaped prism enters the bottom and is driven into the sediment by its weight. The piston ensures that the prism enters the bottom slowly and does not disturb the sediment - water interface. Additional lead weights can be attached to the prism cradle to assist prism penetration if required.

On impact with the bottom, a trigger activates a time delay on the camera shutter release and a digital photograph is taken when the prism comes to rest. Because the sediment is photographed directly against the face plate, turbidity of the ambient seawater does not affect image quality. After the photograph or image is taken, tension on the winch wire raises the prism cradle to the up position, a wiper blade cleans off the face plate, the strobe is recharged and the camera can be lowered for another image. In this manner the SPI assembly can be rapidly 'hopped' over the seabed and a series of images obtained at any one sampling location. After the camera is taken back on board a rubber ring records the depth the camera had penetrated and a counter records the number of successful image shots taken. Specific measurement techniques and interpretive considerations for the analysis of a range of parameters from the SPI images are presented below.

A compact, equally effective diver operated sediment profile camera apparatus (Figure 3) has been developed for operation in shallow waters and shallow areas generally inaccessible by the larger remotely operated machine. As with the remotely operated SPI camera, the camera prism is mounted on a supporting stabiliser frame which can be moved up and down in an action controlled by a hydraulic system. Once the camera's frame touches the bottom, the scientific diver exerts pressure on the prism housing causing it to penetrate the sediment fabric under control of the hydraulic piston. This allows the optical prism to enter the bottom at approximately 6 cm sec^{-1} . The slow fall rate ensures that the descending prism does not impact the bottom at a high rate and therefore minimizes disturbance of the sediment-water interface. The prism is driven several centimeters into the seafloor and the camera trigger is tripped so that a photograph is taken. The diver ensures that the SPI frame is not moved or disturbed in any way while the camera is taking a picture so that any physical disturbance of the sediment detected in a SPI image is not an artifact caused by the instrument itself.

DATA ANALYSIS

Images are captured using Canon EOS 450D digital SLR cameras (12 megapixel) and Nikkor optics and are stored on SD (secure digital) memory cards. They are downloaded to a laptop computer before being analysed in detail. The image analysis system used can discriminate a wide range of different grey scales, so subtle features can accurately be digitised and measured.

Customised software in conjunction with an image analysis system is used for the analysis of a series of 21 physical, chemical and biological parameters on each image. Before all measurements from each SPI image are stored on disk, a summary display is made on the screen so the operator can verify if the values stored in memory for each variable are within expected range; if anomalous values are detected, software options allow re-measurement before storage on disk. All data stored on disks are printed out on data sheets for editing by the principal investigator and as a hard-copy backup of the data stored on disk; a separate data sheet is generated for each SPI image. Disk storage of all SPI parameters allows any variable of interest to be compiled, sorted, graphed, or compared statistically.

A great deal of information about benthic processes is available from sediment profile images. Measurable parameters, many of which are calculated directly by image analysis, include physical / chemical parameters (i.e. sediment type measured as grain size major mode, prism penetration depth providing a relative indication of sediment shear strength, sediment surface relief, condition of mud clasts, redox potential discontinuity depth and degree of contrast, sediment gas voids) and biological parameters (i.e. infaunal successional stage of a well documented successional paradigm for soft marine sediments (see Pearson and Rosenberg, 1978), degree of sediment reworking, dominant faunal type, epifauna and infauna, apparent species richness, depth of faunal activity, presence of microbial aggregations).

A multi- parameter organism-sediment index (OSI) is calculated on the basis of the measured physical and biological parameters. This index characterises habitat quality and has been found to be an excellent parameter for mapping disturbance gradients and the health status of the seabed. Specific analytical and interpretative aspects of the parameters measured from the SPI images are outlined below.

SEDIMENT TYPE DETERMINATION

The sediment grain-size major mode and range are visually estimated from the photographs by overlaying a grain-size comparator, which is at the same scale. This comparator was prepared by using the SPI camera to photograph a series of pre-prepared sediments which were graded according to the Udden-Wentworth size classification scheme. The classes of sediment used ranged from mud to granule. There are seven grain-size classes on the comparator, i.e. $< 0.063\text{mm}$ ($\geq 4\phi$) (i.e. silt clay), $0.063 - 0.125\text{mm}$ ($4-3\phi$) (i.e. very fine sand), $0.125 - 0.25\text{mm}$ ($3-2\phi$) (i.e. fine sand), $0.25 - 0.5\text{mm}$ ($2-1\phi$) (i.e. medium sand), $0.5 - 1.0\text{mm}$ ($1-0\phi$) (i.e. coarse sand), $1.0 - 2.0\text{mm}$ (0 to $-(-)1\phi$) (i.e. very coarse sand), $> 2.0\text{mm}$ ($< -1\phi$) (i.e. gravel). Seven grain-size classes are on this comparator: $\geq 4\phi$, $4-3\phi$, $3-2\phi$, $2-1\phi$, $1-0\phi$, $0-(-)1\phi$, $< -1\phi$. The lower limit of optical resolution of the photographic system is about 0.062mm , allowing recognition of grain sizes equal to or greater than coarse silt. The accuracy of the method has been documented by comparing the SPI estimates with grain-size statistics determined from laboratory sieve analyses.

PRISM PENETRATION DEPTH

The SPI prism penetration depth is determined by measuring both the largest and smallest linear distance between the sediment-water interface and the bottom of the digital

image frame. The **SPI** analysis software automatically averages these maximum and minimum values to determine the average penetration depth. All three values, (maximum, minimum, and average penetration depth) are included on the data sheets. Prism penetration is potentially a noteworthy parameter; if the number of weights used in the camera is held constant throughout a survey, the camera functions as a static-load penetrometer. Comparative penetration values from sites of similar grain-size give an indication of the relative sediment bearing capacity or shear strength.

SEDIMENT BOUNDARY ROUGHNESS

Sediment boundary roughness is determined by measuring the vertical distance (parallel to the digital image border) between the highest and lowest points of the sediment-water interface. In addition, the likely origin (e.g. physical or biogenic) of this small-scale topographic relief is indicated when it is evident. In sandy sediments, boundary roughness can be a measure of sand wave height. On silt-clay bottoms, boundary roughness values often reflect biogenic features such as faecal mounds or surface burrows.

MUD CLASTS

When fine-grained, cohesive sediments are disturbed, either by physical bottom scour or faunal activity (e.g. decapod foraging), intact clumps of sediment are often scattered about the seafloor. These mud clasts can be seen at the sediment-water interface in **SPI** images. During analysis, the number of clasts is counted, the diameter of a typical clast is measured, and their oxidation state is assessed. Depending on their place of origin and the depth of disturbance of the sediment column, mud clasts can be reduced or oxidised (in **SPI** images, the oxidation state is apparent from their reflectance value; see 'Apparent redox potential discontinuity depth' section below). Also, once at the sediment-water interface, these sediment clumps are subject to bottom-water oxygen levels and bottom currents. Based on laboratory microcosm observations of reduced sediments placed within an aerobic environment, oxidation of reduced surface layers by diffusion alone is quite rapid, occurring within 6-12 hours. Consequently, the detection of reduced mud clasts in an obviously aerobic setting suggests a recent origin. The size and shape of mud clasts, e.g. angular versus rounded, is also considered. Mud clasts may be moved about and broken up by bottom currents and/or animals (macro- or meiofauna) (Germano, 1983). Over time, large angular clasts become small and rounded. Overall, the abundance, distribution, oxidation state, and appearance of mud clasts are used to make inferences about the recent pattern of seafloor disturbance in an area.

APPARENT REDOX POTENTIAL DISCONTINUITY (ARDP) DEPTH

In fine-grained coastal areas, when there is oxygen in the overlying water column, the near surface sediment will have a higher reflectance value relative to hypoxic or anoxic sediment underlying it. This is because the oxidised surface sediment contains particles coated with ferric hydroxide (an olive colour when associated with particles), while the sulphidic sediments below this oxygenated layer are grey to black. The boundary between the coloured ferric hydroxide surface sediment and underlying grey to black sediment is defined here as the apparent redox potential discontinuity (abbreviated as the RPD). This 'apparent' depth may, or may not, be equivalent to the actual RPD depth, which is defined as the depth at which the $E_h = 0$ as measured by microelectrodes. As explained below, in most cases, the depth of $E_h = 0$ potential in the sediment differs from the 'apparent' RPD as imaged by SPI.

The difference between the depth of the true RPD ($E_h = 0$) and the imaged apparent RPD can be explained as follows. As dissolved oxygen diffuses into sediment pore water, it is consumed by a variety of biological and geo-chemical reactions. One of these reactions involves the oxidation of iron, which is precipitated onto mineral grains located at, or near, the sediment surface. Once oxidised, these ferric hydroxide-coated particles are bioturbated downward into pore-waters, which lack free molecular oxygen (negative E_h). However, the ferric hydroxide coatings are meta-stable, and reduction of the iron is a slow process relative to the rate of bioturbation. This explains the presence of oxidised grain coatings (high optical reflectance sediment) in reducing pore waters. In the presence of bioturbating infauna, the thickness of the RPD directly reflects the particle bioturbation depth.

The areal extent of the RPD is determined by digitising its unique reflectance value. This oxidised, high-reflectance area is digitised, measured to scale, and divided by the prism window width to obtain a mean depth for the RPD (or particle bioturbation depth). The RPD depth is given special attention in these analyses, because it is a sensitive indicator of the biological mixing depth, infaunal successional status, and within-station sediment patchiness. In the absence of bioturbating infauna, the RPD will achieve a maximum depth of up to 5 mm solely by diffusion depending on the concentration gradient of dissolved oxygen, reducing substrates within the sediment, water temperature (reaction rates), and sediment permeability.

The configuration of the **RPD** boundary is also of significance. In sandy sediments, physical forces dominate surface relief and **RPD** depth, which tends to be constant or uniform and does not necessarily follow the surface contours provided by bed-forms. In muddy sediments, the **RPD** is more complex and convoluted. Here, the **RPD** layers tend to be broadly uniform and more or less follow the contours of surface sediments. However, smaller scale convolutions are superimposed on this pattern in response to biogenic reworking by a resident infauna. Biogenic structures are regions of enhanced biological and geo-chemical activity where the activities of infaunal organisms can increase flux across the oxic-anoxic sediment interface (Diaz and Schaffner, 1988). Consequently, the **RPD** boundary is a complicated surface much greater in actual area than a simple aerial measurement would estimate and with a greater effect on sediment-water interface flux rates than is initially apparent (Diaz and Schaffner, 1988).

Another important characteristic of the **RPD** is the degree of contrast in reflectance values at this boundary. This contrast is related to the interactions among the amount of organic-loading and bioturbational activity in the sediment, and the levels of bottom water dissolved oxygen in an area. High inputs of labile organic material increase sediment oxygen demand, and subsequently sulphate reduction rates (and the abundance of sulphide end-products). This results in more highly reduced (lower-reflectance) sediments at depth and higher **RPD** contrasts. Although the **SPI** image analysis system quantifies the degree of contrast, this value can vary as a function of light intensity controls on the image analysis system, which are adjusted by the operator when a wide range of sediment types (e.g. silt-clay to coarse sand) is encountered. As a result, the quantified **RPD** contrast level may not be a meaningful parameter. However, a qualitative (visual) assessment of the **RPD** contrast (i.e. high versus low) is often considered in the interpretive process.

SEDIMENTARY METHANE

At extreme levels of organic-loading, pore-water sulphate is depleted, and methanogenesis occurs. The process of methanogenesis is detected by the appearance of methane bubbles in the sediment column. These gas-filled voids are readily discernible because of their irregular, generally circular aspect and glassy texture (due to the reflection of the strobe off the gas). If present, the number and total aerial coverage of all methane pockets is measured.

INFAUNAL SUCCESSIONAL STAGE

The mapping of successional stages is based on the theory that organism-sediment interactions follow a predictable sequence after a major seafloor perturbation. This theory states that primary succession results in the predictable appearance of macrobenthic invertebrates belonging to specific functional types following a benthic disturbance. These invertebrates interact with sediment in specific ways. Because functional types are the biological units of interest, this definition does not demand a sequential appearance of particular invertebrate species or genera. This theory is now well established in the scientific literature (see Pearson and Rosenberg, 1978; Rhoads and Boyer, 1982; Rhoads and Germano, 1986).

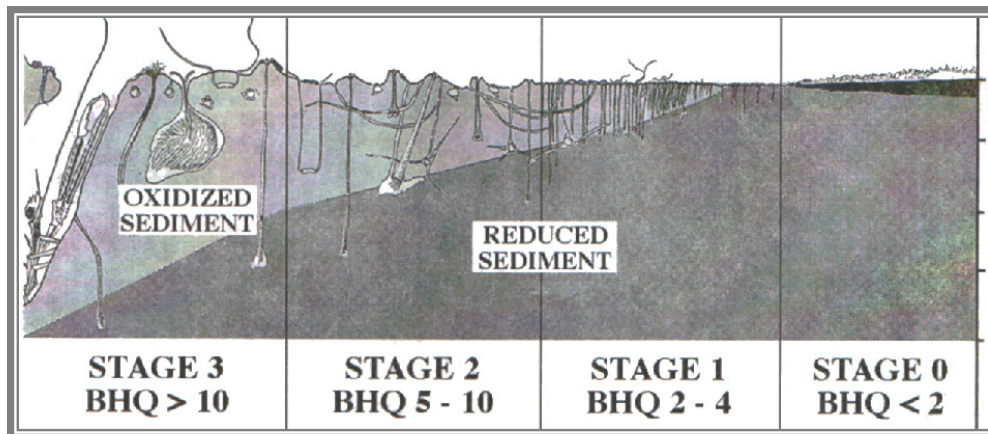
The term disturbance is used here to define natural processes, such as seafloor erosion, changes in seafloor chemistry, foraging disturbances which cause major reorganisation of the resident benthos, or anthropogenic impacts, such as dredged material or sewage sludge dumping, thermal effluents from power plants, pollution impacts from industrial discharge, etc. An important aspect of using this successional approach to interpret benthic monitoring results is relating organism-sediment relationships to the dynamical aspects of end-member seres. This involves deducing dynamics from structure, a technique pioneered by Johnson (1972) for marine soft-bottom habitats. The application of an inverse methods approach to benthic monitoring requires the *in situ* measurements of salient structural features of the organism-sediment relationships measured through SPI technology.

Pioneering (Stage 1) species are the first to colonise a new or newly disturbed bottom and reach high densities in a short time. Pioneering (Stage I) assemblages usually consist of dense aggregations of tubicolous or otherwise sedentary organisms that live near the sediment surface and feed at the surface or from the water column (Pearson and Rosenberg, 1978; Rhoads and Germano, 1986). *Capitella capitata*, *Malacoceros fuliginosus* and Spionidae species are typical forms. These functional types are usually restricted to the near surface of the bottom and their sedimentary effects include (i) the construction of dense tube aggregations which can influence sedimentation/erosion, (ii) deepening of the redox boundary by fluid bioturbation, and (iii) the occlusion of the sediment surface with faecal pellets. These associations are typically characterised by a shallow redox boundary and shallow bioturbation depths, particularly in the earliest stages of colonisation.

In the absence of further physical, chemical or biological disturbance, the pioneering assemblages are replaced by deposit feeders. This is progressive and can be arbitrarily divided into an intermediate and an equilibrium phase (Stages II and III, respectively). Typical Stage II species are shallow dwelling bivalves, tubicolous amphipods and some polychaete species.

Stage III taxa, in turn, represent high-order successional stages typically found in low disturbance regimes. A Stage III or equilibrium assemblage is persistent and is dominated by a bioturbating infauna, which feed at depth within the sediment. Sedimentary effects are distinctive and include (i) the transfer of water and particles over vertical distances of 10 - 20 cm, (ii) the production of homogeneously mixed fabrics by intensive reworking, with faecal pellets at and below the sediment surface, (iii) the creation of void feeding spaces at depth within the bottom, (iv) the extension of the redox boundary to c. 20 cm, and (v) the production of a distinctive surface microtopography unless smoothed over by tidal resuspension. Such deep-dwelling species as the polychaetes, *Pectinaria* sp., Maldanidae sp., the echinoderm, *Trachythyone elongata*, *Amphiura* sp. and *Echinocardium* sp. and the crustaceans *Lysiosquilla* sp., *Nephrops* sp. and *Upogebia* sp. These invertebrates are infaunal, and many feed at depth in a head-down orientation. The localised feeding activity results in distinctive excavations called feeding voids. Diagnostic features of these feeding structures include: a generally semicircular shape with a flat bottom and arched roof, and a distinct granulometric change in the sediment particles overlying the floor of the structure. This relatively coarse-grained material represents particles rejected by the head-down deposit-feeder. These deep-dwelling infaunal taxa preferentially ingest the finer sediment particles. In the retrograde transition of Stage III to Stage I, it is sometimes possible to recognise the presence of relict (i.e. collapsed and inactive) feeding voids. (It should be added to the above generalisations that pioneering and higher successional species may coexist, if disturbance involves only the superficial sediment layers).

These end-member stages (Stages I and III) are easily recognised in SPI images by the presence of dense assemblages of near-surface polychaetes and/or the presence of subsurface feeding voids. Both types of assemblages may be present in the same image.



The distribution of benthic infaunal successional stages along a gradient of increased environmental disturbance from left to right (from Nilsson and Rosenberg, 1997 – after Pearson and Rosenberg, 1978) and the associated Benthic Habitat Quality index (described in table 3-1 above. The successional stages are similar but not identical to those described by Rhoads and Germano (1986)

ADDITIONAL BIOLOGICAL PARAMETERS

Several additional biological parameters are measured from the digital images using the computer image analysis system. These include: the density per linear cm of polychaete and/or amphipod tubes at the sediment water interface; the minimum and maximum depth of faecal pellet layers and the minimum and maximum depth of feeding voids. Dominant faunal type (i.e. epifauna or infauna) and apparent species richness are also estimated.

SPI ORGANISM-SEDIMENT INDEX (OSI)

A multi-parameter SPI Organism-Sediment Index (OSI) has been constructed to characterise habitat quality and the method of its calculation is shown in Table 1.

The OSI is the sum of values allocated to the various physical/chemical and biological SPI parameters measured and it has a potential value range of -10 to +11. The Organism-Sediment Index is calculated automatically from the software after completion of all measurements from each digital image. This index has been found to be an excellent parameter for mapping disturbance gradients in an area and documenting eco-system recovery after disturbance.

Habitat quality is defined relative to two end-member standards. The lowest value is given to those bottoms which have low or dissolved oxygen in the overlying bottom water, no apparent macrofaunal life, and methane gas present in the sediment. The **SPI OSI** value for such a condition is minus 10. At the other end of the scale, an aerobic bottom with a deeply depressed **RPD**, evidence of a mature macrofaunal assemblage, and no apparent methane gas bubbles at depth will have a **SPI OSI** value of plus 11.

Chemical parameters	Index value	Biological parameters	Index value
Mean apparent RPD depth (cm)		Successional stage (Primary succession)	
0	0		
>0 - 0.75	1	Azoic	-4
0.76 - 1.50	2	Stage 1	1
1.51 - 2.25	3	Stage 1-2	2
2.26 - 3.00	4	Stage 2	3
3.01 - 3.75	5	Stage 2-3	4
>3.75	6	Stage 3	5
Methane Present	-2	(Secondary succession)	
No / low oxygen	-4	Stage 1 on Stage 2	5
		Stage 2 on Stage 3	5

Table 1. Method of calculating the Organism - Sediment Index (OSI) value.

From experience with mapping this parameter, values of +7 to +11 are typical of undisturbed sediments while values ≤ 6 tend to be found at sites which have experienced recent physical disturbance (e.g. bottom erosion by currents or disturbance of the bottom by scavenging fish or crustaceans) or are chemically stressed, organically loaded, sulphidic or contaminated in some way. In dealing with areas which are subject to organic enrichment (which may have a variety of origins ranging from natural runoff to anthropogenic inputs), OSI values in the range +6 to +1 generally indicate an overload situation where inputs exceed the capacity of the system and organic matter accumulates on the bottom. Index values which fall in the range +1 to -10 identify varying degrees of habitat degradation

associated with a continual accumulation of organic matter and an oxygen depletion on the bottom. At the upper end of the scale, it has been found that OSI values of the order of +11 may reflect a productivity enhancement stage of organic enrichment where natural plant and animal production is increase in response to the ready availability of particulate organic material.

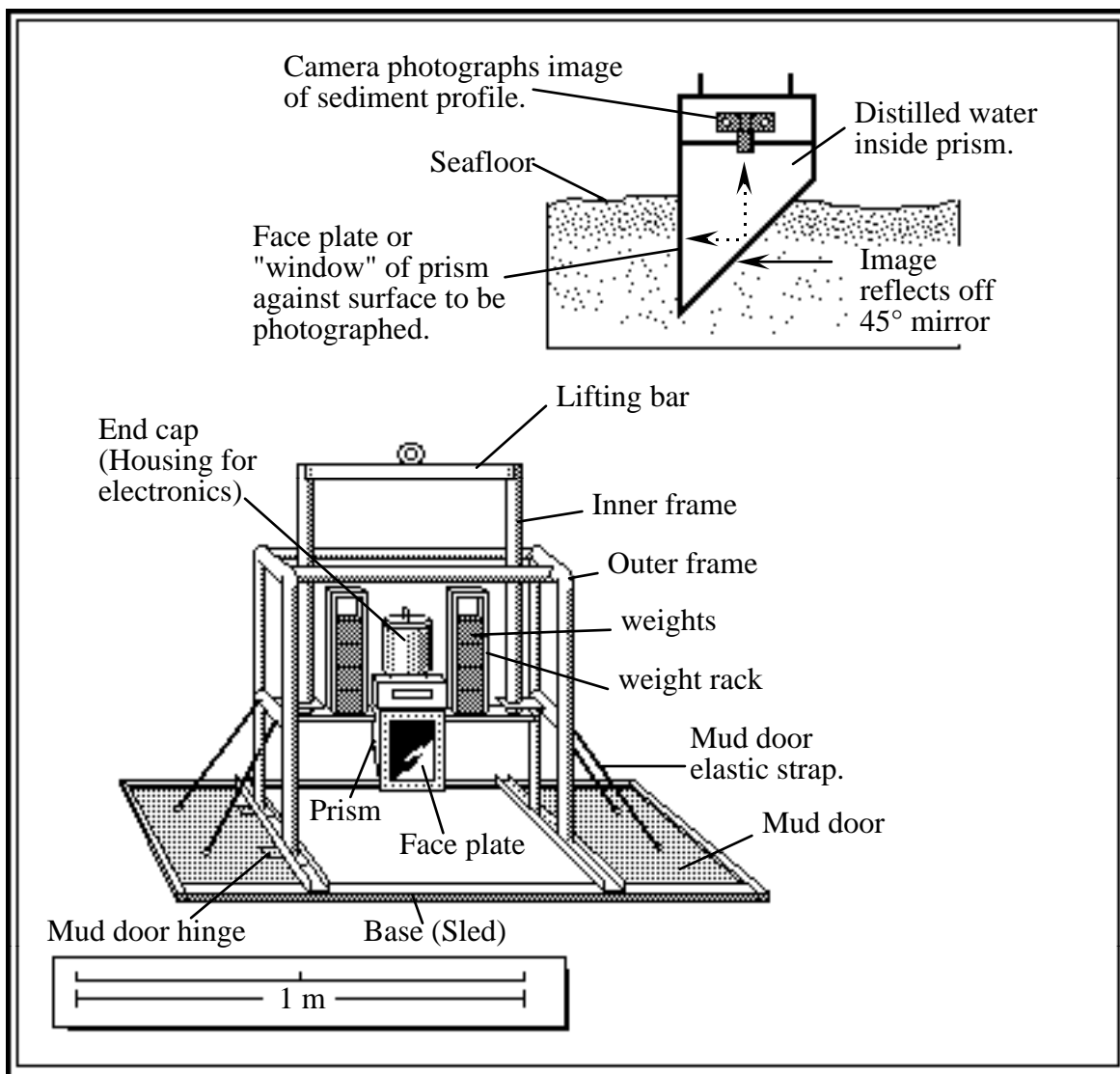


Figure 1. Representation of the remotely operated **Sediment Profile Imagery** camera.

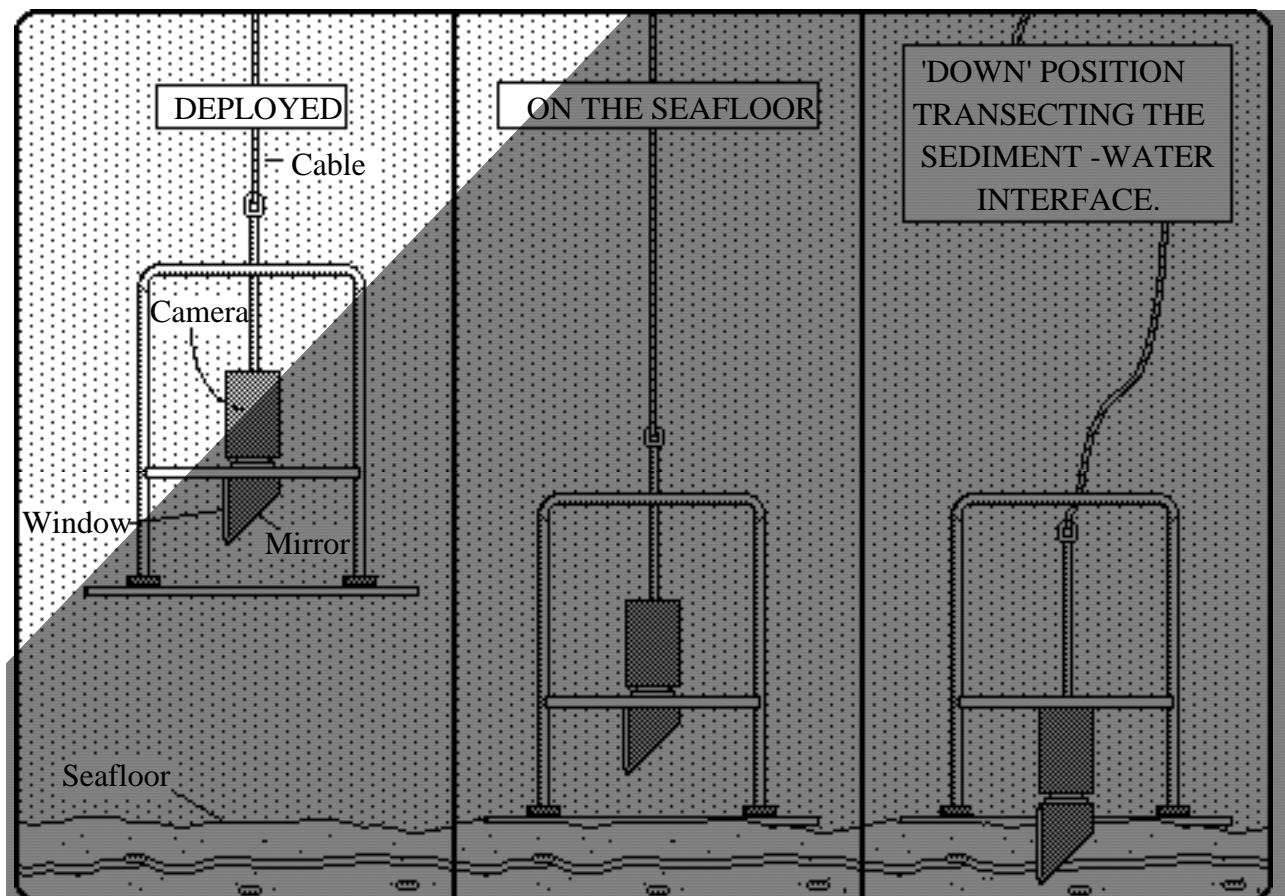


Figure 2. Sediment Profile Imagery (SPI): camera deployment on the seafloor.

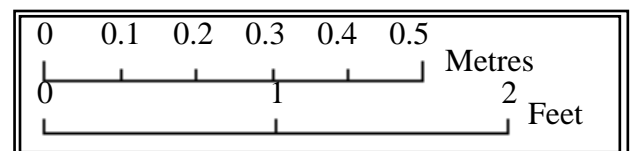
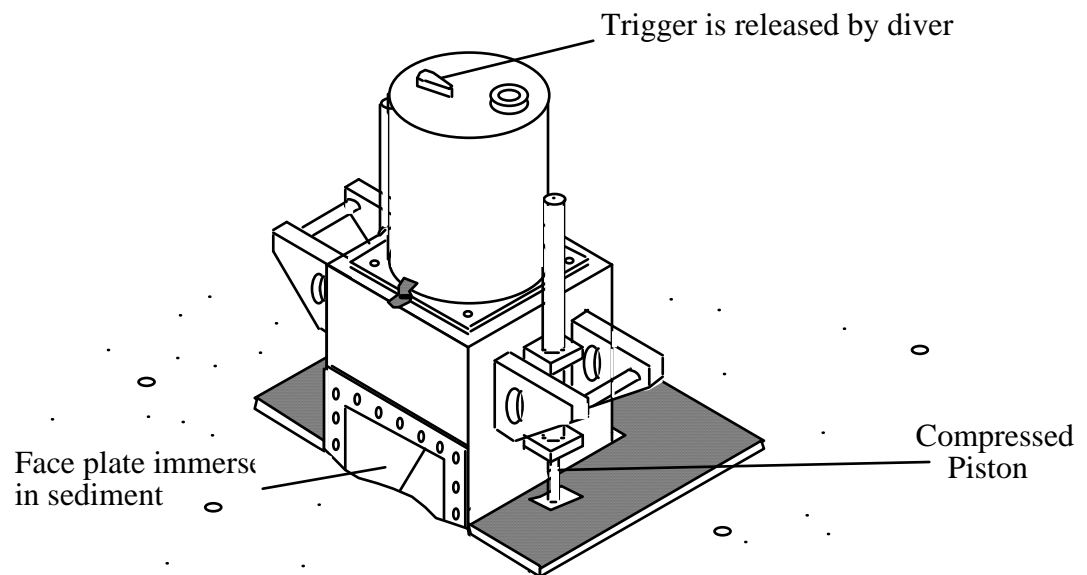
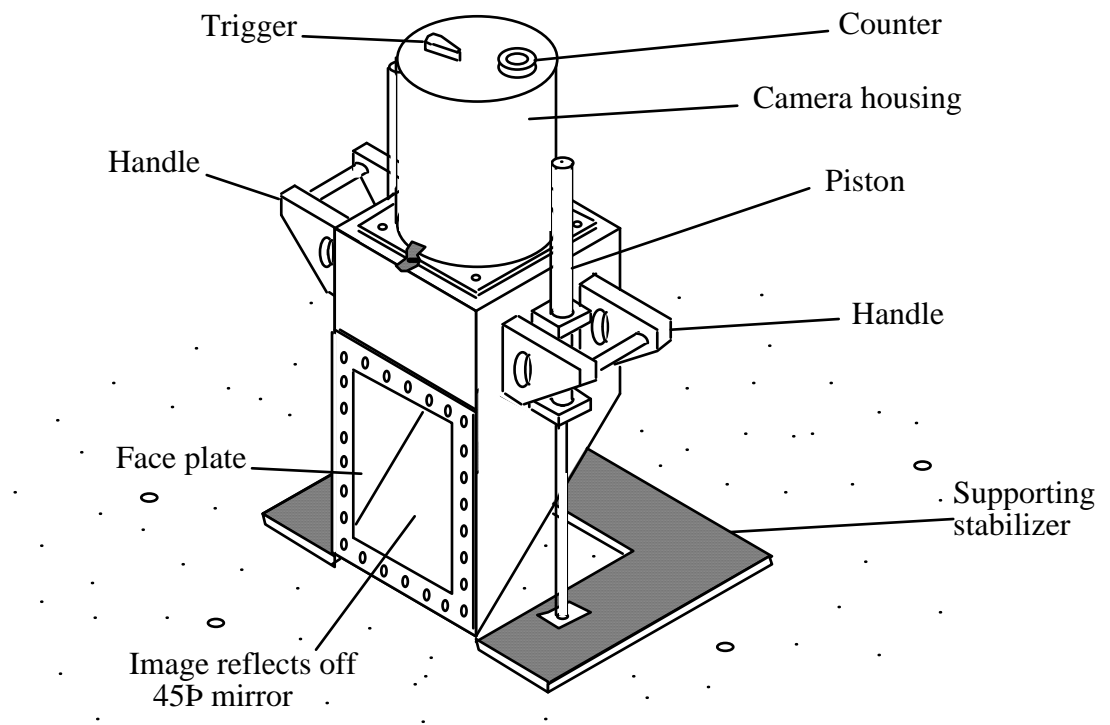


Figure 3. Details of the diver operated **S**ediment **P**rofile **I**magery (**SPI**) camera.

Appendix D
Intertidal Sediment Results

Granulometry

Station	Gravel (%)	Very Coarse Sand (%)	Coarse Sand (%)	Medium Sand (%)	Fine Sand (%)	Very Fine Sand (%)	Silt-Clay (%)
T1S1	33.2	4.1	6.5	16.3	34.6	2.3	2.9
T1S2	18.9	4.8	8	16.2	42.4	5.6	4.2
T1S3	15.6	3	3.4	15.5	56.5	4.1	1.8
T1S4	29.3	3.6	6.5	17.9	33.7	5	4.1
T2S1	23.3	12.2	11.4	13.5	31.3	3.7	4.6
T2S2	0.4	0	0.9	3.1	74.3	11.9	9.4
T2S3	0	0.1	0.7	1.8	89.2	6.5	1.7
T2S4	15.4	3.9	4	12.7	53.8	6.3	3.9
T3S1	16.9	6.3	9.3	17.1	27.2	15.3	7.8
T3S2	58.6	6.1	6.5	10.5	10.3	5.2	2.8
T3S3	17	4.4	9.4	31.5	26.1	7.4	4.3
T3S4	7.6	12	24.4	35.4	15.1	3.3	2.1

Organic Carbon

Station	Organic-Carbon (%)
T1S1	0.95
T1S2	0.47
T1S3	0.15
T1S4	0.36
T2S1	1.03
T2S2	0.38
T2S3	0.15
T2S4	0.19
T3S1	1.48
T3S2	1.72
T3S3	1.01
T3S4	1.26

Appendix E
Intertidal Species List

Table 1: Species list from the strandline Transect 1 Station 1 (T1S1).

Station			T1S1a	T1S1b	T1S1c	T1S1d	T1S1e	T1S1 Total
NEMATODA	HD	1						
Nematoda sp.	HD	1	0	0	0	0	1	1
ANNELIDA	P	1						
PHYLLODOCIDA	P	3						
Cirratulidae	P	822						
Cirratulidae sp.	P	822	0	0	1	0	0	1
Tharyx sp.	P	847	1	1	0	0	0	2
OLIGOCHAETA	P	1402						
Oligochaeta sp.	P	1402	0	0	2	12	20	34
TUBIFICIDA	P	1403						
Tubificoides pseudogaster	P	1498	7	0	0	0	0	7
Enchytraeidae sp.	P	1501	0	3	6	0	0	9
CRUSTACEA	R	1						
MAXILLOPODA	R	13						
Balanoidea	R	59						
Semibalanus nalanoides	R	69	1	0	0	0	0	1

Table 2: Species list from the upper shore Transect 1 Station 2 (T1S2).

Station			T1S2a	T1S2b	T1S2c	T1S2d	T1S2e	T1S2 Total
NEMATODA	HD	1						
Nematoda sp.	HD	1		1	2	6		9
NEMERTEA	G	1						
Nemertea sp.	G	1			1	3	3	7
ANNELIDA	P	1						
SPIONIDA	P	707						
Spionidae	P	720						
Spionidae sp.	P	720					1	1
Pygospio elegans	P	776				3		3
Cirratulidae	P	822						
Tharyx sp.	P	847	2		5		1	8
OLIGOCHAETA	P	1402						
Oligochaeta sp.	P	1402		23	2		31	56
TUBIFICIDA	P	1403						
Heterochaeta costata	P	1479	1					1
Tubificoides benedii	P	1490			6	3		9
Enchytraeidae sp.	P	1501	16		43	50		109
CRUSTACEA	R	1						
AMPHIPODA	S	97						
Corophiidae	S	604						
Corophium arenarium	S	609			1			1
MOLLUSCA	W	1						

Station			T1S2a	T1S2b	T1S2c	T1S2d	T1S2e	T1S2 Total
VENEROIDA	W	1815						
Cardiidae	W	1938						
Cerastoderma edule	W	1961				4		4
HEXAPODA								
Diptera								
Chironimidae larvae							1	1

Table 3: Species list from the middle shore Transect 1 Station 3 (T1S3).

Station			T1S3a	T1S3b	T1S3c	T1S3d	T1S3e	T1S3 Total
NEMATODA	HD	1						
Nematoda sp.	HD	1		1	1		2	4
SIPUNCULA	N	1						
Sipuncula sp.	N	1			1			1
ANNELIDA	P	1						
PHYLLODOCIDA	P	3						
Phyllodocidae	P	114						
Eteone longa	P	118		1	3	1	5	10
Syllidae	P	346						
Exogone hebes	P	421	6	8	8	3	8	33
Nereididae	P	458						
Nereidae sp.	P	458					1	1
Nereis sp.	P	473			1			1
Nephtyidae	P	490						
Nephtys sp.	P	494		1		1	2	4
Nephtys hombergii	P	499	1		1		1	3
ORBINIIDA	P	654						
Orbiniidae	P	655						
Scoloplos armiger	P	672		1			1	2
SPIONIDA	P	707						
Spionidae	P	720						
Pygospio elegans	P	776	3	3	2	2	2	12
Cirratulidae	P	822						
Cirratulidae sp.	P	822			2		2	4
Aphelochaeta sp.	P	823			2			2
Caulleriella zetlandica	P	831		1				1
Chaetozone sp.	P	832			1			1
Tharyx sp.	P	847	66	64	167	69	103	469
CAPITELLIDA	P	902						
Capitellidae	P	903						
Capitellidae sp.	P	902					1	1
Capitella sp.	P	906	4	7	7	1		19
Heteromastus filiformis	P	917	1					1
Notomastus latericeus	P	921	1	1	3	2	1	8

Station			T1S3a	T1S3b	T1S3c	T1S3d	T1S3e	T1S3 Total
OWENIIDAE	P	1089						
Oweniidae	P	1090						
Galathowenia oculata	P	1093			1			1
OLIGOCHAETA	P	1402						
Oligochaeta sp.	P	1402		3				3
TUBIFICIDA	P	1403						
Tubificoides pseudogaster	P	1498		3	4	5	2	14
Tubificoides benedii	P	1490	8	3	22	20	16	69
Enchytraeidae sp.	P	1501	2				2	4
CRUSTACEA	R	1						
AMPHIPODA	S	97						
Corophiidae	S	604						
Corophium arenarium	S	609	1	8	10		1	20
MOLLUSCA	W	1						
VENEROIDA	W	1815						
Cardiidae	W	1938						
Cardiidae sp.	W	1938					1	1
Cerastoderma edule	W	1961	1	1				2
Tellinidae	W	2008						
Macoma balthica	W	2029		1				1
Semelidae	W	2057						
Abra alba	W	2059		2			1	3

Table 4: Species list from the lower shore Transect 1 Station 4 (T1S4).

Station			T1S4a	T1S4b	T1S4c	T1S4d	T1S4e	T1S4 Total
CNIDARIA	D	1						0
ACTINIARIA	D	662						0
Cerus pedunculatus	D	662	5	1	6	13	5	30
Sagartia sp.	D	712		1				1
NEMATODA	HD	1						0
Nematoda sp.	HD	1	2		1			3
ANNELIDA	P	1						0
PHYLLODOCIDA	P	3						0
Pholoidae	P	90						0
Pholoe inornata	P	92				1		1
Phyllodocidae	P	114						0
Eteone longa	P	118	1					1
Anaitides mucosa	P	145			2			2
Eumida sp.	P	163				4		4
Syllidae	P	346						0
Exogone hebes	P	421	1					1
Nereididae	P	458						0
Hediste diversicolor	P	462	1					1

Station			T1S4a	T1S4b	T1S4c	T1S4d	T1S4e	T1S4 Total
Nephtyidae	P	490						0
Nephtys hombergii	P	499		1			1	2
ORBINIIDA	P	654						0
Orbiniidae	P	655						0
Scoloplos armiger	P	672				1		1
SPIONIDA	P	707						0
Spionidae	P	720						0
Aonides oxycephala	P	722					3	3
Pygospio elegans	P	776		1	2			3
Cirratulidae	P	822						0
Cirratulidae sp.	P	822	1					1
Aphelochaeta sp.	P	823				1		1
Tharyx sp.	P	847	59	12	28	18	16	133
CAPITELLIDA	P	902						0
Capitellidae	P	903						0
Capitella sp.	P	906	4		2	6	4	16
Heteromastus filiformis	P	917					5	5
OWENIIDA	P	1089						0
Oweniidae	P	1090						0
Galathowenia oculata	P	1093				2		2
TEREBELLIDA	P	1099						0
Ampharetidae	P	1118						0
Melinna cristata	P	1121					2	2
Melinna palmata	P	1124	1					1
Serpulidae	P	1324						0
Pomatoceros sp.	P	1339				2		2
OLIGOCHAETA	P	1402						0
Oligochaeta sp.	P	1402		2				2
TUBIFICIDA	P	1403						0
Heterochaeta costata	P	1479	1	2			10	13
Tubificoides sp.	P	1487			1			1
Tubificoides pseudogaster	P	1498	3	14	9	6	6	38
Tubificoides benedii	P	1490	52	24	44	14	15	149
Enchytraeidae sp.	P	1501	1		4		3	8
CRUSTACEA	R	1						0
MAXILLOPODA	R	13						0
Balanoidea	R	59						0
Balanus balanus	R	76				1		1
MOLLUSCA	W	1						0
MYTILOIDA	W	1689						0
Mytilidae	W	1691						0
Mytilus edulis	W	1695					3	3
VENEROIDA	W	1815						0
Cardiidae	W	1938						0
Cerastoderma edule	W	1961				1		1
HEXAPODA								0

Station			T1S4a	T1S4b	T1S4c	T1S4d	T1S4e	T1S4 Total
Diptera								0
Chironimidae larvae			1					1

Table 5: Species list from the strandline Transect 2 Station 1 (T2S1).

Station			T2S1a	T2S1b	T2S1c	T2S1d	T2S1e	T2S1 Total
CNIDARIA	D	1						0
ACTINIARIA	D	662						0
Sagartia sp.	D	662				1		1
NEMATODA	HD	1						0
Nematoda sp.	HD	1				2		2
NEMERTEA	G	1						0
Nemertea sp.	G	1				1		1
ANNELIDA	P	1						0
PHYLLODOCIDA	P	3						0
Phyllodocidae	P	114						0
Eteone longa	P	118			1		2	3
Nereididae	P	458						0
Hediste diversicolor	P	462					2	2
Nereis sp.	P	473					4	4
Nephtyidae	P	490						0
Nephtys sp.	P	494					1	1
SPIONIDA	P	707						0
Spionidae	P	720						0
Malacoceros fuliginosus	P	737		1	1	2		4
Pygospio elegans	P	776					2	2
Cirratulidae	P	822						0
Aphelochaeta sp.	P	823	49	2				51
Chaetozone sp.	P	832	4					4
Cirratulus cirratus	P	836	12	9	12	41		74
Cirriformia tentaculata	P	839		3		1		4
Tharyx sp.	P	847	2	109	13	76	57	257
CAPITELLIDA	P	902						0
Capitellidae	P	903						0
Capitella sp.	P	906				4		4
Maldanidae	P	938						0
Maldanidae sp.	P	938				1		1
TEREBELLIDA	P	1099						0
Ampharetidae	P	1118						0
Ampharete acutifrons				9	3	6	1	19
OLIGOCHAETA	P	1402						0
TUBIFICIDA	P	1403						0
Heterochaeta costata	P	1479			1	2		3
Tubificoides pseudogaster	P	1498		16	4	2	17	39
Tubificoides benedii	P	1490	7	67	32	103	135	344

Station			T2S1a	T2S1b	T2S1c	T2S1d	T2S1e	T2S1 Total
Enchytraeidae sp.	P	1501	2	14	1			17
CRUSTACEA	R	1						0
MAXILLOPODA	R	13						0
Balanoidea	R	59						0
Balanus balanus	R	76		30	13	7		50
AMPHIPODA	S	97						0
Hyalidae	S	221						0
Hyale pontica	S	226	1	4		3		8
Melitidae	S	495						0
Abludomelita obtusata	S	498		1				1
Melita palmata	S	525	2	6	1	1		10
Corophiidae	S	604						0
Corophium arenarium	S	609			1			1
DECAPODA	S	1276						0
Goneplacidae	S	1603						0
Monodaeus couchi	S	1609		2	2			4
MOLLUSCA	W	1						0
MYTILOIDA	W	1689						0
Mytilidae	W	1691						0
Mytilus edulis	W	1695		4	5	14	1	24
VENEROIDA	W	1815						0
Cardiidae	W	1938						0
Cerastoderma edule	W	1961	1	2		1		4

Table 6: Species list from the upper shore Transect 2 Station 2 (T2S2).

Station			T2S2a	T2S2b	T2S2c	T2S2d	T2S2e	T2S2 Total
NEMATODA	HD	1						0
Nematoda sp.	HD	1					3	3
NEMERTEA	G	1						0
Nemertea sp.	G	1	1					1
ANNELIDA	P	1						0
PHYLLODOCIDA	P	3						0
Phyllodocidae	P	114						0
Eteone longa	P	118	4		2	1	3	10
Nereididae	P	458						0
Hediste diversicolor	P	462	4	7		6	1	18
Nereis sp.	P	473		1	1		1	3
Nephtyidae	P	490						0
Nephtys sp.	P	494					1	1
Nephtys hombergii	P	499					1	1
SPIONIDA	P	707						0
Spionidae	P	720						0
Pygospio elegans	P	776	3		7	2	3	15
Spio sp.	P	787	1					1
Cirratulidae	P	822						0

Station			T2S2a	T2S2b	T2S2c	T2S2d	T2S2e	T2S2 Total
Cirratulidae sp.	P	822	1			1	1	3
Cirratulus cirratus	P	836			1			1
Tharyx sp.	P	847	8	1	178	6	21	214
CAPITELLIDA	P	902						0
Capitellidae	P	903						0
Capitellidae sp.	P	902				1		1
Capitella sp.	P	906	1					1
OLIGOCHAETA	P	1402						0
Oligochaeta sp.	P	1402			1			1
TUBIFICIDA	P	1403						0
Heterochaeta costata	P	1479	1	462				463
Tubificoides pseudogaster	P	1498	11	22			11	44
Tubificoides benedii	P	1490	162		169	81	77	489
Enchytraeidae sp.	P	1501	1	80	5	1		87
CRUSTACEA	R	1						0
AMPHIPODA	S	97						0
Gammaridae	S	464						0
Gammaridae sp.	S	464			1			1
Gammarus tigrinus	S	482		3				3
Corophiidae	S	604						0
Corophium arenarium	S	609			1			1
DECAPODA	S	1276						0
Goneplacidae	S	1603						0
Monodaeus couchi	S	1609	1					1
MOLLUSCA	W	1						0
MESOGASTROPODA	W	256						0
Semelidae	W	2057						0
Abra alba	W	2059			1		2	3

Table 7: Species list from the middle shore Transect 2 Station 3 (T2S3).

Station			T2S3a	T2S3b	T2S3c	T2S3d	T2S3e	T2S3 Total
NEMATODA	HD	1						0
Nematoda sp.	HD	1		1		2		3
ANNELIDA	P	1						0
PHYLLODOCIDA	P	3						0
Phyllodocidae	P	114						0
Eteone longa	P	118				1		1
Nereididae	P	458						0
Nereis sp.	P	473				1		1
Nephtyidae	P	490						0
Nephtys sp.	P	494	3	1		1	1	6
Nephtys hombergii	P	499	2				3	5
ORBINIIDA	P	654						0
Orbiniidae	P	655						0

Station			T2S3a	T2S3b	T2S3c	T2S3d	T2S3e	T2S3 Total
Scoloplos armiger	P	672				1		1
SPIONIDA	P	707						0
Spionidae	P	720						0
Pygospio elegans	P	776	3	6	1	2	4	16
Spio sp.	P	787	4					4
Cirratulidae	P	822						0
Tharyx sp.	P	847	1	1	1			3
OLIGOCHAETA	P	1402						0
TUBIFICIDA	P	1403						0
Heterochaeta costata	P	1479	1					1
Tubificoides pseudogaster	P	1498	7	18	7	7		39
Tubificoides benedii	P	1490	7	11	2	79	9	108
Enchytraeidae sp.	P	1501	3		1	1		5
CRUSTACEA	R	1						0
DECAPODA	S	1276						0
Goneplacidae	S	1603						0
Monodaeus couchi	S	1609			1			1
MOLLUSCA	W	1						0
MYTILOIDA	W	1689						0
VENEROIDA	W	1815						0
Cardiidae	W	1938						0
Cerastoderma edule	W	1961					2	2
Tellinidae	W	2008						0
Macoma balthica	W	2029				1		1

Table 8: Species list from the lower shore Transect 2 Station 4 (T2S4).

Station			T2S4a	T2S4b	T2S4c	T2S4d	T2S4e	T2S4 Total
NEMATODA	HD	1						0
Nematoda sp.	HD	1		1		2		3
ANNELIDA	P	1						0
PHYLLODOCIDA	P	3						0
Polynoidae	P	25						0
Harmothoe sp.	P	50				1		1
Phyllodocidae	P	114						0
Eteone longa	P	118				1		1
Syllidae	P	346						0
Exogone hebes	P	421	2	4		6	3	15
Nereididae	P	458						0
Nereis sp.	P	473		1				1
Nephtyidae	P	490						0
Nephtys sp.	P	494	1					1
Nephtys hombergii	P	499	1					1
SPIONIDA	P	707						0
Spionidae	P	720						0

Station			T2S4a	T2S4b	T2S4c	T2S4d	T2S4e	T2S4 Total
Polydora sp.	P	748		1	1	2		4
Pygospio elegans	P	776		3	2	2	1	8
Cirratulidae	P	822						0
Cirratulidae sp.	P	822			3			3
Tharyx sp.	P	847	20	67	2	41	12	142
CAPITELLIDA	P	902						0
Capitellidae	P	903						0
Capitella sp.	P	906	6	1		1		8
Heteromastus filiformis	P	917				1		1
Maldanidae	P	938						0
Micromaldane sp.	P	977		3				3
TEREBELLIDA	P	1099						0
Ampharetidae	P	1118						0
Melinna cristata	P	1121					1	1
Terebellidae	P	1179						0
Lanice conchilega	P	1195	1					1
SABELLIDA	P	1256						0
OLIGOCHAETA	P	1402						0
Oligochaeta sp.	P	1402			6			6
TUBIFICIDA	P	1403						0
Tubificoides pseudogaster	P	1498	14	14		5	4	37
Tubificoides benedii	P	1490	2	3			1	6
CRUSTACEA	R	1						0
AMPHIPODA	S	97						0
Melitidae	S	495						0
Melita palmata	S	525	1	1				2
DECAPODA	S	1276						0
Goneplacidae	S	1603						0
Monodaeus couchi	S	1609	1		1			2
MOLLUSCA	W	1						0
VENEROIDA	W	1815						0
Cardiidae	W	1938						0
Cerastoderma edule	W	1961				1	1	2

Table 9: Species list from the strandline Transect 3 Station 1 (T3S1).

Station			T3S1a	T3S1b	T3S1c	T3S1d	T3S1e	T3S1 Total
NEMATODA	HD	1						0
Nematoda sp.	HD	1	4		1		2	7
ANNELIDA	P	1						0
PHYLLODOCIDA	P	3						0
Nereididae	P	458						0
Hediste diversicolor	P	462			1	4	2	7
Nereis sp.	P	473	1				1	2
Cirratulidae	P	822						0

Station			T3S1a	T3S1b	T3S1c	T3S1d	T3S1e	T3S1 Total
Tharyx sp.	P	847	4					4
OLIGOCHAETA	P	1402						0
Oligochaeta sp.	P	1402	25					25
TUBIFICIDA	P	1403						0
Heterochaeta costata	P	1479	211	346	552	326	306	1741
Tubificoides sp.	P	1487					40	40
Tubificoides pseudogaster	P	1498	54	36	132	58		280
Tubificoides benedii	P	1490	2					2
Enchytraeidae sp.	P	1501		168	396	214	576	1354
ECHINODERMATA	ZB	2						0
OPHIUROIDEA	ZB	105						0
OPHIURIDA	ZB	121						0
Amphiura sp.	ZB	149					2	2
HEXAPODA								0
Diptera								0
Chironimidae larvae			16	21	19	11	6	73
Chironimidae pupae				2	1			3

Table 10: Species list from the upper shore Transect 3 Station 2 (T3S2).

Station			T3S2a	T3S2b	T3S2c	T3S2d	T3S2e	T3S2 Total
NEMATODA	HD	1						0
Nematoda sp.	HD	1	10	8				18
ANNELIDA	P	1						0
PHYLLODOCIDA	P	3						0
Nereididae	P	458						0
Hediste diversicolor	P	462	4	5	5	2		16
Cirratulidae	P	822						0
Tharyx sp.	P	847	14					14
OLIGOCHAETA	P	1402						0
TUBIFICIDA	P	1403						0
Heterochaeta costata	P	1479	488	418	566	178		1650
Tubificoides pseudogaster	P	1498	54	44	48	124		270
Tubificoides benedii	P	1490	2					2
Enchytraeidae sp.	P	1501	92	68	92	146		398
CRUSTACEA	R	1						0
AMPHIPODA	S	97						0
Gammaridae	S	464						0
Echinogammarus sp.	S	465		4				4
Gammarus tigrinus	S	482	7		3	8		18
Janiridae	S	883						0
Janiropsis brevicornis	S	919		1		1		2
HEXAPODA								0
Diptera								0
Chironimidae larvae			4		5	6		15

Table 11: Species list from the middle shore Transect 3 Station 3 (T3S3).

Station			T3S3a	T3S3b	T3S3c	T3S3d	T3S3e	T3S3 Total
NEMATODA	HD	1						0
Nematoda sp.	HD	1	2		1			3
ANNELIDA	P	1						0
PHYLLODOCIDA	P	3						0
Nereididae	P	458						0
Hediste diversicolor	P	462		2		1		3
Nereis sp.	P	473	2		3	1	3	9
Cirratulidae	P	822						0
Tharyx sp.	P	847	2					2
OLIGOCHAETA	P	1402						0
Oligochaeta sp.	P	1402			1275	1016	613	2904
TUBIFICIDA	P	1403						0
Heterochaeta costata	P	1479	142	148	1			291
Tubificoides pseudogaster	P	1498	12	120	17			149
Tubificoides benedii	P	1490	22					22
Enchytraeidae sp.	P	1501	1176	1484	30			2690
HEXAPODA								0
Diptera								0
Dipterid larvae				1				1
Chironimidae larvae			2	6	7	1	1	17
Chironimidae pupae				2				2

Table 12: Species list from the lower shore Transect 3 Station 4 (T3S4).

Station			T3S4a	T3S4b	T3S4c	T3S4d	T3S4e	T3S4 Total
NEMATODA	HD	1						0
Nematoda sp.	HD	1			2		3	5
ANNELIDA	P	1						0
PHYLLODOCIDA	P	3						0
Nereididae	P	458						0
Nereidae sp.	P	458					4	4
Hediste diversicolor	P	462	1	2	1	1	6	11
Nereis sp.	P	473	1		2	4		7
SPIONIDA	P	707						0
Spionidae	P	720						0
Pygospio elegans	P	776			1			1
Cirratulidae	P	822						0
Cirratulidae sp.	P	822					1	1
Tharyx sp.	P	847			2	3		5
OLIGOCHAETA	P	1402						0
TUBIFICIDA	P	1403						0
Heterochaeta costata	P	1479	81	210	149	137	153	730
Tubificoides pseudogaster	P	1498	64	25	35	40	30	194

Station			T3S4a	T3S4b	T3S4c	T3S4d	T3S4e	T3S4 Total
Tubificoides benedii	P	1490			2	1	5	8
Enchytraeidae sp.	P	1501	16	3	27	12	11	69
HEXAPODA								0
Diptera								0
Chironimidae larvae			16	11	3	13	18	61
Chironimidae pupae			2	1				3

Appendix F
cSAC Site Synopsis

SITE SYNOPSIS

SITE NAME : MALAHIDE ESTUARY

SITE CODE : 000205

Malahide Estuary is situated immediately north of Malahide and east of Swords. It is the estuary of the River Broadmeadow. The site is divided by a railway viaduct built in the 1800s.

The outer part of the estuary is mostly cut off from the sea by a large sand spit, known as "the island". The outer estuary drains almost completely at low tide, exposing sand and mud flats. There is a large bed of Eelgrass (*Zostera noltii* and *Z. angustifolium*) in the north section of the outer estuary, along with Tassel Weed (*Ruppia maritima*) and extensive mats of green algae (*Enteromorpha* spp., *Ulva lactuca*). Cordgrass (*Spartina anglica*) is also widespread in this sheltered part of the estuary.

The dune spit has a well developed outer dune ridge dominated by Marram Grass (*Ammophila arenaria*). The dry areas of the stabilised dunes have a dense covering of Burnet Rose (*Rosa pimpinellifolia*), Red Fescue (*Festuca rubra*) and species such as Yellow Wort (*Blackstonia perfoliata*), Field Gentian (*Gentianella amarella*), Hound's Tongue (*Cynoglossum officinale*), Carlina Thistle (*Carlina vulgaris*) and Pyramidal Orchid (*Anacamptis pyramidalis*). Much of the interior of the spit is taken up by a golf course. The inner stony shore has frequent Sea-holly (*Eryngium maritimum*).

Well-developed saltmarshes occur at the tip of the spit. Atlantic salt meadow is the principle type and is characterised by species such as Sea Purslane (*Halimolobos portulacoides*), Sea Aster (*Aster tripolium*), Thrift (*Armeria maritima*), Sea Arrowgrass (*Triglochin maritima*) and Common Saltmarsh-grass (*Puccinellia maritima*). Elsewhere in the outer estuary, a small area of Mediterranean salt meadow occurs which is characterised by the presence of Sea Rush (*Juncus maritimus*). Below the salt marshes there are good examples of pioneering Glasswort swards and other annual species, typified by *Salicornia dolichostachya* and Annual Sea-blite (*Suaeda maritima*).

The inner estuary does not drain at low tide apart from the extreme inner part. Here, patches of saltmarsh and salt meadows occur, with Sea Aster, Sea Plantain (*Plantago maritima*) and Sea Clubrush (*Scirpus maritimus*). Tassel Weed (*Ruppia maritima*) occurs in one of the channels.

The site includes a fine area of rocky shore south-east of Malahide and extending towards Portmarnock. This represents the only continuous section through the fossiliferous Lower Carboniferous rocks in the Dublin Basin, and is the type locality for several species of fossil coral.

The estuary is an important wintering bird site and holds an internationally important population of Brent Geese and nationally important populations of a further 15 species. Average maximum counts during the 1995/96-1997/98 period were Brent Geese 1217; Great Crested Grebe 52; Mute Swan 106; Shelduck 471; Pochard 200; Goldeneye 333; Red-breasted Merganser 116; Oystercatcher 1228; Golden Plover 2123; Grey Plover 190; Redshank 454; Wigeon 50; Teal 78; Ringed Plover 106; Knot 858; Dunlin 1474; Greenshank 38; Pintail 53; Black-tailed Godwit 345; Bar-tailed Godwit 99. The high numbers of diving birds reflects the lagoon-type nature of the inner estuary.

The estuary also attracts migrant species such as Ruff, Curlew Sandpiper, Spotted Redshank and Little Stint. Breeding birds of the site include Ringed Plover, Shelduck and Mallard. Up to the 1950s there was a major tern colony at the southern end of the island and the habitat remains suitable for these birds. The inner part of the estuary is heavily used for water sports. A section of the outer estuary has recently been infilled for a marina and housing development.

This site is a fine example of an estuarine system with all the main habitats represented. The site is important ornithologically, with a population of Brent Geese of international significance.