

Comparison of the fluctuations in hydraulic and salinity
dynamics of two coastal field sites.

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Abstract

Little is known about the saline/freshwater interface that occurs around coastlines. It is for this reason that the focus of this project is on how the unconfined Fylde aquifer interacts with the coastal environment at two site locations. The locations that are used are of contrasting characteristics to broaden the scope of the project. Prior to the beach studies, an experiment using a Darcy tank was implemented in an attempt to simulate groundwater conditions that may be experienced at the beach locations. The results from this experiment showed that as distance from a fluctuating boundary condition increased, the height of the fluctuations that were registered decreased, and the time before a given maximum was recorded increased. With this knowledge, a series of boreholes were positioned at each of the beach locations and were monitored hourly for changes in water level, the electrical conductance of the water, and the water temperature. A change in the water level would hopefully reinforce what had been experienced with the Darcy tank. Monitoring the electrical conductivity and the temperature would allow the saline/freshwater boundary to be identified. Increased levels of salt in the water yielded a higher conductivity reading implying that the water was more saline than fresh. Results from the beach studies had a high degree of variability in the data that was produced; however conclusions were drawn regarding the presence of any fresh water and the inland propagation of the tidal cycle.

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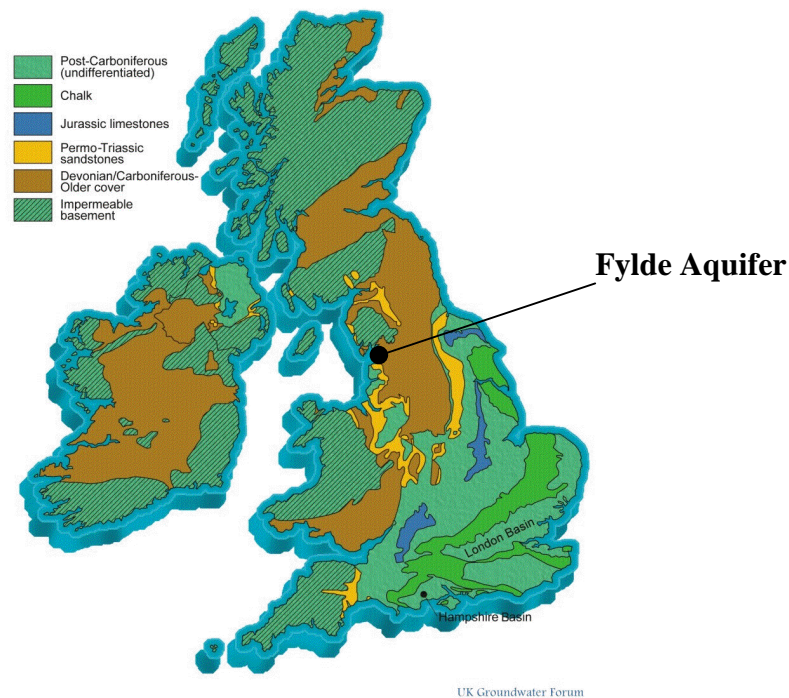
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Chapter 1

Section 1

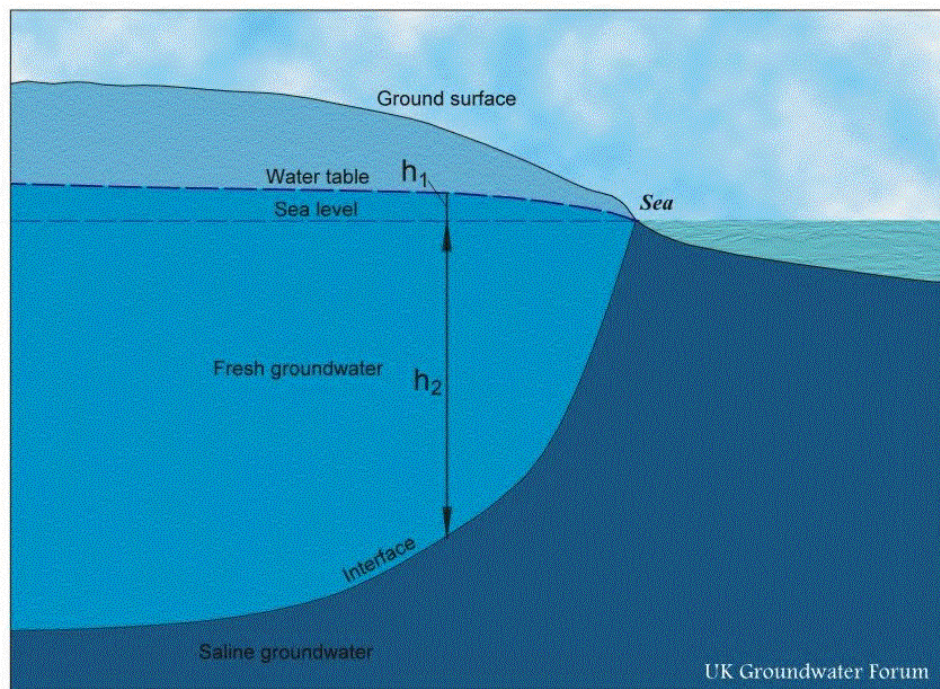
Little is known about the saline/freshwater interface that occurs around coastlines. Investigation into this area is on going, but to date a large proportion of this has been based on modelling. It is recognized that this saline mixing zone plays a major role in governing the dispersal of pollutants and contaminants that enter the system through groundwater flow. Submarine groundwater discharge can influence significantly the near-shore transport and flux of chemicals into the oceans (Paulsen *et al*, 2001). To complement some of the work that has already been carried out in this field, my project will investigate the fluctuations in hydraulic and salinity dynamics at the coastal interface of a tidally affected aquifer. The aquifer that the study will be based around is located on the North West coast of England and is shown on the map below.

Figure 1.1: Map displaying the Aquifers located in the British Isles



Groundwater discharge from unconfined aquifers to coastal waters can be a complex system, characterised by a fluctuating water table due to tidal activity, density-dependant flow along the saline/freshwater transition zone, and a dynamic ground water discharge region within the inter tidal zone (Robinson *et al*, 1998). An idealised sketch of the saline/freshwater interface can be seen in figure 1.2.

Figure 1.2: Idealised sketch of the saline/freshwater interface in an unconfined tidally affected aquifer.



This idealised sketch shows how the tidal mixing zone should occur in the environment. The denser saline water is forced to move under the lighter fresh water creating a steeply declining interface with a sharp boundary between the two. This occurrence is relatively unseen in the natural environment, in reality there tends to be a mixing of salt water and freshwater in a zone of diffusion around the interface (Freeze 1979).

Section 2

The project will be carried out in two separate parts that will hopefully lead to a better understanding of this subject. The first part of the experiment is based in the laboratory. The use of a Darcy tank will be implemented in an attempt to simulate groundwater conditions that may be experienced at a beach. The Darcy tank is a simple piece of equipment that allows the user to create an idealised representation of groundwater movement. Two schematic representations of the Darcy tank are shown over leaf in figures 1.3 and 1.4.

Figure 1.3: Plan View of the Darcy Tank

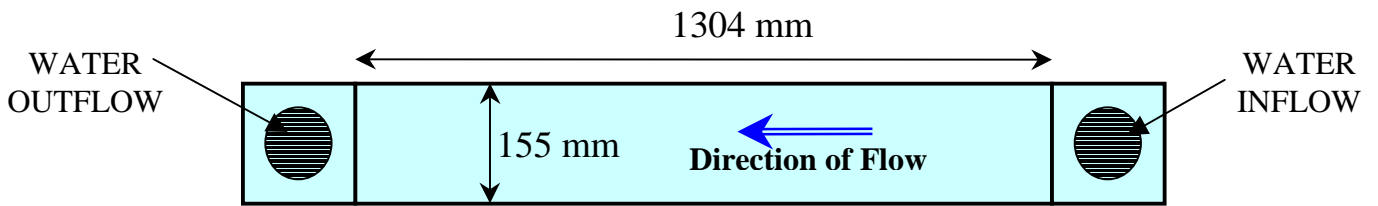
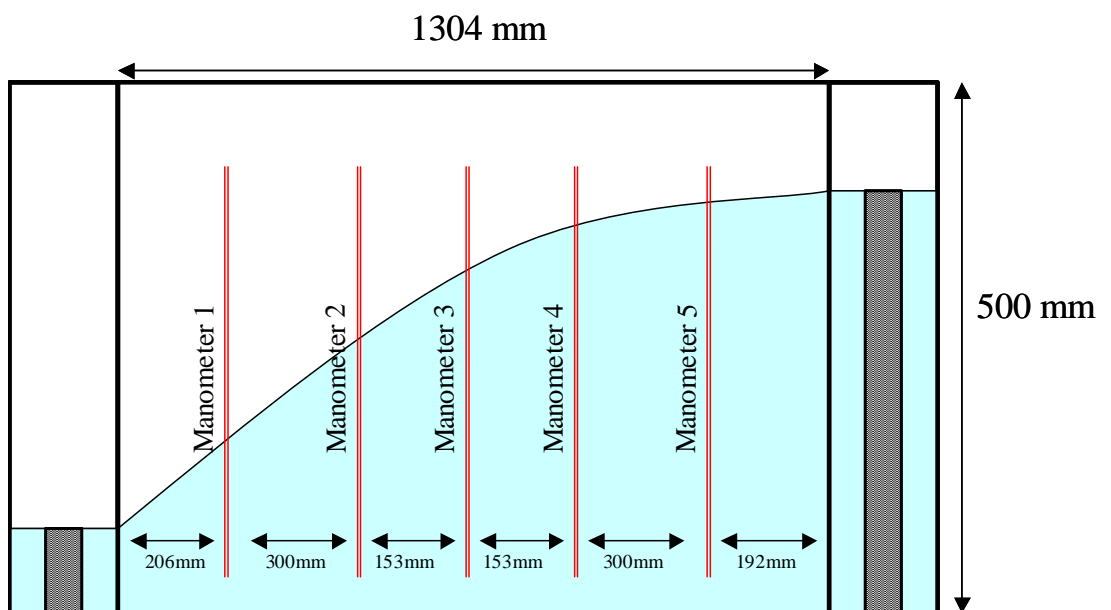


Figure 1.4: The Darcy Tank in Section



We can see from figures 1.3 and 1.4 the relative dimensions of the Darcy tank.

The inside of the tank measures 1304 mm in length by 155 mm in width, and has a height of 500 mm. The tank is filled with coarse sand and the water table is created using in and outflow pipes that are adjustable in height to suit the requirements of the user. These can be seen on the left and right hand sides on the two figures. In the representation shown above, the inflow to the tank is set much higher than the out flow to produce the shape of the water table shown. Also shown on figure 1.4 are the positions of the five manometers on the side of the tank that are used to measure the changes in the water table.

Section 3

The second part of the project will focus on the comparison of two separate locations along the North West part of the Fylde coastline. These locations have been chosen for their contrasting characteristics. The two locations are shown on the map below with descriptions of some of their prominent features.

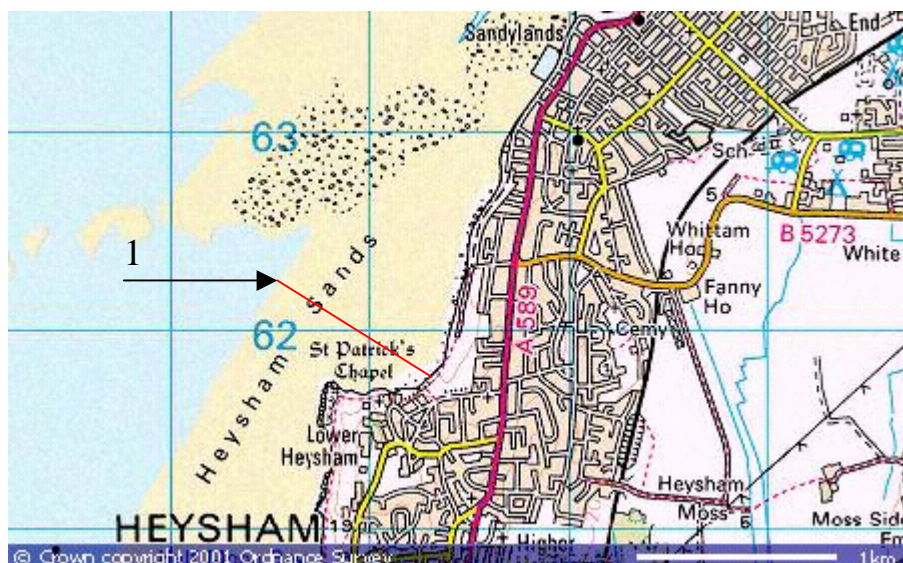
Figure 1.5: Map displaying the two study locations



Location 1 is Heysham Bay

Location 2 is Rossall Beach

Figure 1.6: Map of location 1 - Heysham Bay



Point 1 – The line shown here in red illustrates the transect along which the data was recorded.

The bay at Heysham has a long beach at approximately 1 km in length that is backed by coastal defences. Coinciding with the long beach, the gradient of the water table should be shallow. The beach sediments consist of relatively fine sand throughout. The combination of all of these factors should result in the generation of low permeability conditions.

Figure 1.7: Map of location 2 – Rossall Beach



Point 2 – The line shown here in red illustrates the transect along which the data was recorded.

The beach at Rossall is only about 350 meters in length, about a third of the length of the beach at Heysham. Coastal defences back the beach at Rossall as they do at Heysham but on a slightly larger scale. In contrast to Heysham the water table should be declining at a steeper gradient due to its relative make up. The beach at Rossall consists of largely coarse-grained material. All of the aforementioned factors should generate high permeability conditions, and hence create contrasting results to those attained at Heysham. An additional benefit of the study at Rossall is that the engineers of the coastal defence need to know how the beach system functions. This knowledge would allow them to understand the effectiveness of the sea defence and how any alterations to the structure could improve the localised environment.

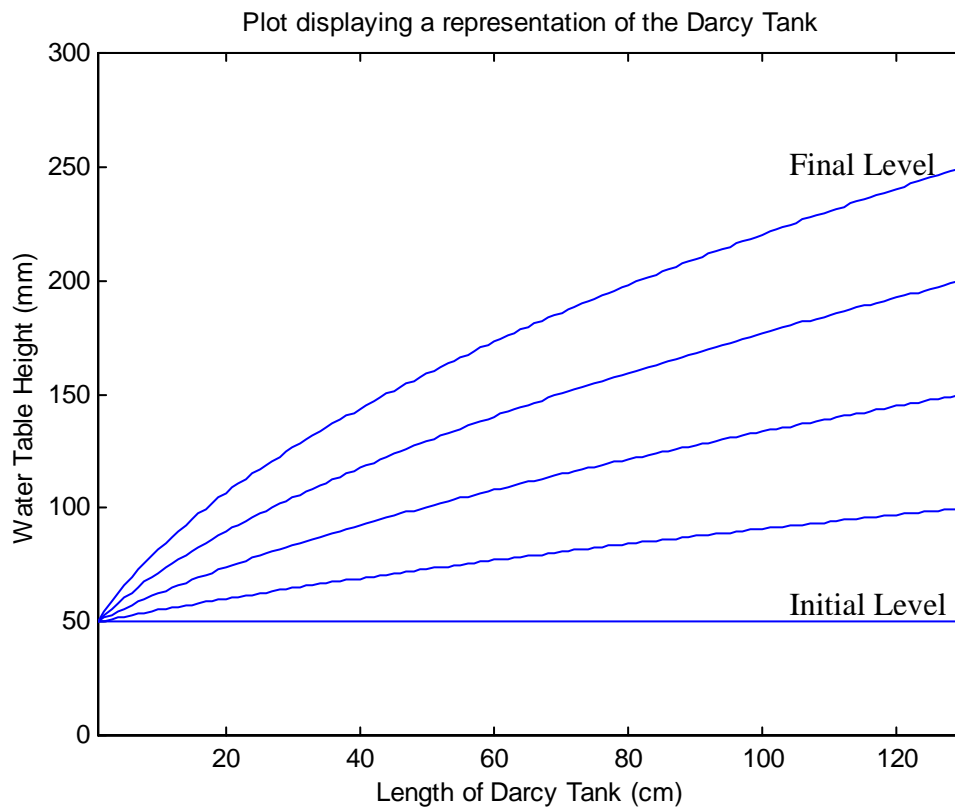
Chapter 2

Section 1

The Darcy Tank, Techniques Involved

To simulate the groundwater conditions that may be experienced at a beach, a rough idea of the properties of the tank was needed. This meant that a trial run was necessary to see just how quickly the tank would react to any changes that were made to the water inflow. Starting from a point where the water table was at its lowest, with inflow and outflow of the system set to 50 mm above the base of the tank, the inflow was increased up to 250 mm above the base of the tank. This meant that the water table had to increase in depth at the inflow side of the tank. Figure 2.1 shows how the water table in the Darcy tank may have looked at set intervals during its rise.

Figure 2.1: Plot displaying the increasing water table height from a horizontal start



We can see from the plot the variations that occurred within the Darcy tank. The height of the water table gradually increased in response to the raising of the inflow level. This increase was simulated using ASM, a two-dimensional aquifer simulation model. The data that was produced was then plotted using MATLAB, a programming language. The

water table increased to the maximum height of 250 mm above the base of the tank on the right hand side, and formed a series of parabolic shaped water tables over the period it took to stabilise. From beginning to end, it took approximately 1 hour for the water table to fully stabilise. A table displaying the data from the trial run of the Darcy tank can be found in Appendix 1, figure A1.1. This meant that if the Darcy tank were going to truly represent a beach system, then a full tidal cycle would have to last approximately 4 hours. For the Darcy tank to represent a beach system, it would have to be modified. The normally stationary outflow pipe had to be altered in such a way that would allow it to be manually repositioned at set time intervals to create a sinusoidal fluctuation at the outflow side of the tank. This would allow for the creation of a tidal effect within the tank and to hopefully give some ideas about how a beach reacts to the continually altering water levels. After a number of different ideas were put forth, a final decision was made. The outflow pipe of the Darcy tank was attached to a wooden board that was positioned above the outflow end of the tank. On the board a series of points were marked off at 5 mm intervals and covered a range of 100 mm. For one full cycle it would take approximately four hours, so a series of calculations were made that would enable the user to manually alter the height of the outflow over this time period. The sine wave was created by rising and then lowering the outflow pipe 5 mm at a time over the calculated time intervals, each time interval varying according to the part of the cycle being created. The table for this procedure can be seen in Appendix 1, figure A1.2. The results of creating this fluctuating water level at the outflow end of the tank should show that as distance from the outflow increased then the amplitude of the waves would decrease. The experiment should also demonstrate a lag period in respect of when a given maximum reaches each of the manometers, increasing with distance from the outflow end of the tank. The results can be seen in Section 1 of the next Chapter.

Section 2

The Beach Study, Techniques Involved

The investigations at the two chosen locations were completed over the course of a weeklong period in June 2001. Two studies were completed at Heysham Bay on 14th and 21st, and one at Rossall on 20th. The investigations were completed using a set of boreholes drilled deep enough to penetrate the water tables at the specific points. These boreholes were placed along perpendicular transects to the coastline (shown on figures 1.6 and 1.7), with a theodolite positioned directly behind them adjacent to or on the coastal defences. Within these boreholes a half-meter section of plastic tubing was inserted, leaving enough of the tubing above the ground level to allow the boreholes to be relocated. The plastic piping used at all of the locations was 2.5 cm in diameter and had previously had holes drilled at 10 - 15 cm intervals along its length to allow the movement of groundwater to occur. All of the boreholes were installed at low tide to allow the movement of water to be monitored as the tide advanced up the beach. Schematic representations of the situations of the boreholes can be seen in Chapter 3, Section 3.

Using the theodolite that had been set up behind the transect line of the boreholes, readings were taken positioning the point of low water and of the ground level adjacent to each of the boreholes. Measurements consisted of horizontal and vertical distance from the instrument. A series of measurements were then taken at each of the boreholes to provide information about the hydraulic and salinity dynamics of the two locations. These measurements are outlined below.

- Using a tape measure, the height of the piping protruding above the ground level was measured to allow calculations to be made regarding the depth to the water table. These are covered in Chapter 4, Section 2.
- The depth to the water table from the top of the piping was measured. This was done using a dipping probe. When the tip of the probe meets the water, an electrical circuit is formed which sounds a small buzzer. The subsequent height is then read off the tape measure that is attached to the probe. The pressure generated in the beach system by the tidal movements will affect these measurements. Monitoring this level will

hopefully show fluctuations in the tide propagating up the beach. In coastal aquifers in contact with the ocean, sinusoidal fluctuations of groundwater levels occur in response to tides. If the sea level varies with a simple harmonic motion, a train of sinusoidal waves are propagated inland from the submarine outcrop of the aquifer. With distance, inland amplitudes of the waves decrease and the time lag of a given maximum increases (Todd, 1980).

- Using a CDM conductivity meter (CDM 200), measurements of electrical conductivity were made. This technique will allow any changes in the saline/freshwater content of the water to be observed. This simple probe works in the same way as the dipping probe, but instead of triggering a buzzer, the meter measures how strong the circuit is. Saline water is more conductive than fresher water due to its high salt content, thus causing a stronger circuit to be formed.
- The temperature of the water was measured simultaneously with the electrical conductivity using the conductivity meter. Temperature variations occur within the water, which are dependent on the proportion of fresh to saline water but often are not reliable. These measurements will possibly aid in distinguishing the salinity of the water contained in the boreholes.

The measurements that have been outlined were made at hourly intervals throughout the day. The survey periods that were achieved depended on the relative heights of the tides and hours of daylight that still enabled readings to take place. All of the plastic piping was removed from the beaches at the end of the day.

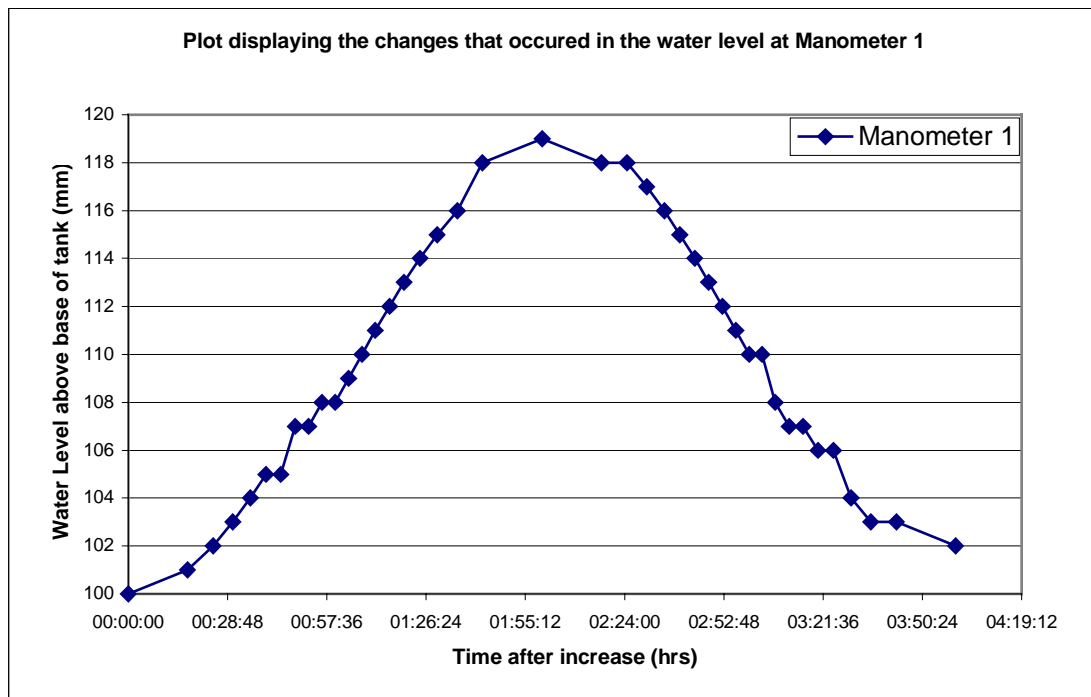
Chapter 3

Section 1

Results from the Darcy Tank Experiment

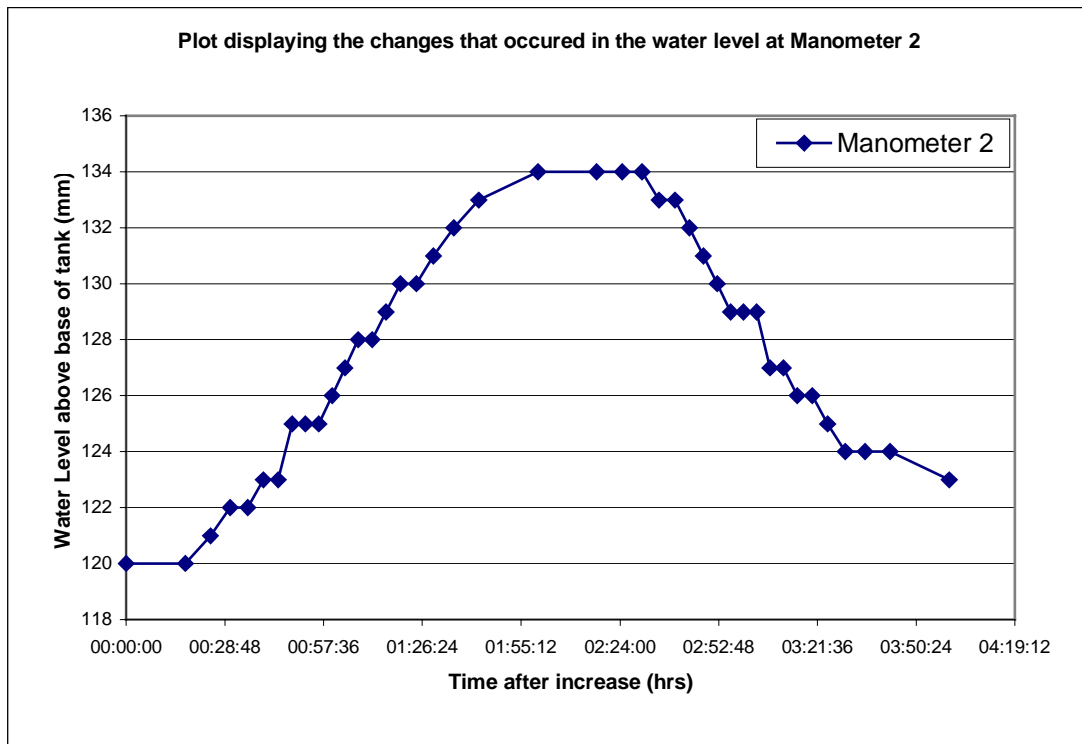
When the Darcy tank experiment was conducted, it produced the data displayed in Appendix 1, figure A2. This data was then used to plot the following graphs, figures 3.1 to 3.6.

Figure 3.1: Plot displaying results from manometer 1 of the Darcy tank



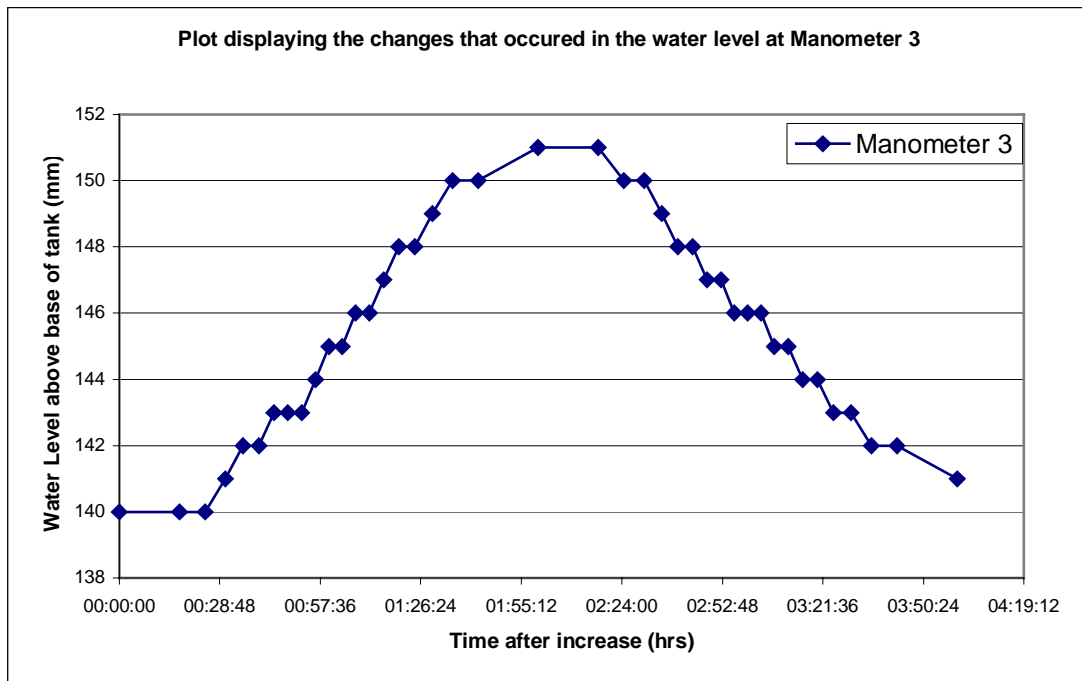
Manometer 1 is situated 206 mm from the outflow of the Darcy tank making it the closest manometer. A peak of 119 mm was recorded at 2 hours into the experiment. The starting water level at manometer 1 was 100 mm above the base of the tank. This therefore means that the total height change that occurred at manometer 1 was 19 mm.

Figure 3.2: Plot displaying results from manometer 2 of the Darcy tank



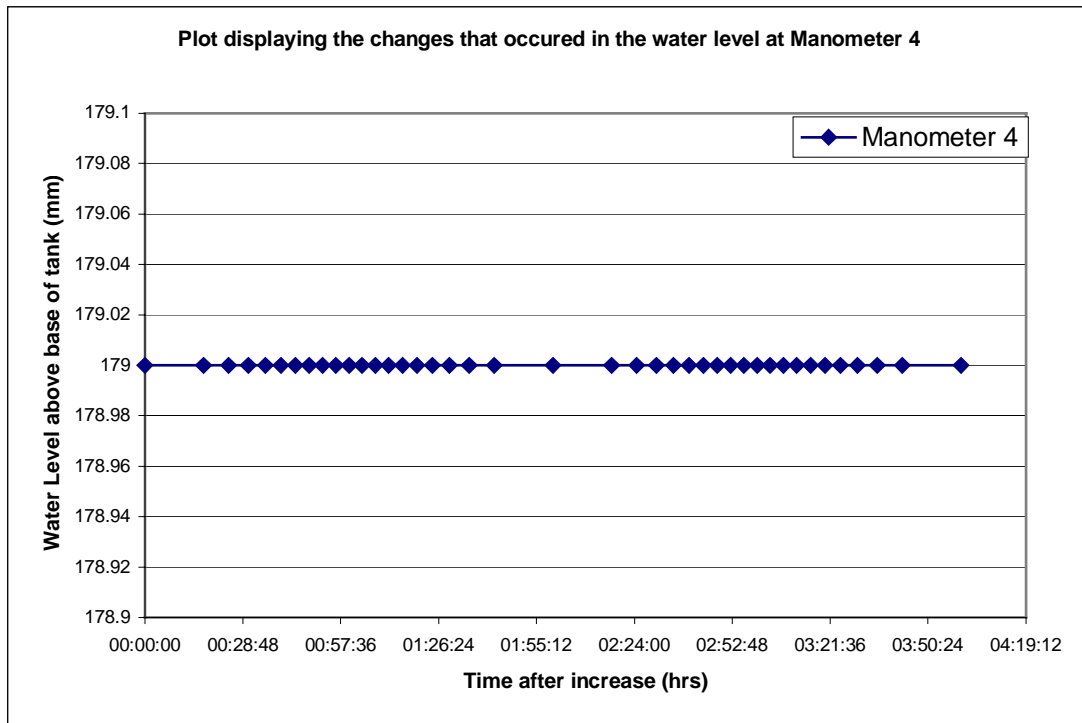
Manometer 2 is situated 506 mm from the outflow of the Darcy tank. A peak of 134 mm was recorded at the same 2 hours mark as manometer 1 although unlike manometer 1 this peak lasted for approximately 30 minutes until starting to fall. The starting water level at manometer 2 was 120 mm above the base of the tank. This therefore means that the total height change that occurred at manometer 2 was 14 mm. A short lag can also be seen at the start of the experiment before any change in the water level was recorded.

Figure 3.3: Plot displaying results from manometer 3 of the Darcy tank



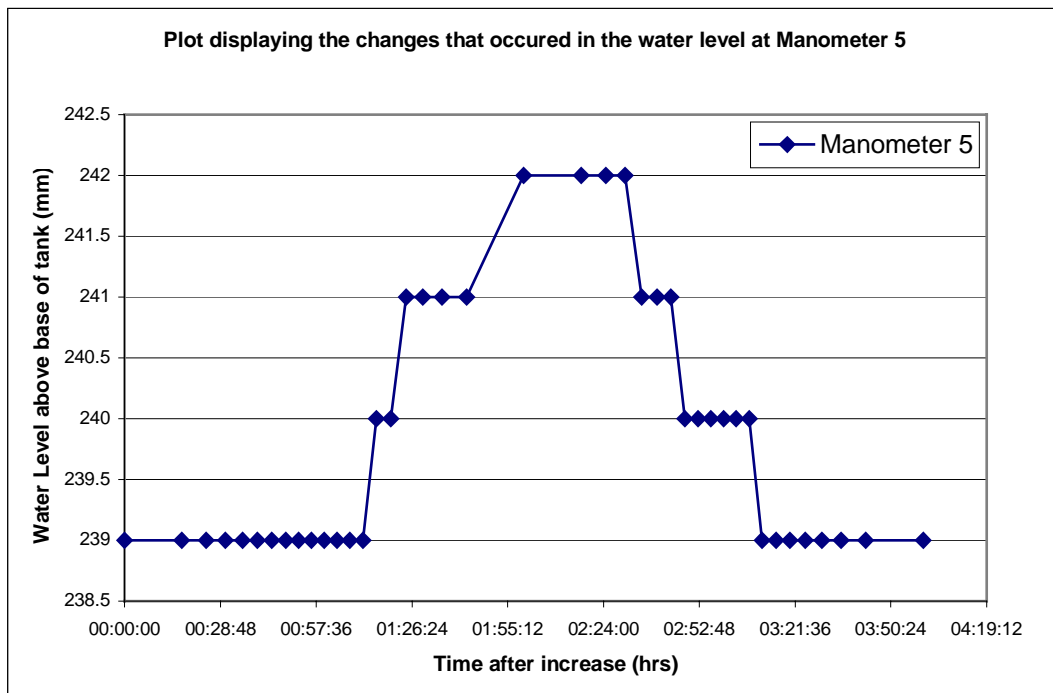
Manometer 3 is situated 659 mm from the outflow of the Darcy tank. A peak of 151 mm was recorded at the same 2 hours mark as manometers 2 and 3, although unlike manometer 2 this peak only lasted for approximately 17 minutes, just over half the time of manometer 2. The starting water level at manometer 3 was 140 mm above the base of the tank. This therefore means that the total height change that occurred at manometer 3 was 11 mm. A short lag can also be seen at the start of the experiment before any change in the water level was recorded.

Figure 3.4: Plot displaying results from manometer 4 of the Darcy tank



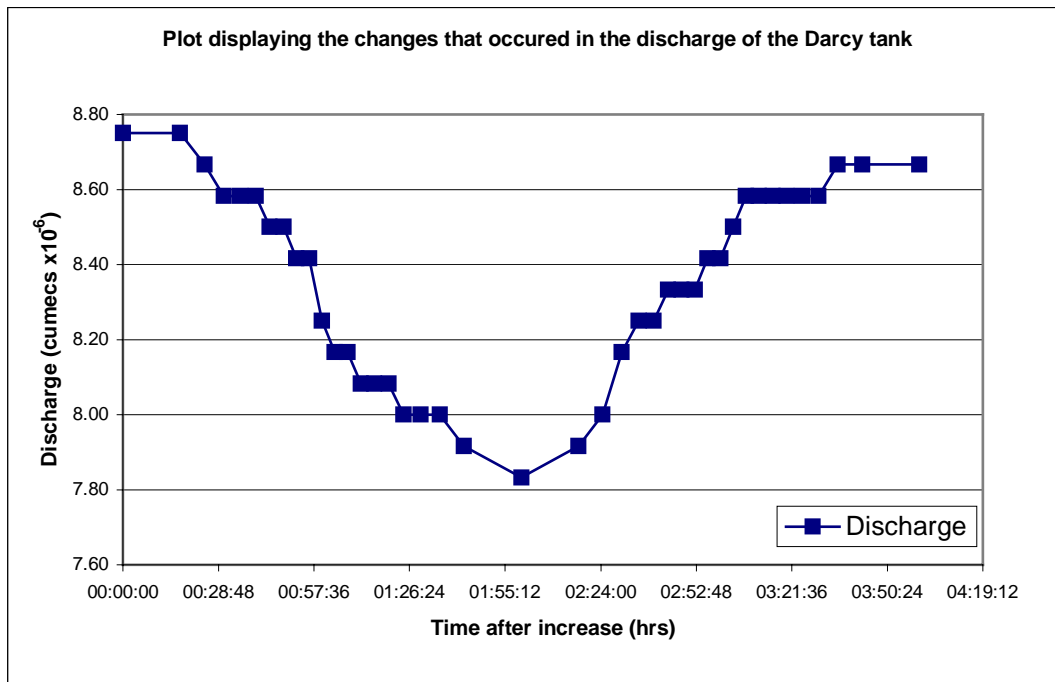
Manometer 4 is situated 812 mm from the outflow of the Darcy tank. Manometer 4 did not register any change in its water level, through out the experiment, suggesting that it was not functioning properly.

Figure 3.5: Plot displaying the results from manometer 5 of the Darcy tank



Manometer 5 is situated 1112 mm from the outflow of the Darcy tank. A peak of 242 mm was recorded at the same 2 hours mark as manometers 2 and 3, and just as manometer 2, the peak lasted for approximately 30 minutes. The starting water level at manometer 5 was 239 mm above the base of the tank. This therefore means that the total height change that occurred at manometer 5 was only 3 mm. The lag time at the start of the experiment before any change in the water level was recorded can also be seen to increase. This shape of this figure can be seen to have a stepped appearance.

Figure 3.6: Plot displaying the results of the discharge measurements of the Darcy tank



Discharge measurements from the tank were made with a large measuring cylinder and were to the nearest 5 ml. This meant that they were relatively inaccurate. This probably accounts toward the stepped appearance of this plot. This plot mirrors figures 3.1 to 3.5 in that as the water table increases in depth, the discharge from the tank decreases. The maximum discharge from the tank was measured at 8.75×10^{-6} cumecs and occurred at the very start of the experiment.

Section 2

The Darcy Tank, Errors and Improvements

Trying to simulate groundwater conditions that may be experienced at a beach location is not easy, many problems were encountered using the Darcy tank and hopefully these will all be outlined in this section.

The biggest problem that was encountered using the Darcy tank was accuracy. Outlined below are numerous ways in which inaccuracies could have been incurred.

Positioning of the inflow and outflow pipes to the tank. This was done using a ruler on the outside of the tank and line of sight. If either or both of the pipes had been wrongly positioned it could have a bearing on the water levels in the manometers and on the discharge of the tank either raising or lowering them from what they should have been. This problem could have been slightly reduced by measuring the distances from inside the tank before the start of the experiment and then marking the heights on the in and outflow pipes to make adjusting them easier and more accurate.

Measurements made at the manometers. The measurements that were made at the individual manometers were done so using eyelevel and a series of rulers attached to the outside of the tank. Inaccuracies could have occurred via human error in that the water level was read wrongly. Errors were also incurred whilst reading the water level of the rulers. These readings were only accurate to 1 mm when ideally even the smallest changes should have been recorded. This could be solved using a more accurate measuring device. Errors could also have been made in the timings of the readings. Due to the fact that only one manometer reading can be made at any one time, if one of the manometers had taken slightly longer to measure than normal then the other four would be read slightly later. Marking the changes in water table height on the manometers and measuring the changes at a later date could have reduced this

Measurements made of the discharge from the tank. Measurements made of the discharge were done using a large measuring cylinder. Errors will have occurred when reading off the water level from the side of the cylinder because the measuring cylinder was only accurate to 5 millilitres. This meant that anything in-between two markers was estimated or rounded up or down. The solution to this problem would have been to use a more accurate measuring cylinder, and even then, human error may have meant that some of the readings were incorrect.

The movement of the outflow pipe to create a sine wave effect. The method used to create the sine wave involved altering the height of the outflow pipe in 5 mm increments over the set time intervals. This could have caused some errors because the pipe may not have been placed at the exact level, because it had to be lined up by sight. This problem could have been solved by marking the height changes on the pipe as opposed to the wooden board situated above the outflow side of the tank. Another solution would have been to have a mechanism that altered the height automatically.

Measurements made of the manometer positions. This was carried out using a tape measure. This will not have caused any inaccuracies with the experimental data, although it should be acknowledged that the numbers for the distances between the manometers used in some of the figures for this project could be slightly inaccurate. This measurement was made three times and then averaged. For a higher degree of accuracy, the tank would have to be emptied and then the positions could be measured from inside the tank.

One of the major errors that arose during the experiment was that the time period that the experiment was measured over was too long. This meant that the Darcy tank reacted to the changes in the height of the outflow far quicker than anticipated. This is another factor that has contributed to the stepped appearances of figures 3.1 to 3.6. This could be improved by altering the duration of the experiment.

There was also an error that was beyond the control of the user. Errors also occurred inside the tank. It was noticeable that a large capillary fringe developed above the water table that ascended almost all of the way to the top of the tank, and the surface of the sand. This could have caused inaccuracies, causing water levels to be higher than they should have been, although one benefit of this occurring is that in the natural environment this will also occur.

Another error that could have been incurred was that the manometers could have been slightly blocked or in the case of manometer 4, was totally blocked. This would then have reduced the water levels that were being measured. This problem will be explained further in Chapter 4, Section 1.

Section 3.1

Results from the Beach Studies at Heysham Bay on 14th June 2001

Figure 3.1.1: Plan view representation of the Beach Profile at Heysham Bay

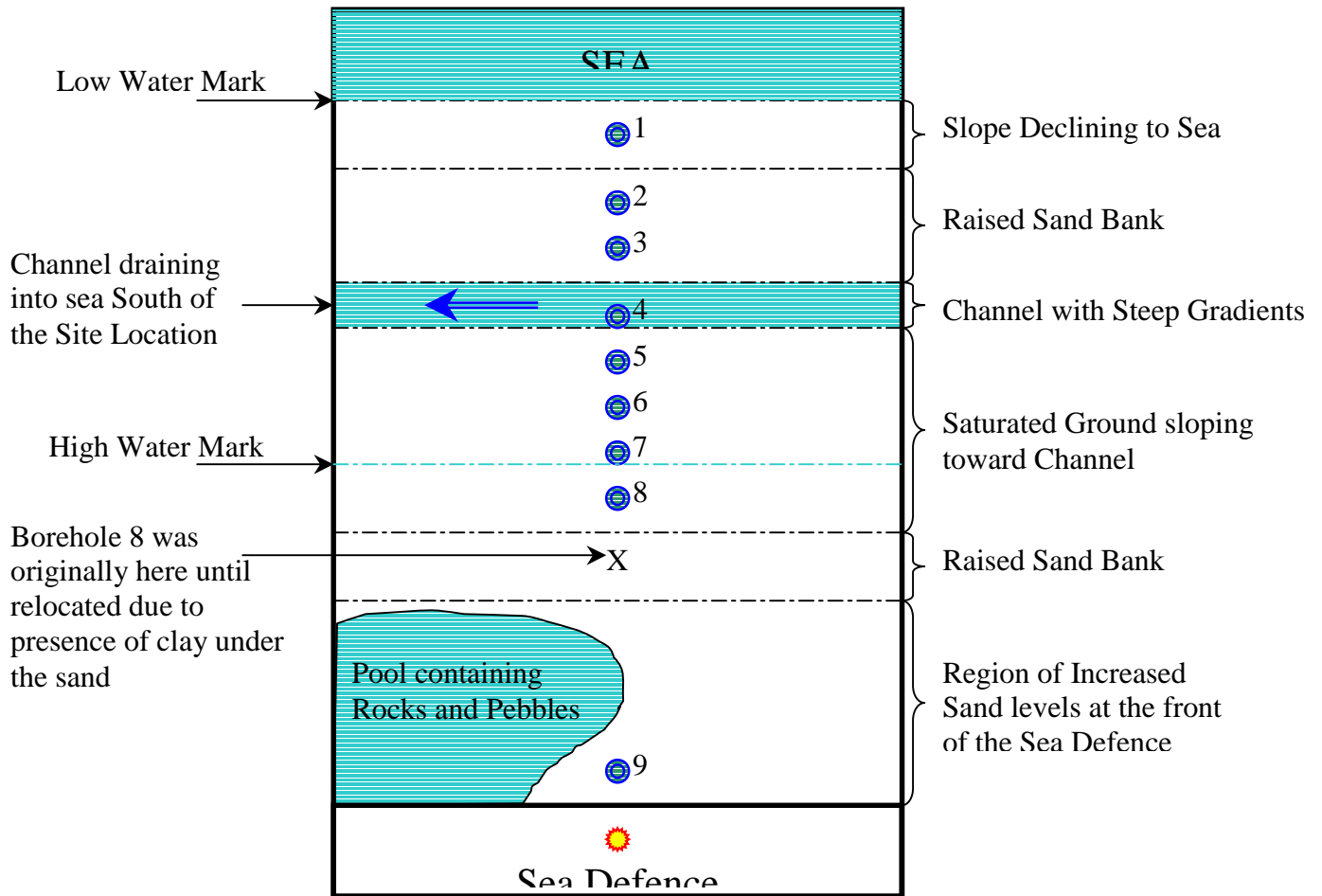
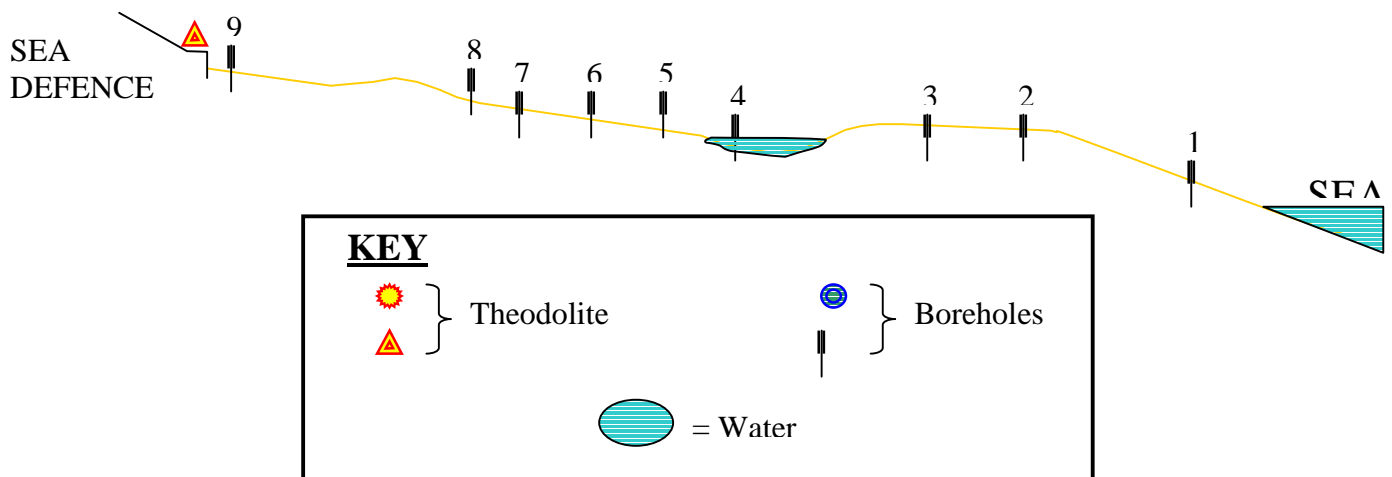


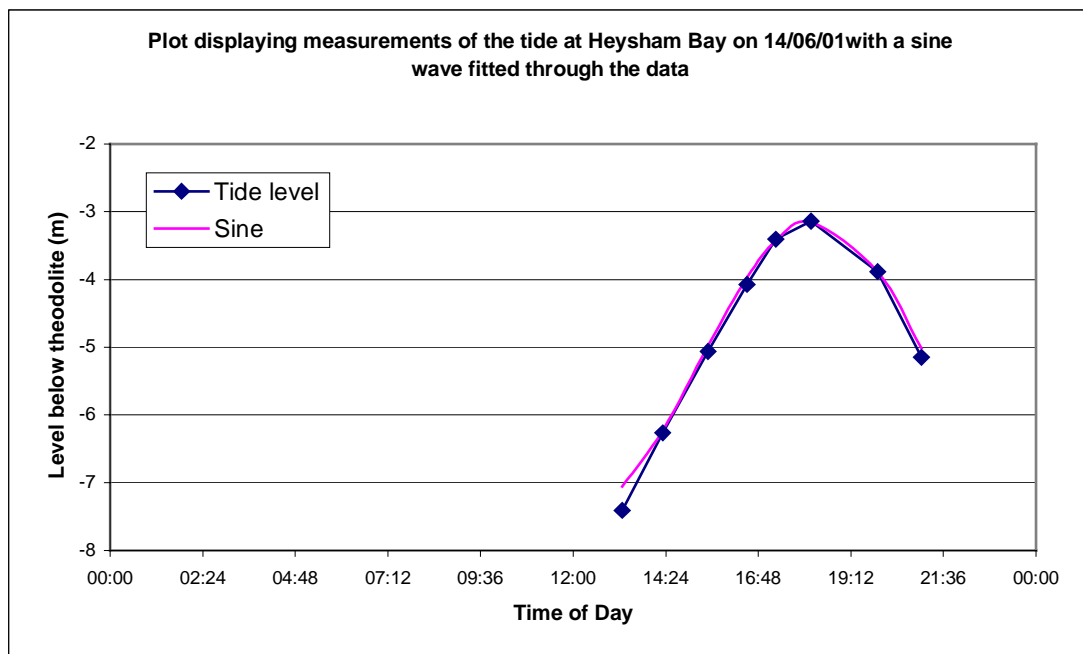
Figure 3.1.2: Representation of Heysham Bay beach profile shown in Section



Figures 3.1.1 and 3.1.2 show the positions of all of the major features of the beach on the 14th June, relative to the positions of the boreholes and theodolite.

From this set up, readings were made approximately every hour from one until nine o'clock. Readings were taken starting at the furthest point, which was always the sea level and then working back up the beach toward the theodolite. In this section of the report the general results will be outlined. Figure 3.1.3 displays all of the data that was collected for the tide levels. The data used to create this plot can be found in Appendix 2, figure A2.1: Tidal heights and sine wave for Heysham Bay 14/06/01 for data.

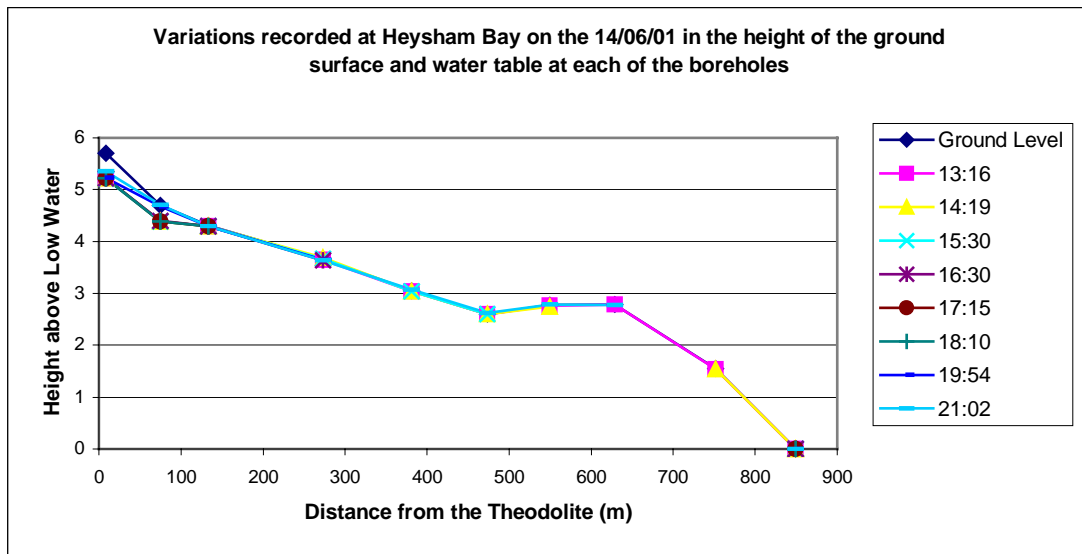
Figure 3.1.3: Height of the tide measured at Heysham Bay



The data collected follows the shape of a sine wave, which has been shown by fitting a sine wave through the data. The sine wave that a tide will follow will fit a period of approximately 6 hours between its maximum and minimum level. The data collected shows the time of the high tide to be at 18:10, the height of the tide measured by Her Majesties Coastguard Liverpool was 17:59 British Summer Time. It is likely that the difference between the two is caused by the time that our reading was taken.

Figure 3.1.4: Boreholes and water table levels at each of the boreholes at Heysham Bay

14/06/01

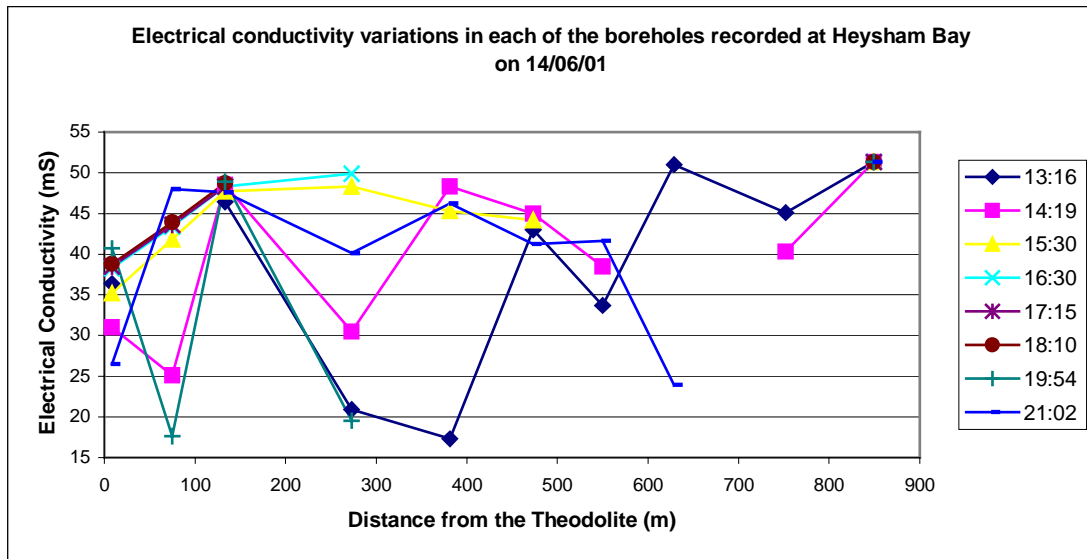


The point that is on the x – axis is the lowest tide measurement taken on that day.

The data used to create this plot can be found in Appendix 2, figure A2.5: Calculations of the ground and water levels for the boreholes at Heysham Bay on 14/06/01.

The figure displays all of the data that was collected for the ground and water levels at Heysham on the 14/06/01. The changes in the height and shape of the ground level readings shows that at Heysham there is a difference in height of approximately 6 meters between low water and the height of borehole 9 on that day. The figure also shows that between the low water mark and borehole 9 there is a distance of approximately 850 meters. A simple calculation means that the gradient of the beach at Heysham on the 14/06/01 was only 0.0076° . The shape of the ground level line shows a good resemblance to the representation shown in figure 3.1.2. From the figure it is clear that there is only a negligible change in the water tables for boreholes 1 – 7 if any. There is however up to half a meter change registered at boreholes 8 and 9 for some of the time readings.

Figure 3.1.5: Electrical conductivity variations in the boreholes at Heysham Bay on 14/06/01.

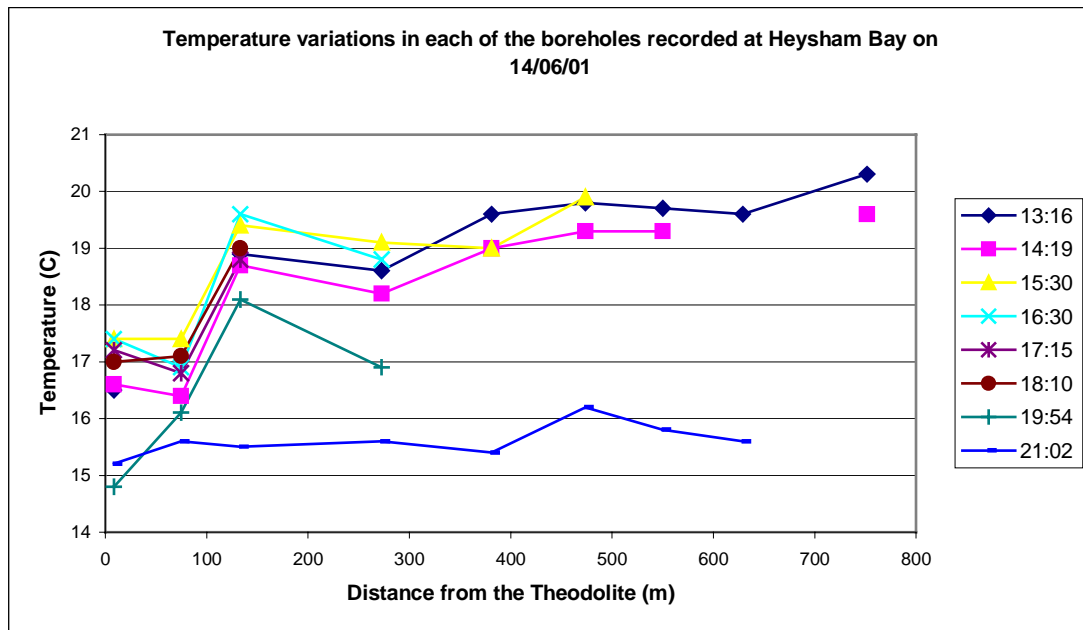


The data point at approximately 850 meters is a reading of the sea.

The data used to create this plot can be found in Appendix 2, figure A2.6: Electrical conductivity variations at Heysham on the 14/06/01.

At first glance this figure does not appear to show a great deal of information. The variations in the boreholes ranged between approximately 17 and 52 mS. A detailed examination of this data will be carried out in Chapter 4, Section 2.

Figure 3.1.6: Temperature variations in the boreholes at Heysham Bay on 14/06/01



The data used to create this plot can be found in Appendix 2, figure A2.7: Temperature variations in the boreholes at Heysham on 14/06/01.

The data in this figure does follow a vague pattern. As the boreholes get closer to the sea, there seems to be a rise in the temperature. The average temperature range in each of the boreholes looks to be approximately 3°C. All of this will be examined in Chapter 4, Section 2.

Section 3.2

Results from the Beach Studies at Heysham on 21st June 2001

Figure 3.2.1: Plan view representation of the Beach Profile at Heysham Bay

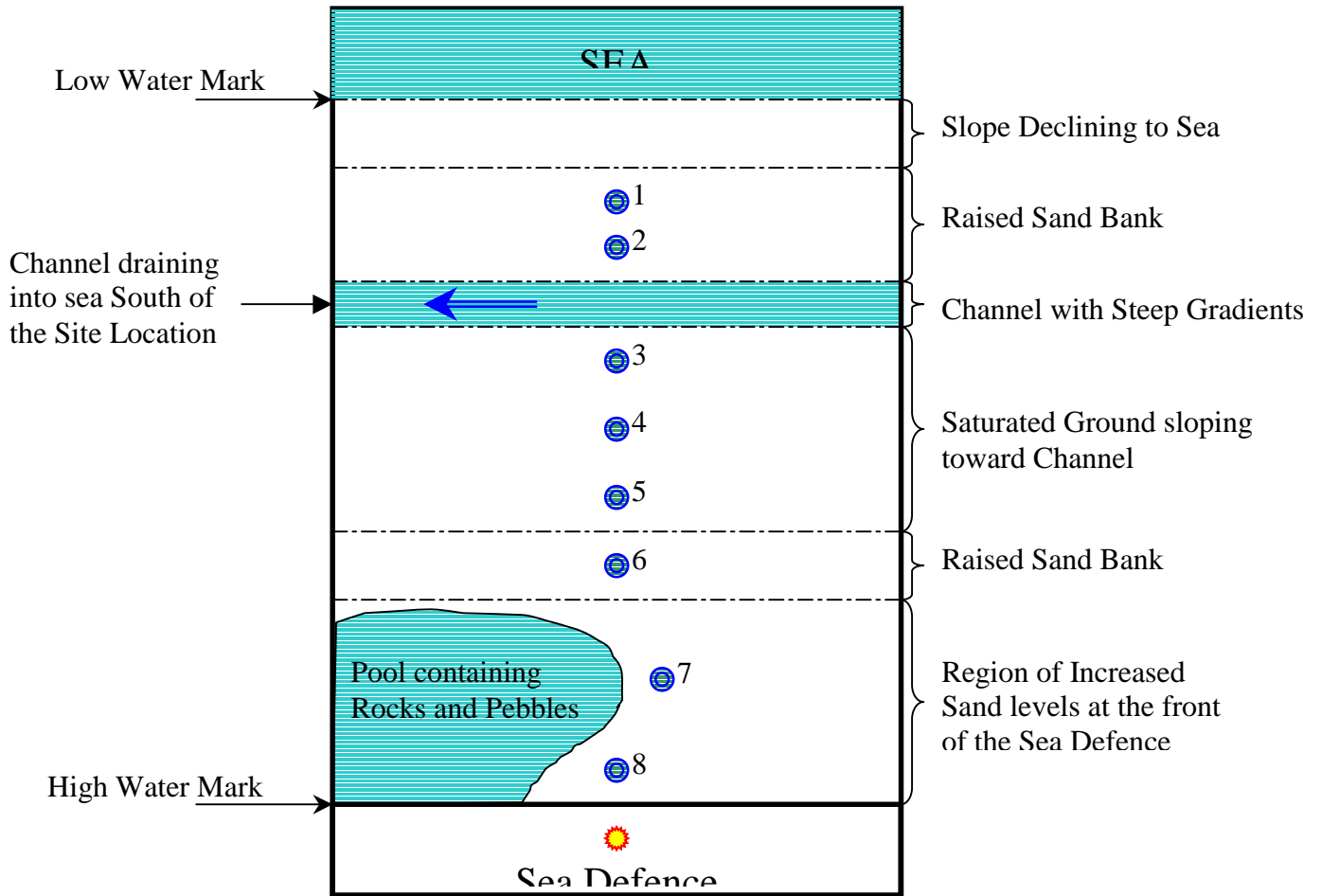
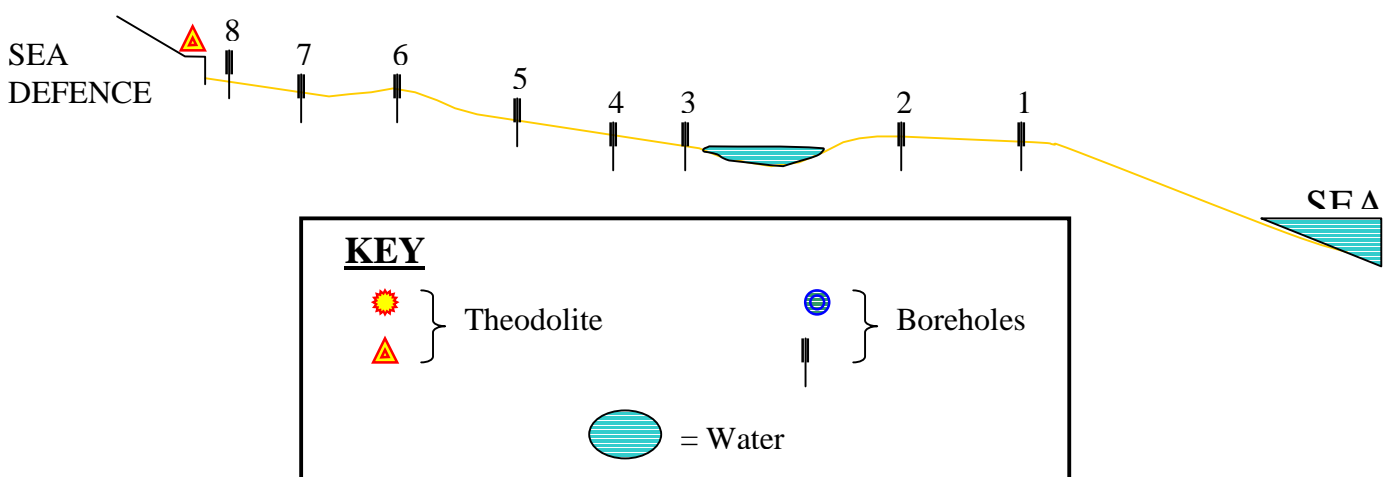


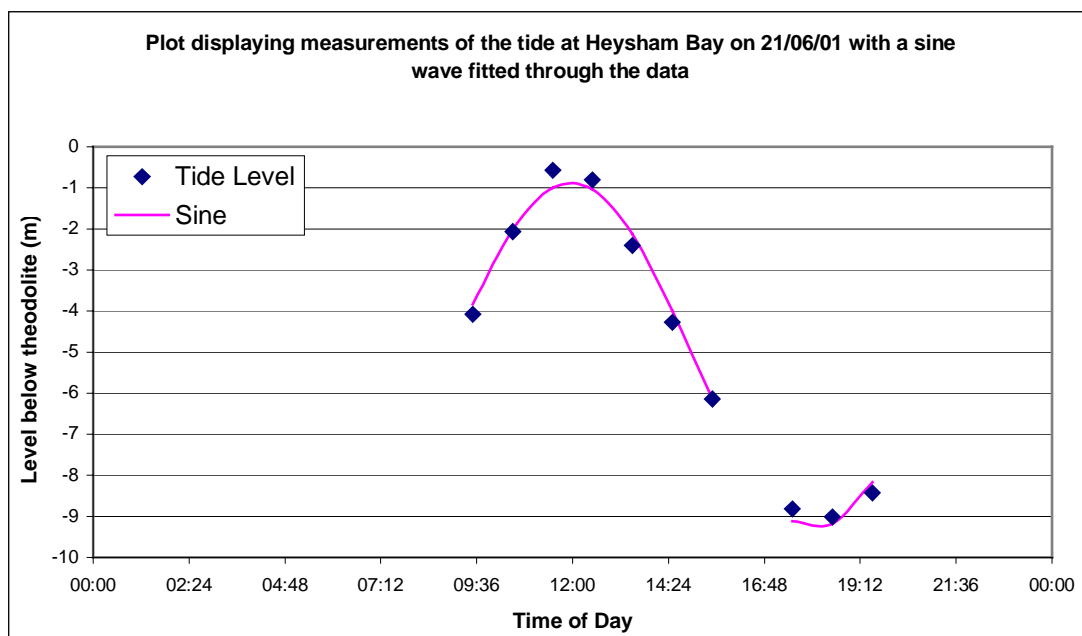
Figure 3.2.2: Representation of Heysham Bay beach profile shown in Section



Figures 3.2.1 and 3.2.2 show the positions of all of the major features of the beach on 21st June relative to the positions of the boreholes and theodolite.

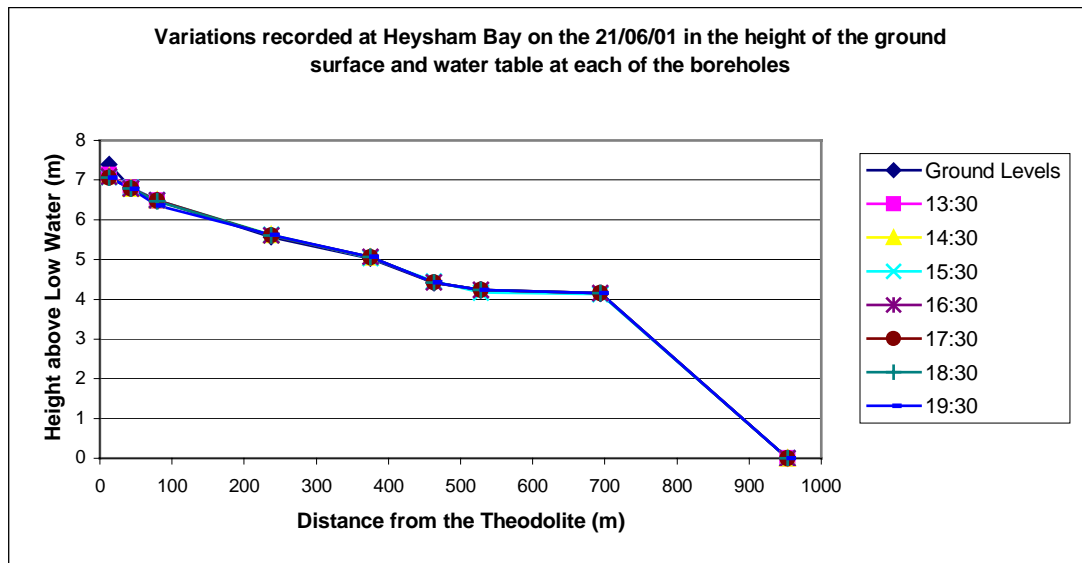
From this set up, readings were made approximately every hour from 08:30 to 19:30. Readings were taken starting at the furthest point, which was always the sea level and then working back up the beach toward the theodolite. In this section of the report the general results will be outlined. Figure 3.2.3 displays all of the data that was collected for the tide levels. The data used to create this plot can be found in Appendix 2, figure A2.8: Tidal heights and sine wave for Heysham Bay 21/06/01.

Figure 3.2.3: Height of the tide measured at Heysham Bay 21/06/01



The data collected follows the shape of a sine wave, which has been shown by fitting a sine wave through the data. The sine wave that a tide will follow will fit a period of approximately 6 hours between its maximum and minimum level, a similar time is shown with the data. The high tide being recorded at 11:30 and the low tide being recorded at 18:30. The data displays a time period of 7 hours, but this will have been affected by the times that the readings were taken. The times of the high and low tide according to Her Majesties Coastguard Liverpool were 11:53 and 18:30 respectively. (All times are in British Summer Time). A difference of approximately 6.5 hours.

Figure 3.2.4: Boreholes and water table levels at each of the boreholes at Heysham Bay
21/06/01

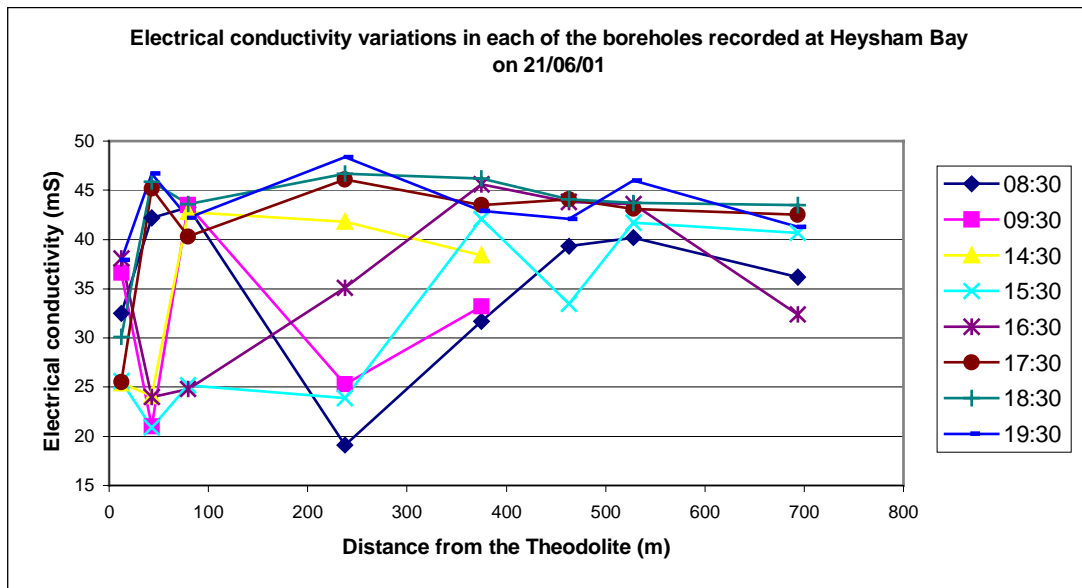


The point that is on the x – axis is the lowest tide measurement taken on that day.

The data used to create this plot can be found in Appendix 2, figure A2.12: Calculations of the ground and water levels for the boreholes at Heysham Bay on 21/06/01.

The figure displays all of the data that was collected for the ground and water levels at Heysham on the 21/06/01. The change in the height and shape of the ground level readings shows that on this day at Heysham there is a difference in height of approximately 7.5 meters between low water and the height of borehole 8. The figure also shows that between the low water mark and borehole 8 there is a distance of approximately 950 meters. A simple calculation means that the gradient of the beach at Heysham on the 21/06/01 was only 0.0079° . The shape of the ground level line shows a good resemblance to the representation shown in figure 3.2.2. From the figure it is clear that there is only a negligible change in the water tables for boreholes 1 – 7 if any. There is however up to half a meter change registered at borehole 8 for some of the time readings.

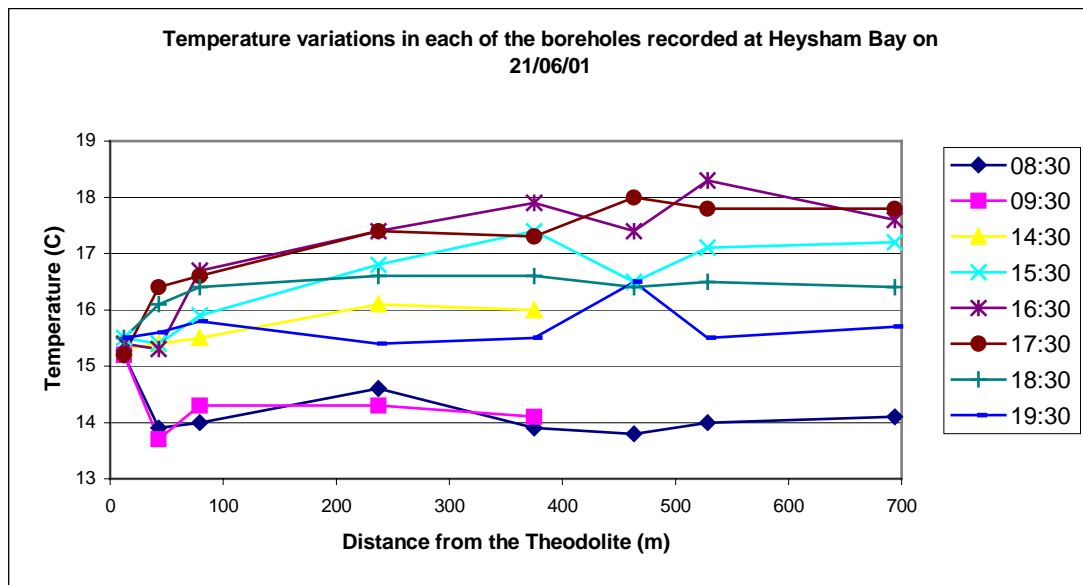
Figure 3.2.5: Electrical conductivity variations in the boreholes at Heysham Bay on 21/06/01



The data used to create this plot can be found in Appendix 2, figure A2.13: Electrical conductivity variations at Heysham on the 21/06/01.

Like the conductivity on the 14th at Heysham, at first glance this figure does not appear to show a great deal of information. The variations in the boreholes ranged between approximately 19 and 48 mS. A detailed examination of this data will be carried out in Chapter 4, Section 2.

Figure 3.2.6: Temperature variations in the boreholes at Heysham Bay on 21/06/01



The data used to create this plot can be found in Appendix 2, figure A2.14: Temperature variations in the boreholes at Heysham on 21/06/01.

The data in this figure does follow a vague pattern. The temperature in the boreholes increases through out the day in to late afternoon, but then appears to decrease into early evening. This will be examined Chapter 4, Section 2. The average temperature range in each of the boreholes looks to be between 1 and 3°C.

Section 3.3

Results from the Beach Studies at Rossall Bay on 20th June 2001

Figure 3.3.1: Plan view representation of the Beach Profile at Heysham Bay

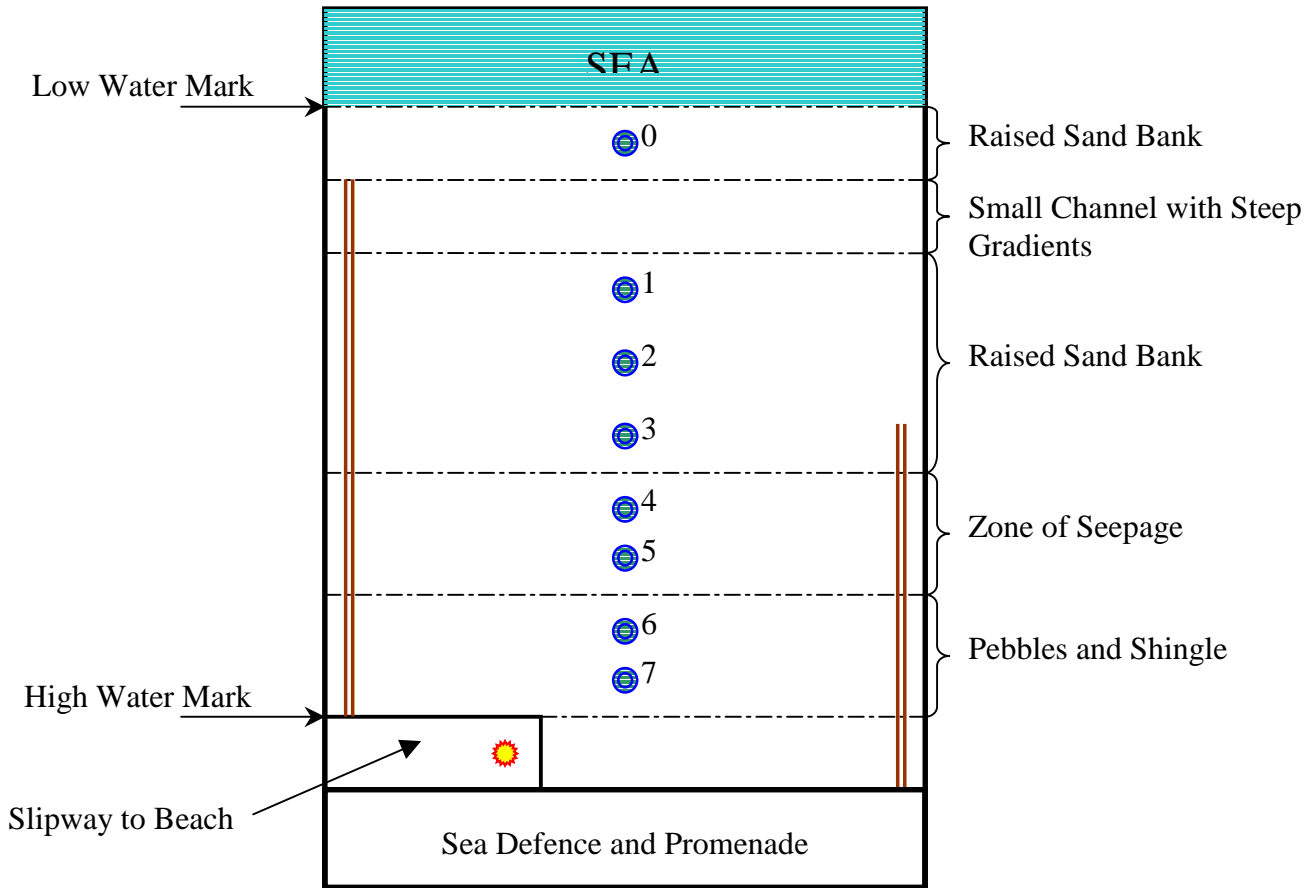
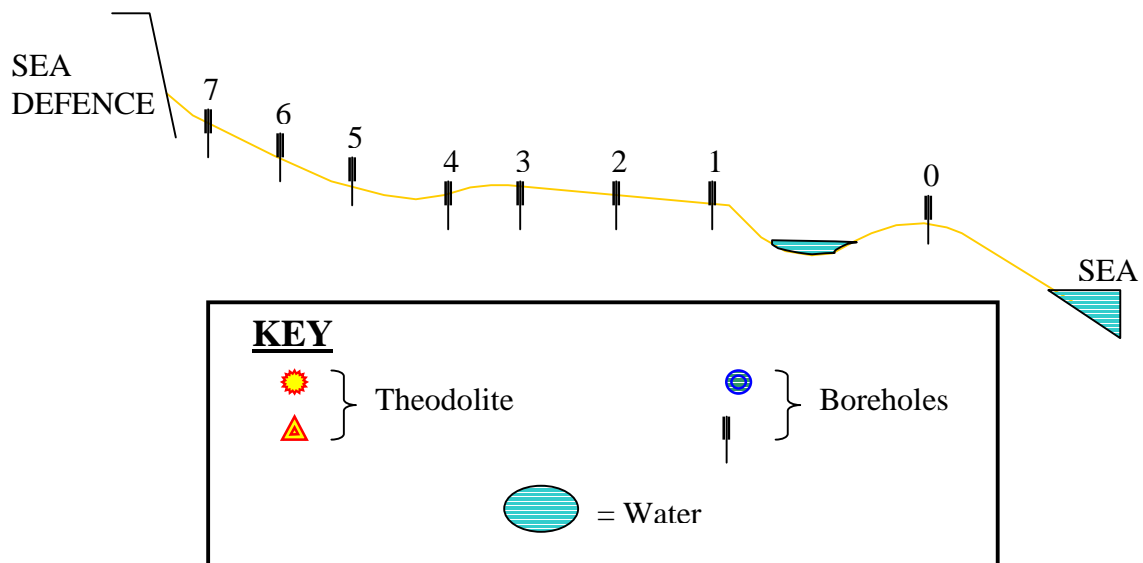


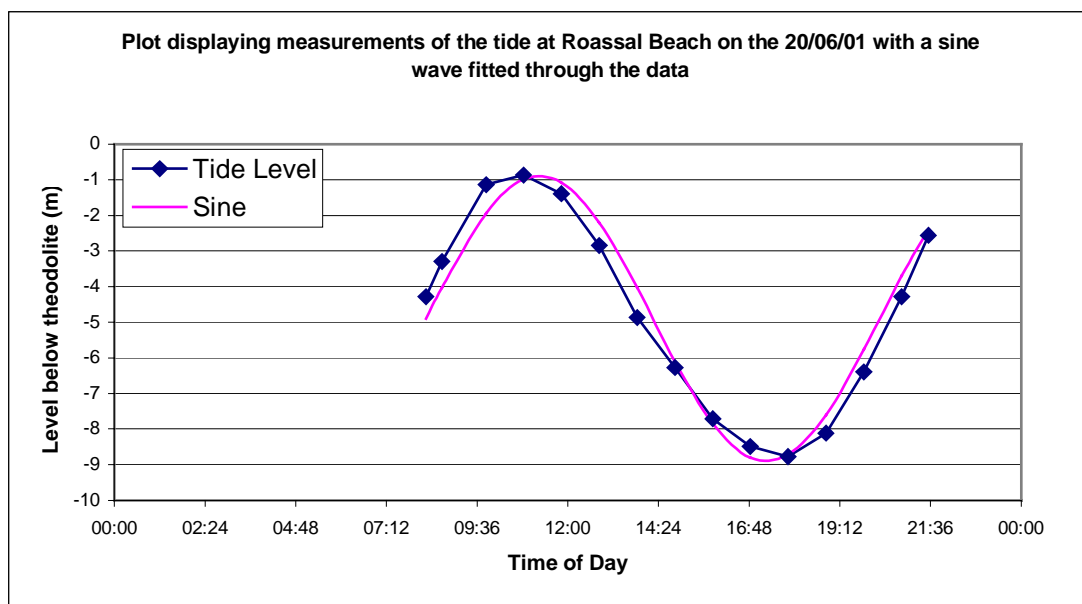
Figure 3.3.2: Representation of Heysham Bay beach profile shown in Section



Figures 3.3.1 and 3.3.2 show the positions of all of the major features of the beach on 20th June relative to the positions of the boreholes and theodolite.

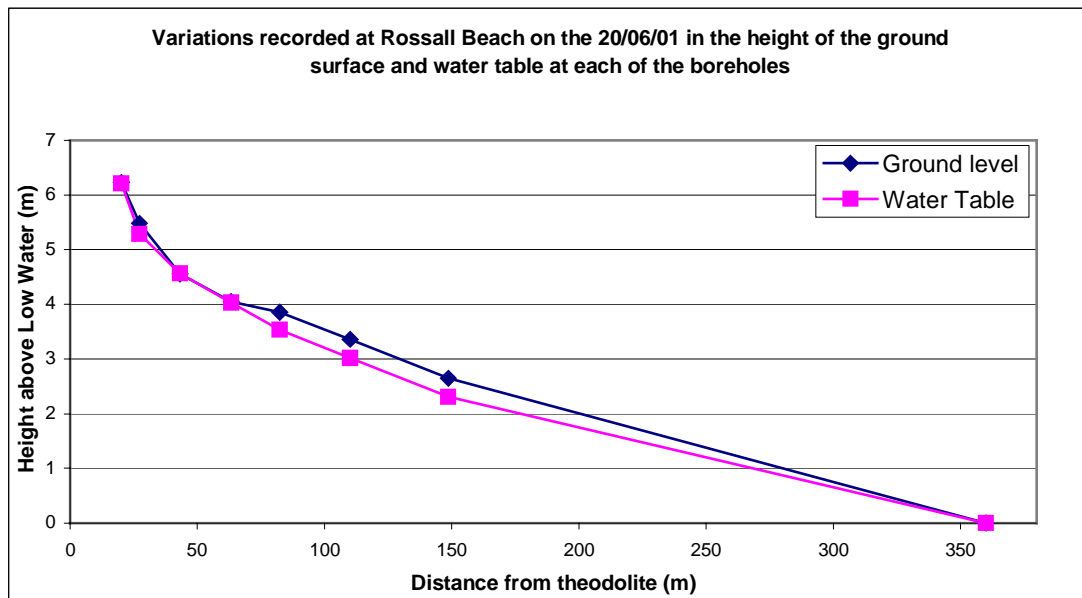
From this set up, readings were made approximately every hour from 08:15 to 21:30. Readings were taken starting at the furthest point, which was always the sea level and then working back up the beach toward the theodolite. In this section of the report the general results will be outlined. Figure 3.3.3 displays all of the data that was collected for the tide levels. The data used to create this plot can be found in Appendix 2, figure A2.15: Tidal heights and sine wave for Rossall Beach 20/06/01.

Figure 3.3.3: Height of the tide measured at Rossall Beach 20/06/01



The data collected follows the shape of a sine wave, which has been shown by fitting a sine wave through the data. The sine wave that a tide will follow will fit a period of approximately 6 hours between its maximum and minimum level, a similar time is shown with this data. The high tide being recorded at 10:50 and the low tide being recorded at 17:50. The data displays a time period of 7 hours, but this will have been affected by the times that the readings were taken. The times of the high and low tide according to Her Majesties Coastguard Liverpool were 11:07 and 17:45 respectively. (All times are in British Summer Time). The difference between the two is approximately 6.5 hours.

Figure 3.3.4: Boreholes and water table levels at each of the boreholes at Rossall Beach
20/06/01



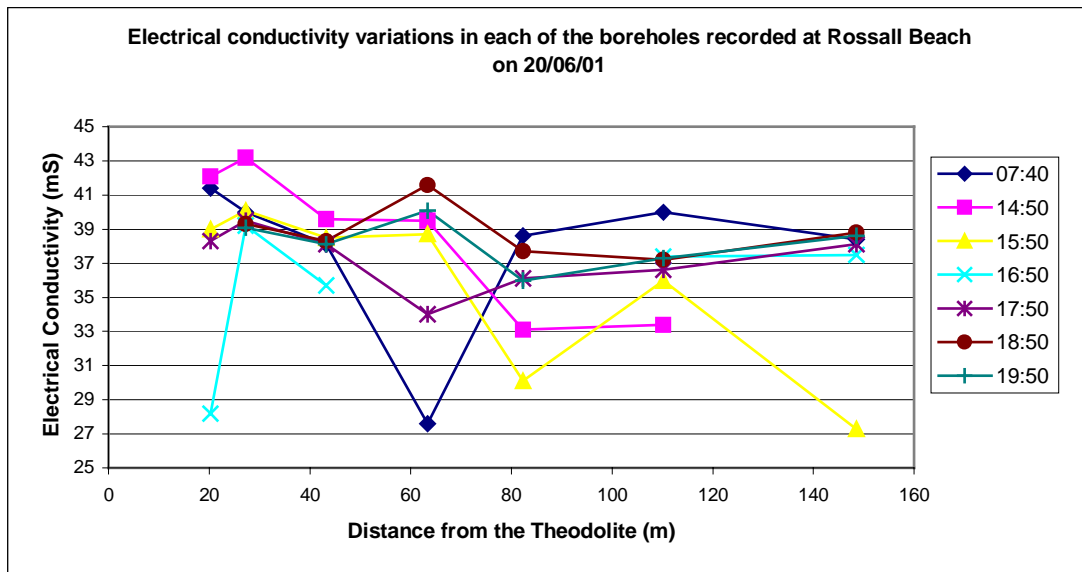
The point that is on the x – axis is the lowest tide measurement taken on that day.

The water table between borehole 1 and sea level is only inferred, because there are no readings for this area.

The data used to create this plot can be found in Appendix 2, figure A2.19: Calculations of the ground and water levels for the boreholes at Rossall Beach on 20/06/01.

The figure only displays data of the ground level and water table at low water. This is due to the fact that the results that were collected for the other times through out the day cannot be relied upon to be correct. The change in the height and shape of the ground level readings shows that at Rossall beach there is a difference in height of approximately 6 meters between low water and the height of borehole 7. The figure also shows that between the low water mark and borehole 7 there is a distance of approximately 350 meters. A simple calculation means that the gradient of the beach at Rossall on 20/06/01 was 0.017° . The shape of the ground level line shows a good resemblance to the representation shown in figure 3.3.2. From the figure we can see that the water table is close to the beach surface at boreholes 4 – 7, but at boreholes 1 – 3 it is approximately half a meter below the surface.

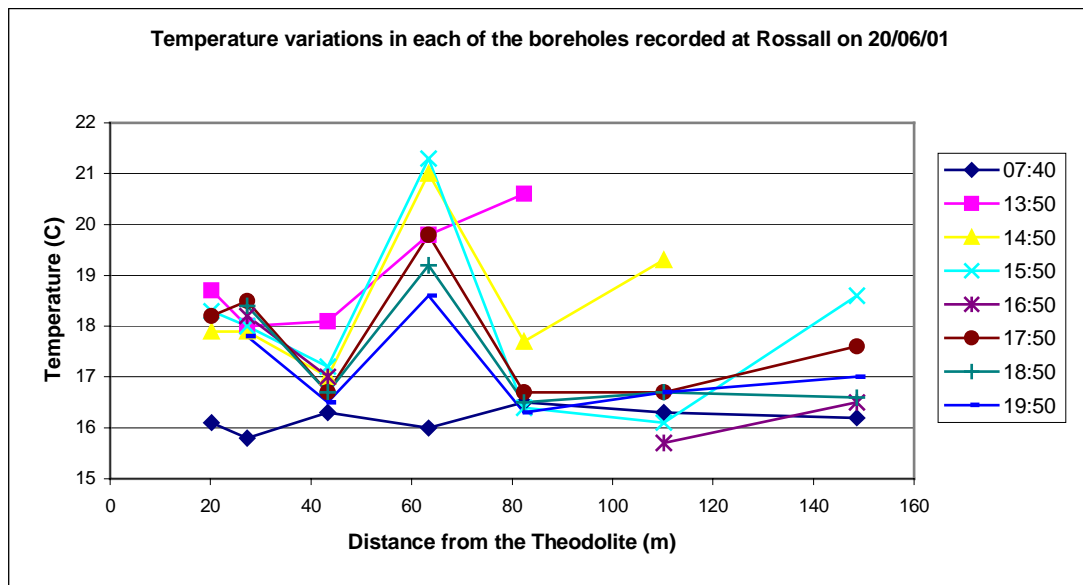
Figure 3.3.5: Electrical conductivity variations in the boreholes at Rossall Beach on 20/06/01



The data used to create this plot can be found in Appendix 2, figure A2.20: Electrical conductivity variations at Rossall Beach on 20/06/01.

Like the two data sets from Heysham, this figure does not appear to show a great deal of useful information. The variations in the boreholes ranged between approximately 27 and 43 mS. A detailed examination of this data will be carried out in Chapter 4, Section 2.

Figure 3.3.6: Temperature variations in the boreholes at Rossall Beach on 20/06/01



The data used to create this plot can be found in Appendix 2, figure A2.21: Temperature variations in the boreholes at Rossall Beach on 20/06/01

A vague pattern is displayed in some of the boreholes. Borehole 4 looks like it may show signs of increasing in temperature early on in the day, and shows signs of decreasing in temperature as the day progresses. The average temperature range in each of the boreholes looks to be approximately 2 - 5°C. All of this data will be examined Chapter 4, Section 2.

Section 4

The Beach Studies, Errors and Improvements

Most of the errors were standard to all three days that studies were conducted and will be outlined below, although some of the errors outlined may only be applicable to one data set.

Errors caused by borehole placements – Boreholes placed along the transect to the coastline should have been done in a perfectly straight line, with the theodolite positioned exactly behind them. Because this was not possible, any of the boreholes that were slightly out of line will have a reading from the theodolite that is not quite right. Laying out a straight line along the beach could have solved this. This would also have enabled the boreholes to be placed at equal distances from each other. However, laying out a line that at Heysham would have to be at least two thirds of a mile (~1000 meters) long is time consuming and impractical.

Distance readings from the reflective staff – To take readings of horizontal distances using the theodolite, a reflective staff is necessary to reflect the beam of light back to the theodolite. A slightly off vertical staff, which is more than likely due to the exposure of the beaches could cause small errors in the distance measurements. This could have been solved using a tripod, but once again this is impractical.

Time of measurements of high and low tide – Because measurements could only be taken at hourly intervals, measurements of the high and low tides was made difficult. Measurements made at the beaches will be close to the actual values give or take approximately half an hour. A comparison between the actual values and the measured ones can be seen in Appendix 3, figure A1. For more accurate measurements, the time interval between readings would have to be decreased.

Boreholes should have spanned the high water mark – For a true representation of the ground water movements, the set of boreholes should have spanned the high water mark. This was not possible on all days due to restrictions caused by depth of the water table and/or the height of the tide. A solution to this problem would be to use bigger drilling equipment to enable boreholes to be set higher up the beach.

Clogging of the boreholes – Some of the boreholes that were used became clogged with sand and rendered them useless until they were cleaned out. This causes problems when they are not reset in exactly the same place as previously. This also means that data from

the set is missing meaning that any conclusions that may be drawn up are not as reliable. Covering holes placed in the tubing with a fine wire mesh could solve this problem. This will still allow interaction with the water table to take place but prevent sand from clogging the pipe. Making slits in the tubing instead of holes could be an alternative solution.

Loss of boreholes – When the tide rose above the height of the boreholes it submerged them, but when the tide retreated down the beach, the borehole tubings had been washed away. This causes big problems when trying to reset a borehole in a similar position. This problem was experienced at a large scale at Rossall, Demonstrated in the surveying of the boreholes figure A2.18, Appendix 2. The solution to this problem is to use more advanced drilling equipment to allow the boreholes to be set deeper in the beach.

Positioning of the theodolite – At the start of the day, the theodolite should be positioned at a safe distance from the high water mark so that if the tide does reach the high water mark, the theodolite will not have to be moved. Relocating the theodolite causes problems with the data sets. Boreholes effectively have two different positions. This was necessary at Heysham on 21/06/01 to avoid having the theodolite washed away.

Number of boreholes – On each of the studies that were conducted a set number of boreholes should have been used, to allow easy comparisons to be drawn. All three of the days had different numbers of boreholes used.

Length of study time – For a complete data set to be produced, each of the location sites should have been studied for at least 24 hours. This was not possible due to day light restrictions, but this problem could be overcome if data loggers were implemented. This however is an expensive process. A better data set would be produced if ideally the experiment was conducted over a longer time period.

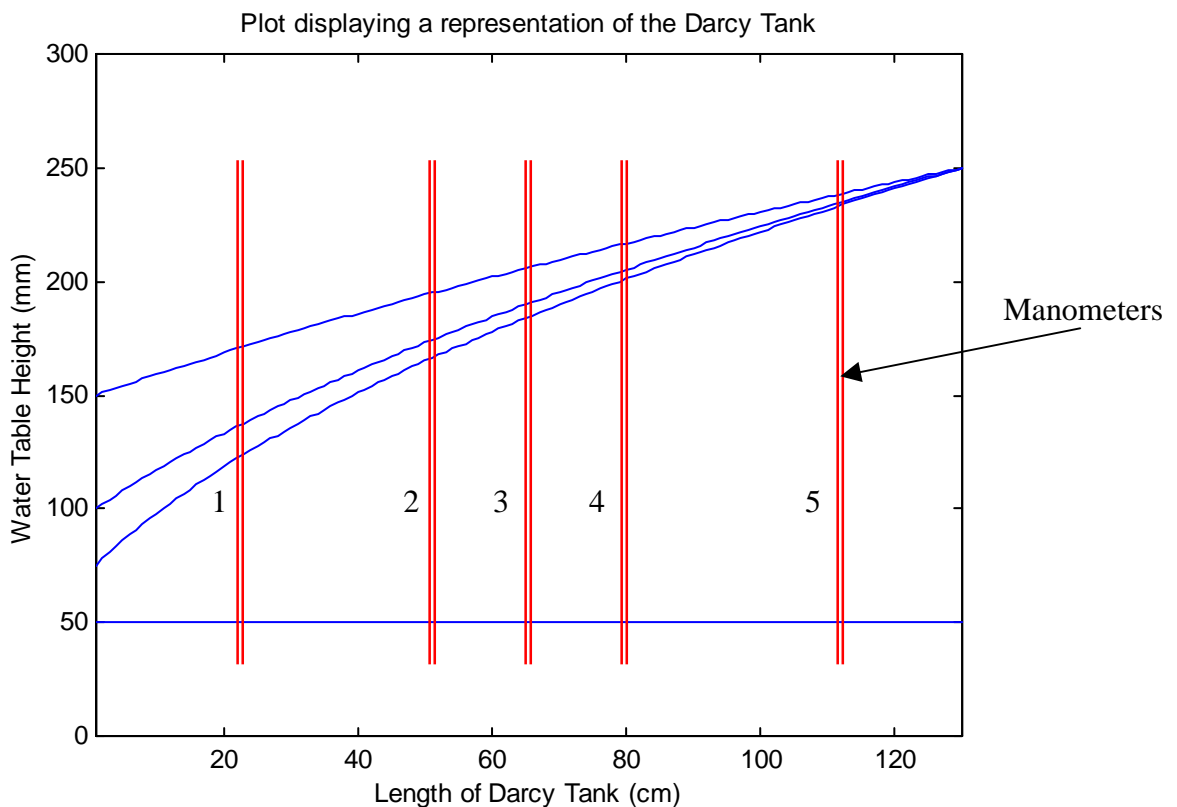
Chapter 4

Section 1

Discussion of the Results from the Darcy Tank Experiment

Examination of the results from the Darcy tank shows that as the distance from the outflow of the tank increases, the range in the data of the manometers decreases. This relationship can be demonstrated using figure 4.1. This figure is a representation of how the Darcy tank will have reacted to the increases that were made to the water level at the outflow side of the tank. It can be seen on this figure that the manometer that is closest to the outflow will have the biggest increase in water level. The increase at manometer 1 was recorded to be 19 mm, but if we look at manometer 5, the changes in the water table are only minimal. This is reflected in the results with manometer 5 having a range of data that was only 3 mm.

Figure 4.1: Representation of the changes in water level in the Darcy tank



This relationship can be reiterated using figures A1.4 to A1.7 that are displayed in Appendix 1. These figures are a sequence of plots created using the Aquifer Simulation Model (ASM). In this sequence the decline in the water table can be seen from studying

the contour lines on each of the plots. The contour spacing on all of the plots has been set to 10 mm. This forms a relationship between the contour lines and the slope, showing the closer the contour lines are from one another, the steeper the slope declines.

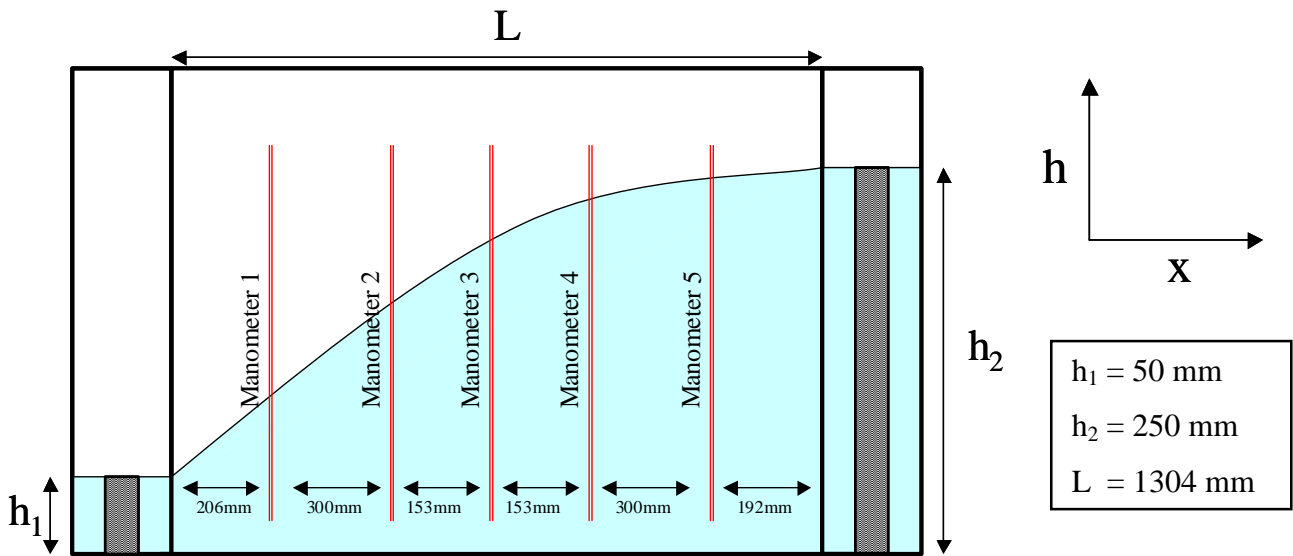
It is also evident from the results that there is a direct relationship between the changes in the water level and the discharge of the tank. An increase in the water level at the outflow of the tank causes a proportional decrease in the discharge from the tank. This result makes perfect sense. Because water flows under the effect of gravity, by raising the water level at the outflow of the tank, the gradient of the slope of the water table is decreased. This then infers a decrease in the effect that gravity will have on the water and hence the discharge from the tank is reduced.

Fluctuating the outflow of the tank to simulate the effect that tidal conditions may have on a beach system worked reasonably well. The data does seem to follow the shape of a sine wave even though it is stepped in appearance. The results from this do show signs that they have responded in the intended manner. The peaks in the levels of each of the manometers do not all demonstrate the lag time that would be expected, the times that each manometer experiences its initial increase to the water level changes does follow this pattern. The fact that the peaks in each of the water levels all occurred at the same point is due to the properties of the tank. The results suggest that the tank reacted far quicker than expected to the changes in the water levels. If it did, then this may also partly explain the stepped appearances of the figures in Section 1 of Chapter 3. Using the results from the trial run of the Darcy tank, displayed in Appendix 1, figure A1, it is possible to calculate the hydraulic conductivity, K of the tank. This may provide the answer.

Did the tank react too quickly to the changes in the water level?

The calculations of this are displayed over leaf. Figure 4.2 shows the dimensions of the Darcy tank that have been used in the calculations.

Figure 4.2: Representation of the Dimensions of the Darcy tank



Using $h^2 = ax + b$

at $x = 0$ $h_1^2 = a(0) + b$

$b = h_1^2$

$b = h_1^2 = (50)^2 = 2500 \text{ mm}$

at $x = C$ $h_2^2 = aL + h_1^2$

$a = \frac{(h_2^2 - h_1^2)}{L}$

$a = \frac{(250)^2 - (50)^2}{1304} = 46.01 \text{ mm}$

$a = 46.01 \text{ mm}$	$b = 2500 \text{ mm}$
------------------------	-----------------------

Using the formulas displayed below, it is then possible to calculate the Hydraulic Conductivity (K).

$Q = WK \left(\frac{hdh}{dx} \right)$ and $h^2 = ax + b$

$\frac{2hdh}{dx} = a$ therefore $\frac{hdh}{dx} = \frac{a}{2}$

substituting gives $Q = \frac{WKa}{2}$

Rearranging $Q = \frac{WKa}{2}$ we get $K = \frac{2Q}{Wa}$

$$a = 46.01 \text{ mm} = 4.601 \times 10^{-2} \text{ m}$$

$$W = 155 \text{ mm} = 0.155 \text{ m}$$

$$Q = 310 \text{ ml min}^{-1} \rightarrow \text{dividing by } 6 \times 10^7 = 5.167 \times 10^{-6} \text{ m}^3 \text{ s}^{-1}$$

$$K = \frac{2Q}{Wa} \quad K = \frac{2(5.167 \times 10^{-6})}{(4.601 \times 10^{-2})(0.155)}$$

$$K = 1.449 \times 10^{-3} \text{ m s}^{-1}$$

This value for the hydraulic conductivity can then be compared to standard values for different materials. Figure 4.3 displays hydraulic conductivity values for some materials that are similar to those found in the Darcy tank.

Figure 4.3: Hydraulic conductivity values for certain materials (Todd, 1980)

Material	Hydraulic Conductivity (m/day)
Fine Gravel	450
Coarse Sand	45
Medium Sand	12
Fine Sand	2.5
Silt	0.08
Clay	0.0002

Todd 1980

Using this table it was then possible to create figure 4.4.

Figure 4.4: Hydraulic conductivity values for certain materials

Material	Hydraulic Conductivity			
	m day ⁻¹	m hr ⁻¹	m min ⁻¹	m sec ⁻¹
Fine Gravel	450	18.75	0.3125	0.005208
Coarse Sand	45	1.875	0.03125	0.000521
Medium Sand	12	0.5	0.008333	0.000139
Fine Sand	2.5	0.104167	0.001736	2.89E-05
Silt	0.08	0.003333	5.56E-05	9.26E-07
Clay	0.0002	8.33E-06	1.39E-07	2.31E-09
Darcy Tank	125.1936	5.2164	0.08694	0.001449

Figure 4.4 shows the values used by Todd (1980), but also shows the value of the Darcy tank converted into the same units as those used by Todd (1980). We can see from the figures that the hydraulic conductivity of the Darcy tank lies between those of Fine Gravel and Coarse Sand (the relative sizes of these materials can be seen in figure A1.3, Appendix 1). This suggests that the water movements in the tank did indeed occur too quickly to witness any lag time experienced in the peak water levels in individual manometers.

It is likely that the problems that were experienced in manometer 4 were caused by a blockage. Using the calculations displayed on page 37, it is possible to predict the level that the manometer should have registered at the start of the experiment, when the inflow to the Darcy tank was set to 250 mm above the base of the tank and the outflow was set to 50 mm above the base of the tank. The predictions of all of the starting water levels can be seen in figure 4.5.

Figure 4.5: Predictions of the starting water levels in individual manometers.

Piezometer	Distance from end (x_a)	Observed level	Predicted using Equation *
	mm	mm	
1	192	100	106.4608848
2	492	120	158.5462708
3	645	140	179.3779529
4	798	179	198.0302502
5	1098	239	230.2585069

* Equation used for prediction is $(ax_a + b)^{0.5}$ where $a = 46.01$ and $b = 2500$

The table shows that it is not only manometer 4 that is not functioning properly, all of the manometers used in the Darcy tank appear to be functioning slightly strangely. The levels that the manometers should have displayed in some cases are out by as much as 40 mm. This variation in the levels of the manometers is probably caused by the variability of the tank. It is possible that if the experiment were carried out on a different day, the variations in the manometers would be different.

Section 2

Discussion of Results from the Beach Studies

The results produced on all of the days that were studied have varying degrees of importance when examining the hydraulic and salinity dynamics of the beach systems.

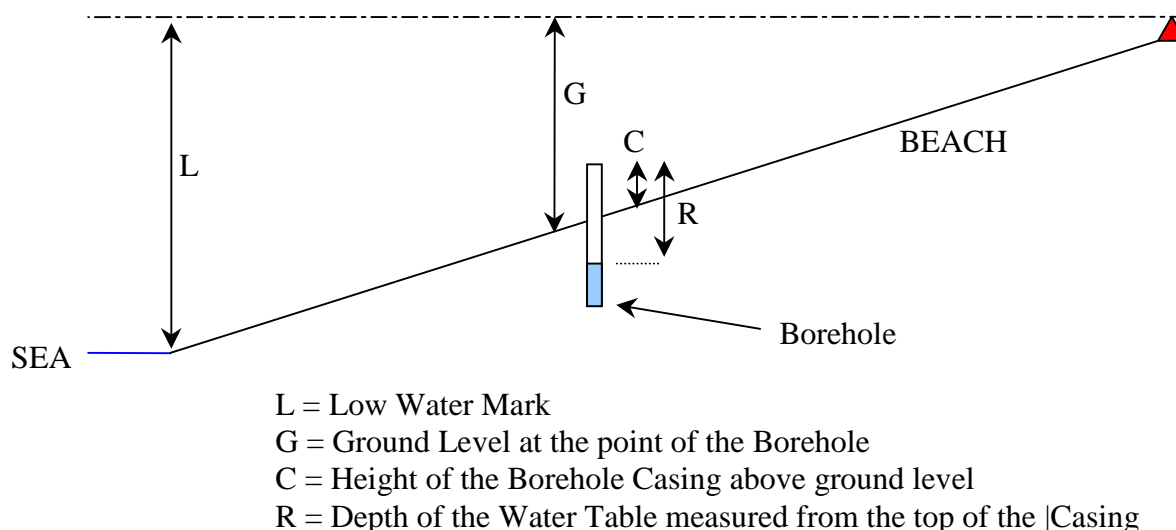
The results that involve the water table were calculated using the following formula:

Height of Water level = (height of BH above LW (G – L) + casing height (C) – reading R)

Height of Water level = (G – L) + (C – R)

This relationship can be seen below in figure 4.6.

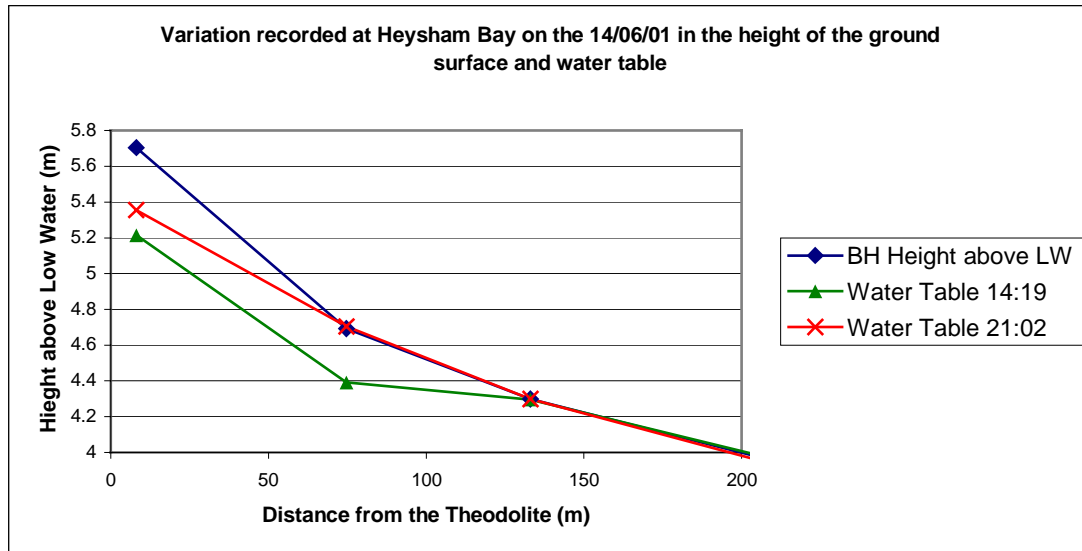
Figure 4.6: Calculations of the water table level



The results that display the groundwater movements throughout each of the study days are limited in what they show. At Heysham Bay, both of the studies showed that the water table of the beach was at the ground surface. The beach at Heysham is saturated with water for almost its entire length. The only changes in the water table that can be seen at Heysham are at the top of the beach close to the coastal defences. On both days that studies were conducted at Heysham, a borehole was placed approximately 1 meter in front of the coastal defences. This borehole does not register much of change in its water level, but demonstrates the effect that the coastal defences have on the beach. The water table at this point was recorded approximately half a meter below the ground surface on both of the study days, which suggests that there has been a build up of sand in front of the coastal defences and that the variation in the water table is only minimal. When the study was conducted on the 14th June 2001, a change was also registered in borehole 8.

The changes that can be seen on figure 3.1.4 in chapter 3 have been enlarged in figure 4.7.

Figure 4.7: Changes in boreholes 8 and 9 at Heysham Bay on 14/06/01



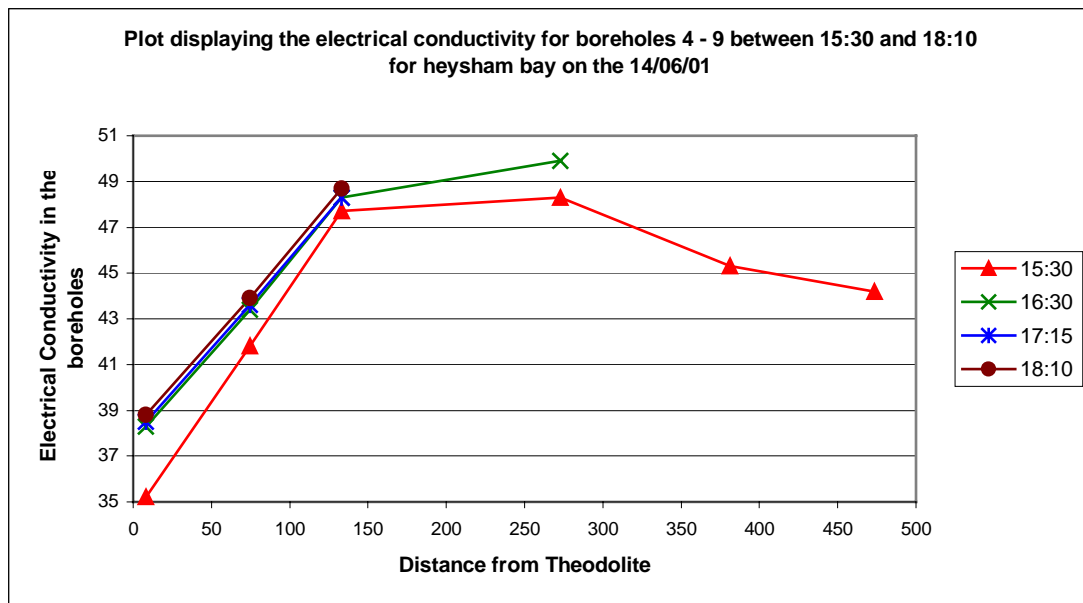
This figure displays the ground level, the water table approximately two hours after low tide (14:19), and the water table approximately three hours after high tide (21:02). (Tide tables can be found in Appendix 3, figure A3.1.)

From this plot we can see that the level of the water at 14:19 is lower than that of the water table at 21:02. This suggests that after the tide begins to fall, the level of groundwater in the beach also begins to fall, but falls so slowly that by the time low tide has passed and the tide starts to move back up the beach, the water table has only dropped in height over the top 150 meters of the beach. This implies that the hydraulic conductivity of the beach is fairly low. The beach sediments at the top of the beach at Heysham consist of fine sand with a layer of clay underneath. Using Figure 4.4 from the previous section, fine sand has a hydraulic conductivity of 2.5 meters per day and clay has a hydraulic conductivity of 0.0002 meters per day. This may account for the fact that the bay at Heysham is almost permanently saturated.

With the data that has been collected it was hoped to prove that as the tide went out, an influx of fresher groundwater would flow into the top part of the beach. If this were to happen then the electrical conductivity measurements would hopefully pick this up. The results for the electrical conductivity on the 14/06/01 did show that the conductivity was

less in boreholes 8 and 9 suggesting that water contained in these boreholes may have contained fresher water but this is unsubstantiated due to the extensive variation that occurred within the boreholes. The results also show that as the tide was approaching high tide, the conductivity in the boreholes that were still hundreds of meters in front were starting to increase. This can be seen in figure 4.8.

Figure 4.8: Data for the electrical conductivity changes in boreholes 4 – 9 between 15:30 and 18:10 for Heysham bay on 14/06/01



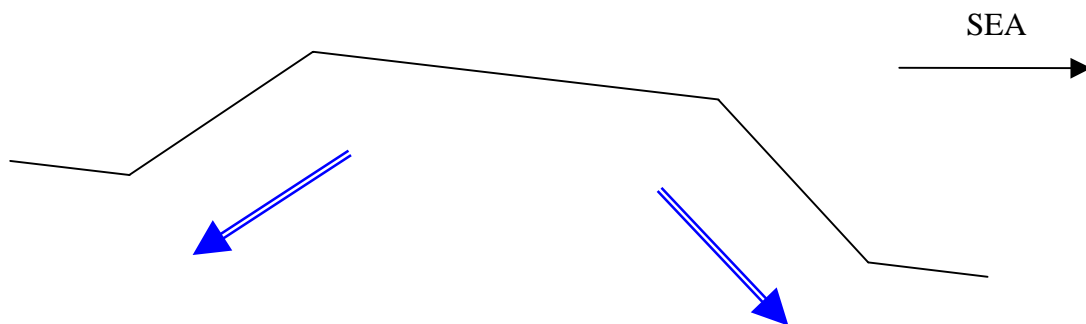
The changes that can be seen on figure 3.1.5 in chapter 3 have been enlarged in figure 4.8. The rest of the data has been edited out of the plot.

The relationship that can be seen in this figure is probably not the effect of the incoming tide due to the distance that the sea is from the boreholes. This relationship is most likely to be the result of evaporation of the water. This would cause the salt to become concentrated and thus increase the conductivity value of the remaining water.

Unfortunately the borehole data for the differences in the water levels from Rossall has proved to be unreliable. The beach profile shown in figures 3.3.1, 3.3.2 and 3.3.4 does however show an interesting feature in regard to groundwater movement. In all of these figures a raised section of the beach can be seen. This raised section of the beach looks like it has been created by the system of groyne that are in place around that stretch of

the coastline. The Groyne to the North of the section of beach that was studied is far shorter than the one to the south of the section. This probably means that sand is carried passed the Groyne to the North of the section and is deposited in the section of beach that was studied. This raised section of beach is of interest because of the way that it drains. When the tide is in, this section of the beach is covered, but when the tide retreats it leaves this section exposed. The water that is contained in this section of the beach then appears to drain in two ways. The figure below is a representation of this sand bank.

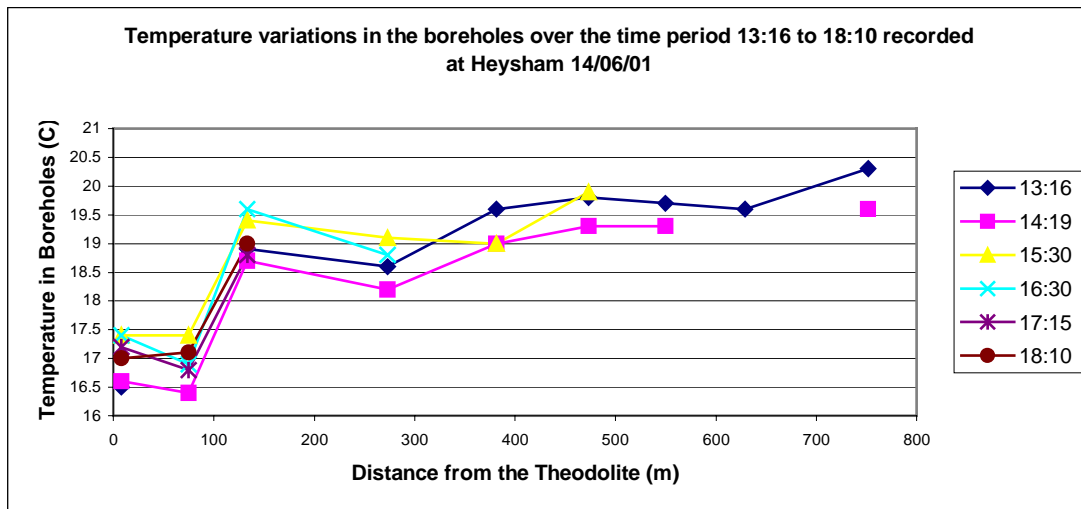
Figure 4.9: Representation of a sand bank at Rossall beach



The water that is held within this raised sand bank drains down the slope toward the sea, but also temporarily drains toward the coastal defences. If there were any movement of fresh water in this beach system it would be affected by this strange section of the beach.

The temperature readings for all of the days that were studied show highly variable results. The data from the 14/06/01 exhibits very strange behaviour. Figure 4.10 displayed overleaf shows that as the boreholes get closer to the sea, the average temperature seems to rise. Borehole 1 that is closest to the sea, records the hottest temperature, whilst as the boreholes increase in distance from the sea they all slightly decrease in temperature.

Figure 4.10: Temperature variations at Heysham 14/06.01



The changes that can be seen on figure 3.1.6 in chapter 3 have been highlighted in figure 4.10.

This change in the temperature makes little sense. If we compare the results from the 14/06/01 to those of the 21/06/01 (shown in figure 3.2.6) and even the data produced at Rossall 20/06/01 (figure 3.3.6), it is clear that there is a large variability in the data. The data for 21/06/01 looks like it has been influenced by the weather. Borehole 8, where the water table is half a meter below the grounds surface does not show much change, however the rest of the boreholes increase in temperature throughout the day, until approximately 17:00 and then begin to fall until a low of 15.5° is experienced at 19:30. The temperature data at Rossall shows the same degree of variability for most of the data, but borehole 4 does seem to follow the same heating and cooling as that displayed at Heysham on 21/06/01.

It should also be recognised that the coastal defences at both of the locations must play a part in the movement of groundwater. With large foundations to support the structure, any groundwater movement that may otherwise occur may be restricted to depths greater than those that were studied on the days that have been outlined.

Chapter 5

Section 1

Conclusion

Fluctuations in hydraulic and salinity dynamics that occur at the coastal interface of a tidally affected aquifer are a complex system. Over the three days that the beach studies were carried out a number of things did not go as planned. This meant that data sets were in places incomplete. The variability in the results from these data sets meant that the data collected showed very little. However, one of the things that it did show was that although it is often said that the tidal cycle follows a sine wave,

“In coastal aquifers in contact with the ocean, sinusoidal fluctuations of groundwater levels occur in response to tides” (Todd, 1980), results from this experiment and others done by Robinson *et al*, (1998) suggest otherwise. The tidal measurements made at Rossall beach show an asymmetric pattern in the cycle (displayed in Chapter 3, figure 3.3.3.). The tide will move between low and high tide approximately 1 hour quicker than it will move from high to low tide. This was calculated using the data provided by Her Majesties Coastguard Liverpool, shown in Appendix 3, figure A3.1. This pattern is due to the asymmetry of the tidal infiltration/draining process: it is easier for the water to flow into the unsaturated sediments at high tide than to drain away at low tide (Nielsen, 1990) (Robinson *et al*, 1998). This long recession as the tide recedes from high to low tide can be seen in data that was produced by Robinson *et al*, (1998) that is shown below in figure 5.1.

Figure 5.1: Water table fluctuation with distance increasing upland.

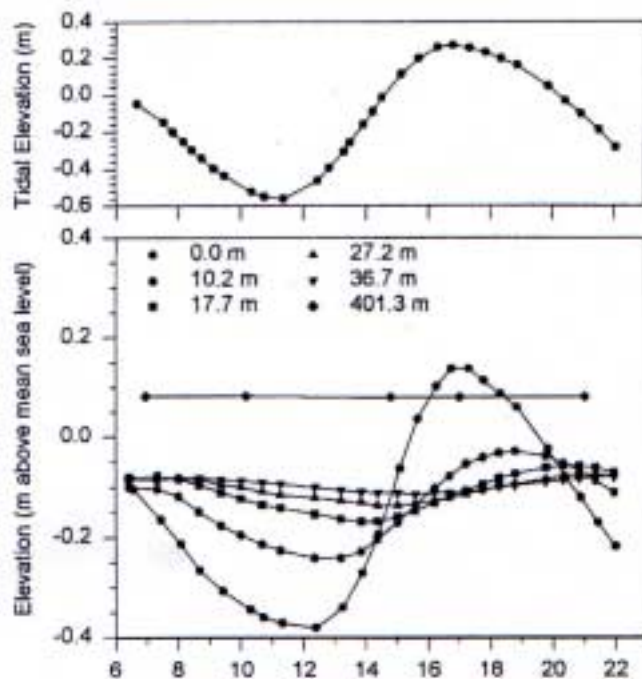
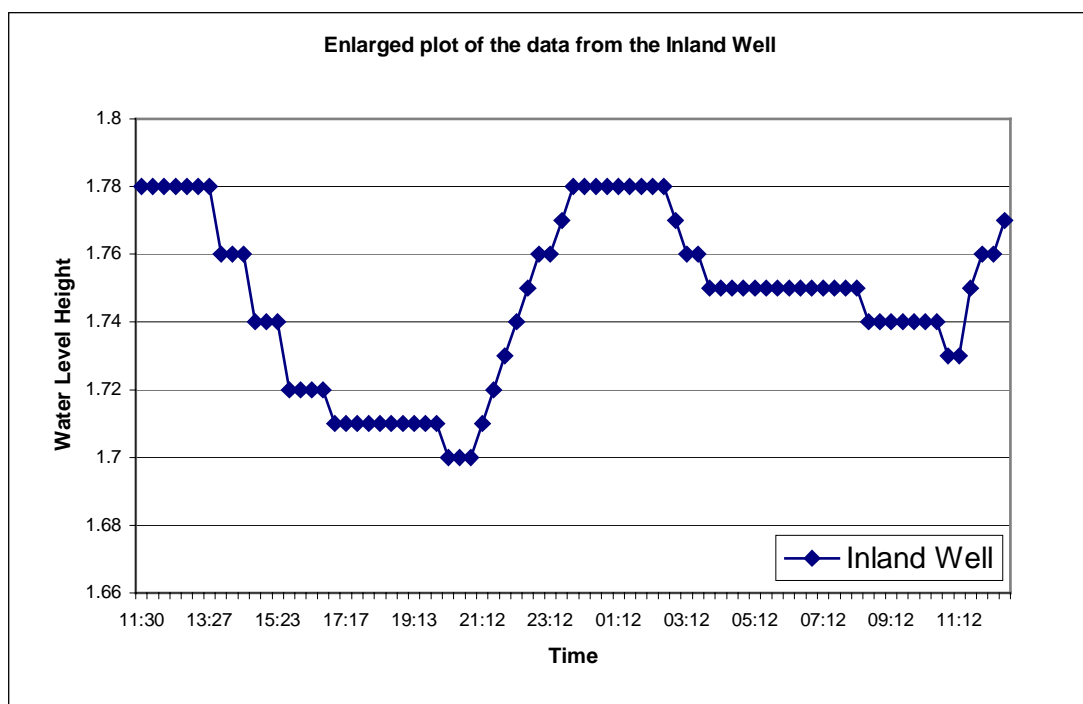


Figure 6. Water table fluctuation with distance increasing upland. Sample date: July 1994.

Robinson *et al*, (1998)

This figure also displays the responses that are experienced at a five inland wells, these can be seen in the lower half of the figure. The magnitude of the water table fluctuations varied with distance inland from the shoreline but still displayed the asymmetric pattern of the tidal wave. The figure demonstrates that there are still interactions between the coastal water and the inland fresher water at up to 37 meters inland. Another example of the propagation of the asymmetric tidal pattern can be seen in figure 5.2.

Figure 5.2: Plot displaying the propagation inland of the asymmetric tidal pattern from an inland well at ICI Ardeer Site.



This plot uses the data displayed in Appendix 3, figure A3.3.

From this plot the asymmetric pattern is clearly visible. The data was produced by measurements made approximately every 20 minutes. The stepped appearance similar to those figures displayed in Chapter 3, but in this case is caused by the limited definition used when measuring the water level heights. One of the problems that could be caused by this extensive interaction distance is with the movement of a contaminant. If a contamination site is close enough to the coast, interaction with the saline water could aid in the dispersal of a pollutant.

Section 2

Further Work

Beach groundwater dynamics have attracted increased attention in recent years (Nielsen and Turner, 2000). To understand the dynamics of the two locations that this project has focused on, it would be necessary to implement a more in-depth study of these two locations. A series of boreholes would need to be installed much deeper in the beach, all of them logging continuously for temperature, electrical conductivity and water levels. Similar boreholes would need to be set up behind the coastal defences to see if any water movement was occurring beyond the beach system. Perhaps a study on the coastal defence would be a good idea. Do the deep foundations of the coastal defence mean that there is no exchange of water between the coastal environment and the inland environment? Does it just force the water beneath it?

To understand the dynamics of any environment, an intensive study over a long time period is necessary.

Acknowledgements

Peter Winship is gratefully acknowledged for his help throughout the duration of this project and thanks must go also to Andrew Binley for his guidance and assistance. Her Majesties Coastguard Liverpool is also gratefully acknowledged for providing information regarding the tides tables.

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- Sea Defence Figures from Wyre Borough Council
<http://www.wyrebc.gov.uk/coastaledufigures.htm>
- Table for particle size distribution from University of Washington
<http://bromide.ocean.washington.edu/oc540/lec01-32/>

APPENDICES

Appendix 1: The Darcy Tank Experiment

Figure A1.1: Table displaying the results from the trial run of the Darcy tank

Time after Increase	Manometer 1	Manometer 2	Manometer 3	Manometer 4	Manometer 5	Discharge
minutes	mm	mm	mm	mm	mm	ml
0	55	55	55	55	55	
10	75	91	114	125	160	110
20	96	140	170	186	223	265
30	103	150	180	196	228	310
40	103	150	180	196	228	310
50	104	150	180	197	228	310
60	104	150	180	197	228	310
70	104	150	180	197	228	310
80	104	150	180	197	228	310
90	104	150	180	197	228	310
100	104	150	180	197	228	310
110	104	150	180	197	228	310
120	104	150	180	197	228	310

Manometer 1 is closest to the outflow

Figure A1.2: Data collected from the Darcy tank Experiment

			Readings					
			Manometer 1	Manometer 2	Manometer 3	Manometer 4	Manometer 5	Discharge
h	Time	Delta t	mm	mm	mm	mm	mm	ml/min
-50	00:00:00	00:00	100	120	140	179	239	525
-45	00:17:14	17:14	101	120	140	179	239	525
-40	00:24:35	07:21	102	121	140	179	239	520
-35	00:30:23	05:48	103	122	141	179	239	515
-30	00:35:25	05:02	104	122	142	179	239	515
-25	00:40:00	04:35	105	123	142	179	239	515
-20	00:44:17	04:17	105	123	143	179	239	510
-15	00:48:22	04:05	107	125	143	179	239	510
-10	00:52:19	03:57	107	125	143	179	239	505
-5	00:56:11	03:52	108	125	144	179	239	505
0	01:00:01	03:50	108	126	145	179	239	495
5	01:03:51	03:50	109	127	145	179	239	490
10	01:07:43	03:52	110	128	146	179	239	490
15	01:11:40	03:57	111	128	146	179	239	485
20	01:15:45	04:05	112	129	147	179	240	485
25	01:20:02	04:17	113	130	148	179	240	485
30	01:24:37	04:35	114	130	148	179	241	480
35	01:29:39	05:02	115	131	149	179	241	480
40	01:35:27	05:48	116	132	150	179	241	480
45	01:42:48	07:21	118	133	150	179	241	475
50	02:00:02	17:14	119	134	151	179	242	470
45	02:17:16	17:14	118	134	151	179	242	475
40	02:24:37	07:21	118	134	150	179	242	480
35	02:30:25	05:48	117	134	150	179	242	490
30	02:35:27	05:02	116	133	149	179	241	495
25	02:40:02	04:35	115	133	148	179	241	495
20	02:44:19	04:17	114	132	148	179	241	500
15	02:48:24	04:05	113	131	147	179	240	500
10	02:52:21	03:57	112	130	147	179	240	500
5	02:56:13	03:52	111	129	146	179	240	505
0	03:00:03	03:50	110	129	146	179	240	505
-5	03:03:53	03:50	110	129	146	179	240	510
-10	03:07:45	03:52	108	127	145	179	240	515
-15	03:11:42	03:57	107	127	145	179	239	515
-20	03:15:47	04:05	107	126	144	179	239	515
-25	03:20:04	04:17	106	126	144	179	239	515
-30	03:24:39	04:35	106	125	143	179	239	515
-35	03:29:41	05:02	104	124	143	179	239	515
-40	03:35:29	05:48	103	124	142	179	239	520
-45	03:42:50	07:21	103	124	142	179	239	520
-50	04:00:04	17:14	102	123	141	179	239	520

Figure A1.3: Particle size distribution table

Class Name		Size Range (mm)	Size Range (μ m)
Boulders	Very Large	4096-2048	
	Large	2048-1024	
	Medium	1024-512	
	Small	512-256	
Cobbles	Large	256-128	
	Small	128-64	
Gravel	Very Coarse	64-32	
	Coarse	32-16	
	Medium	16-8	
	Fine	8-4	
	Very Fine	4-2	
Sand	Very Coarse	2-1	2000-1000
	Coarse	1-0.5	1000-500
	Medium	0.5-0.25	500-250
	Fine		250-125
	Very Fine		125-62
Silt	Coarse		62-31
	Medium		31-16
	Fine		16-8
	Very Fine		8-4
Clay	Coarse		4-2
	Medium		2-1
	Fine		1-0.5
	Very Fine		0.5-0.24

Table from University of Washington
<http://bromide.ocean.washington.edu/oc540/lec01-32/>

Figures A1.4 to A1.7 - Aquifer Simulation Model Plots

Figure A1.4: Simulation of the Darcy Tank with outflow set to 50 mm and inflow set to 250 mm



Figure A1.5: Simulation of the Darcy Tank with outflow set to 75 mm and inflow set to 250 mm

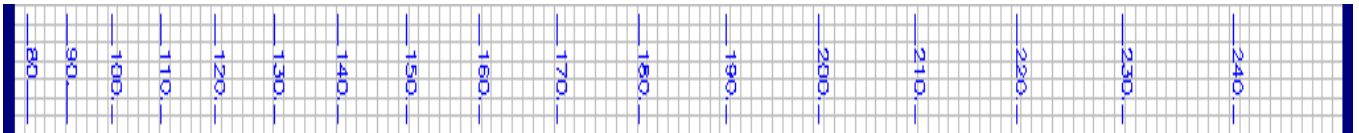


Figure A1.6: Simulation of the Darcy Tank with outflow set to 100 mm and inflow set to 250 mm



Figure A1.7: Simulation of the Darcy Tank with outflow set to 150 mm and inflow set to 250 mm



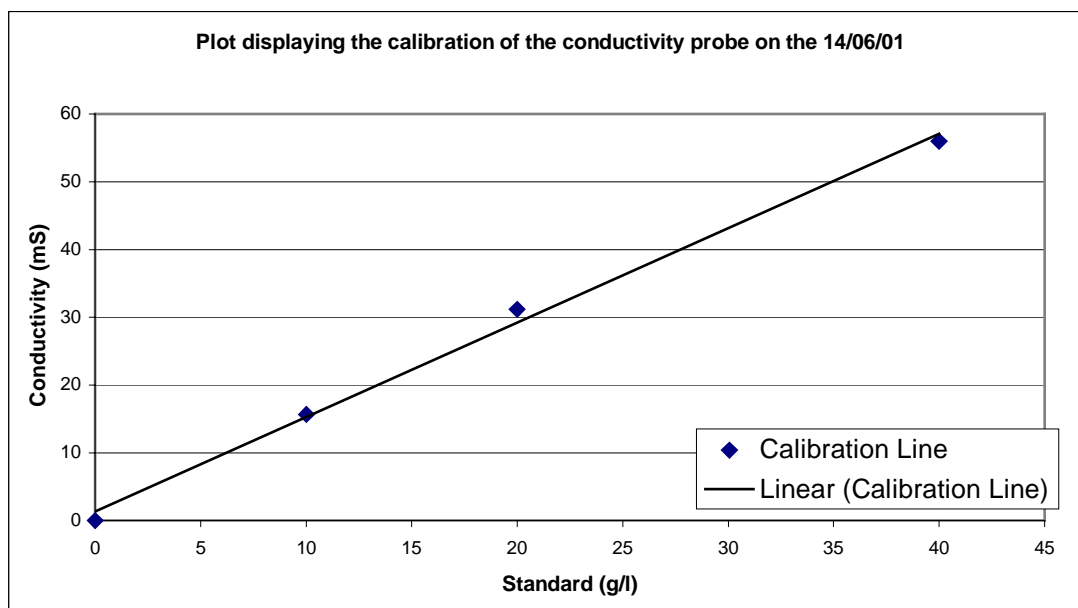
Appendix 2: The Beach Studies

Figure A2.1: Tidal heights and sine wave for Heysham Bay 14/06/01

Time	Vertical Distance	Sine	Sum			
13:16	-7.412	-7.06	0.124312		to	15:15
14:19	-6.268	-6.24	0.001031		Time	12
15:30	-5.062	-4.98	0.007414		Amplitude	2.1
16:30	-4.073	-3.97	0.010282		offset	-5.25
17:15	-3.402	-3.43	0.000861			
18:10	-3.142	-3.15	1E-04		Solver	0.163809
19:54	-3.884	-3.89	4.66E-06			
21:02	-5.153	-5.01	0.019804			

The table above displays the calculations for of the tidal heights and the sine wave to fit the tidal data for the data produced at Heysham bay on the 14th June 2001.

Figure A2.2: Calibration of the Conductivity Probe on 14/06/01 at Heysham Bay



Standard (g/l)	Conductivity (mS)
0	0.0099
10	15.7
20	31.2
40	56

Data produced at Heysham Bay on the 14th June 2001 from calibrating the conductivity probe.

Figure A2.3: Measurements made of the Tide level at Heysham on 14/06/01

Time	Hz	V	Δ	ΔI
13:16	296.766	90.412	849.414	-7.412
14:19	296.646	90.331	779.754	-6.268
15:30	296.572	90.272	692.672	-5.062
16:30	294.997	90.389	336.107	-4.073
17:15	292.783	90.493	186.393	-3.402
18:10	290.468	90.561	137.221	-3.142
19:54	294.595	90.395	303.548	-3.884
21:02	296.481	90.291	666.243	-5.153

Hz = Compass Bearing

V = Vertical Angle

Δ = Horizontal Distance

ΔI = Height from the vertical

The table above is displaying measurements made using the theodolite at Heysham Bay on the 14th June 2001. Measurements were taken of the tide levels approximately every hour.

Figure A2.4: Measurements made of the Boreholes at Heysham on 14/06/01

	Hz	V	Δ	ΔI
Water level	296.646	90.331	779.754	-6.268
BH 1	296.701	90.312	751.829	-5.858
BH 2	296.431	90.266	628.998	-4.627
BH 3	296.194	90.298	549.768	-4.642
BH 4	295.88	90.366	473.426	-4.811
BH 5	295.345	90.387	381.222	-4.365
BH 6	294.253	90.408	272.888	-3.74
BH 7	290.039	90.565	133.077	-3.112
BH 8	282.675	90.706	74.722	-2.72
BH 9	186.879	89.35	8.16	-1.707

Hz = Compass Bearing

V = Vertical Angle

Δ = Horizontal Distance

ΔI = Height from the vertical

The table above is displaying measurements made using the theodolite at Heysham Bay on the 14th June 2001. Measurements were made of the boreholes at 14:19.

Figure A2.5: Calculations of the ground and water levels for the boreholes at Heysham Bay on 14/06/01

	Δ	ΔI	Height	<u>Readings</u>								C	Corrected Height of the water level							
				above LW	13:16	14:19	15:30	16:30	17:15	18:10	19:54		21:02	13:16	14:19	15:30	16:30	17:15	18:10	19:54
Water level	849.414	-7.412	0										0	0	0	0	0	0	0	0
BH 1	751.829	-5.858	1.554	0.525	0.528							0.513	1.542	1.539						
BH 2	628.998	-4.627	2.785	0.19							0.195	0.185	2.78							2.78
BH 3	549.768	-4.642	2.77	0.065	0.08						0.044	0.055	2.76	2.745						2.78
BH 4	473.426	-4.811	2.601	0.285	0.286	0.282					0.258	0.28	2.596	2.595	2.599					2.62
BH 5	381.222	-4.365	3.047	0.23	0.225	0.225					0.2	0.222	3.039	3.044	3.044					3.07
BH 6	272.888	-3.74	3.672	0.1	0.06	0.085	0.114			0.108	0.117	0.08	3.652	3.692	3.667	3.64			3.64	3.64
BH 7	133.077	-3.112	4.3	0.23	0.232	0.23	0.23	0.23	0.232	0.23	0.229	0.227	4.297	4.295	4.297	4.3	4.3	4.3	4.3	4.3
BH 8	74.722	-2.72	4.692		0.611	0.615	0.605	0.611	0.614	0.329	0.299	0.31		4.391	4.387	4.4	4.39	4.39	4.67	4.7
BH 9	8.16	-1.707	5.705	0.51	0.51	0.512	0.509	0.509	0.51	0.5	0.371	0.02	5.215	5.215	5.213	5.22	5.22	5.22	5.23	5.35

BH = Borehole

LW = Low Water

Δ = Horizontal Distance

ΔI = Vertical Distance

C = Height of the borehole casing above ground level

Gaps have been left where no reading has been taken

The calculation that is made to get the Corrected height of the water level uses the following formula

$$\text{Corrected Height of Water level} = (\text{height of BH above LW} + \text{casing height (C)} - \text{reading})$$

Figure A2.6: Electrical conductivity variations at Heysham on the 14/06/01

					Readings (mS)					
	Δ	13:16	14:19	15:30	16:30	17:15	18:10	19:54	21:02	
LW	849.414	51.3	51.3	51.3	51.3	51.3	51.3	51.3	51.3	
BH 1	751.829	45.1	40.3							
BH 2	628.998	51							23.9	
BH 3	549.768	33.7	38.5						41.6	
BH 4	473.426	43	45	44.2					41.2	
BH 5	381.222	17.31	48.3	45.3					46.2	
BH 6	272.888	20.9	30.5	48.3	49.9			19.5	40.1	
BH 7	133.077	46.4	48.5	47.7	48.3	48.3	48.7	48.9	47.6	
BH 8	74.722		25.1	41.8	43.4	43.6	43.9	17.65	48	
BH 9	8.16	36.4	31	35.2	38.3	38.5	38.8	40.7	26.5	

BH = Borehole

LW = Low Water

Δ = Horizontal Distance

Figure A2.7: Temperature variations in the boreholes at Heysham on 14/06/01

	Δ			Temperature (C)						
	Δ	13:16	14:19	15:30	16:30	17:15	18:10	19:54	21:02	
LW	849.414									
BH 1	751.829	20.3	19.6							
BH 2	628.998	19.6							15.6	
BH 3	549.768	19.7	19.3						15.8	
BH 4	473.426	19.8	19.3	19.9					16.2	
BH 5	381.222	19.6	19	19					15.4	
BH 6	272.888	18.6	18.2	19.1	18.8			16.9	15.6	
BH 7	133.077	18.9	18.7	19.4	19.6	18.8	19	18.1	15.5	
BH 8	74.722		16.4	17.4	16.9	16.8	17.1	16.1	15.6	
BH 9	8.16	16.5	16.6	17.4	17.4	17.2	17	14.8	15.2	

BH = Borehole

LW = Low Water

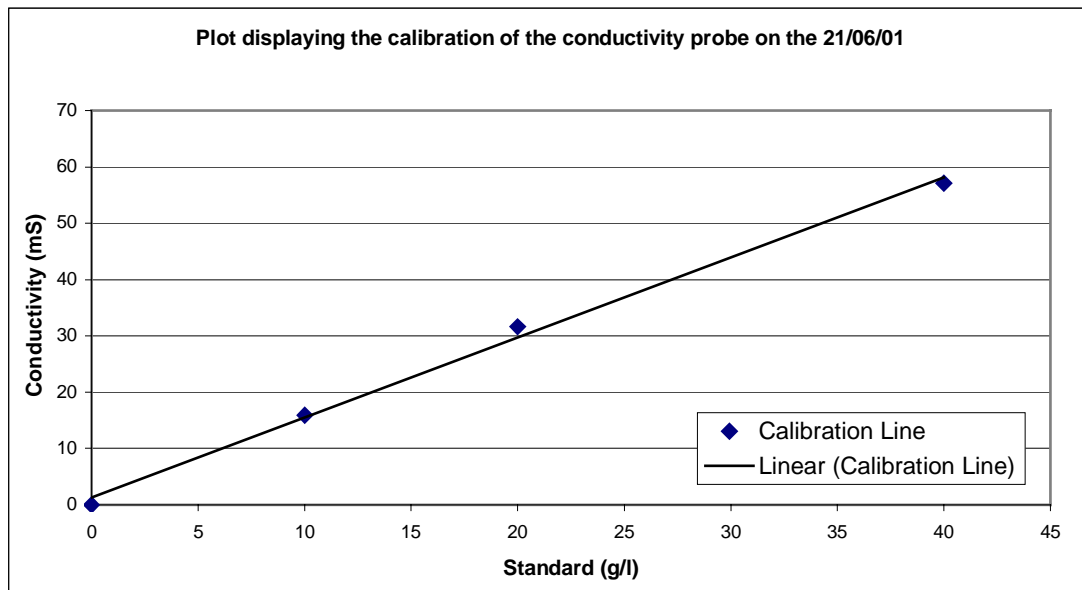
Δ = Horizontal Distance

Figure A2.8: Tidal heights and sine wave for Heysham Bay 21/06/01

Time	Vertical Distance	Sine	Sum			
08:30						
09:30	-4.081	-3.83	0.06			
10:30	-2.068	-2.01	0.00		t0	08:54
11:30	-0.574	-1.00	0.18		T	12.1877
12:30	-0.809	-1.04	0.05		a	4.204902
13:30	-2.402	-2.13	0.07		offset	-5.08214
14:30	-4.274	-3.99	0.08			
15:30	-6.14	-6.14	0.00		Solver	0.63
16:30						
17:30	-8.819	-9.12	0.09			
18:30	-9.01	-9.18	0.03			
19:30	-8.433	-8.17	0.07			

The table above displays the calculations for of the tidal heights and the sine wave to fit the tidal data for the data produced at Heysham bay on the 21st June 2001.

Figure A2.9: Calibration of the Conductivity Probe on 21/06/01 at Heysham Bay



Standard (g/l)	Conductivity (mS)
0	0.001132
10	15.96
20	31.6
40	57.1

Data produced at Heysham Bay on the 21st June 2001 from calibrating the conductivity probe.

Figure A2.10: Measurements made of the Tide level at Heysham on 21/06/01

Time	Hz	V	$\underline{\Delta}$	ΔI
08:30	no signal			
09:30	291.687	90.607	386.385	-5.431
10:30	302.177	92.372	49.93	-3.418
	Moved theodolite to position 2			
11:30	15.715	91.014	142.53	-3.871
12:30	14.675	91.109	142.477	-4.106
13:30	293.943	93.464	71.837	-5.699
14:30	271.377	90.853	418.418	-7.571
15:30	291.779	90.567	822.556	-9.437
16:30	no signal			
17:30	299.08	90.653	949.933	-12.116
18:30	300.816	90.614	953.75	-12.307
19:30	303.358	90.649	922.644	-11.73

Hz = Compass Bearing
V = Vertical Angle
 $\underline{\Delta}$ = Horizontal Distance
 ΔI = Height from the vertical

The table above is displaying measurements made using the theodolite at Heysham Bay on the 21st June 2001. Measurements were taken of the tide levels approximately every hour.

Figure A2.11: Measurements made of the Boreholes at Heysham on 21/06/01

First Surveying

	Hz	V	$\underline{\Delta}$	ΔI
BH 1	no signal			
BH 2	292.412	90.443	520.679	-6.159
BH 3	292.177	90.481	455.922	-5.962
BH 4	291.701	90.497	367.508	-5.333
BH 5	291.166	90.642	230.018	-4.724
BH 6	294.683	91.373	71.961	-3.874
BH 7	312.464	92.322	35.815	-3.602
BH 8	256.331	98.438	5.502	-2.966

Hz = Compass Bearing
V = Vertical Angle
 $\underline{\Delta}$ = Horizontal Distance
 ΔI = Height from the vertical

Second Surveying

	Hz	V	$\underline{\Delta}$	ΔI
BH 1	291.442	90.565	693.699	-8.161
BH 2	292.141	90.731	528.123	-8.07
BH 3	291.902	90.811	463.337	-7.9
BH 4	291.402	90.909	374.95	-7.283
BH 5	290.932	91.303	237.42	-6.747
BH 6	294.153	93.214	79.45	-5.813
BH 7	308.616	95.516	42.969	-5.5
BH 8	276.616	106.078	12.378	-4.918

Hz = Compass Bearing
V = Vertical Angle
 $\underline{\Delta}$ = Horizontal Distance
 ΔI = Height from the vertical

The table above is displaying measurements made using the theodolite at Heysham Bay on the 21st June 2001.

Figure A2.12: Calculations of the ground and water levels for the boreholes at Heysham Bay on 21/06/01

	Δ	ΔI	Height above LW	Readings								C	Corrected Height of the water level						
				13:30	14:30	15:30	16:30	17:30	18:30	19:30	13:30		14:30	15:30	16:30	17:30	18:30	19:30	
Water level	953.75	-12.31	0									0	0	0	0	0	0		
BH 1	693.699	-8.161	4.146			0.685	0.65	0.65	0.65	0.652	0.665			4.126	4.161	4.161	4.161	4.159	
BH 2	528.123	-8.07	4.237			0.43	0.37	0.37	0.37	0.37	0.365			4.172	4.232	4.232	4.232	4.232	
BH 3	463.337	-7.9	4.407			0.205	0.24	0.238	0.24	0.24	0.25			4.452	4.417	4.419	4.417	4.417	
BH 4	374.95	-7.283	5.024		0.463	0.47	0.44	0.455	0.45	0.45	0.49		5.051	5.044	5.074	5.059	5.064	5.064	
BH 5	237.42	-6.747	5.56		0.147	0.15	0.158	0.154	0.158	0.15	0.205		5.618	5.615	5.607	5.611	5.607	5.615	
BH 6	79.45	-5.813	6.494	0.515	0.505	0.505	0.505	0.51	0.525	0.64	0.499	6.478	6.488	6.488	6.488	6.483	6.468	6.353	
BH 7	42.969	-5.5	6.807	0.57	0.575	0.57	0.575	0.579	0.58	0.585	0.56	6.797	6.792	6.797	6.792	6.788	6.787	6.782	
BH 8	12.378	-4.918	7.389	0.82	0.846	0.871	0.87	0.89	0.89	0.89	0.56	7.129	7.103	7.078	7.079	7.059	7.059	7.059	

BH = Borehole

LW = Low Water

Δ = Horizontal Distance

ΔI = Vertical Distance

C = Height of the borehole casing above ground level

Gaps have been left where no reading has been taken

The calculation that is made to get the Corrected height of the water level uses the following formula

$$\text{Corrected Height of Water level} = (\text{height of BH above LW} + \text{casing height (C)} - \text{reading})$$

Figure A2.13: Electrical conductivity variations at Heysham on the 21/06/01

LW Mark	Δ	Readings (mS)											
		08:30	09:30	10:30	11:30	12:30	13:30	14:30	15:30	16:30	17:30	18:30	19:30
BH 1	693.699	36.2							40.7	32.4	42.5	43.5	41.3
BH 2	528.123	40.2							41.7	43.6	43.1	43.7	46
BH 3	463.337	39.3							33.5	43.8	44.1	44.1	42.1
BH 4	374.95	31.7	33.2					38.4	42.1	45.6	43.5	46.2	42.9
BH 5	237.42	19.1	25.3					41.8	23.9	35.1	46.1	46.7	48.4
BH 6	79.45	43.3	43.5					42.3	42.8	25.2	24.8	40.3	43.6
BH 7	42.969	42.2	21	29.5				41.9	24.1	20.9	24	45.2	45.9
BH 8	12.378	32.5	36.6	36.8				33	25.4	25.6	38.1	25.5	30.1

BH = Borehole

LW = Low Water

Δ = Horizontal Distance

Figure A2.14: Temperature variations in the boreholes at Heysham on 21/06/01

LW Mark	Δ	Readings (C)											
		08:30	09:30	10:30	11:30	12:30	13:30	14:30	15:30	16:30	17:30	18:30	19:30
BH 1	693.699	14.1							17.2	17.6	17.8	16.4	15.7
BH 2	528.123	14							17.1	18.3	17.8	16.5	15.5
BH 3	463.337	13.8							16.5	17.4	18	16.4	16.5
BH 4	374.95	13.9	14.1					16	17.4	17.9	17.3	16.6	15.5
BH 5	237.42	14.6	14.3					16.1	16.8	17.4	17.4	16.6	15.4
BH 6	79.45	14	14.3					15.3	15.5	15.9	16.7	16.6	15.8
BH 7	42.969	13.9	13.7	15.5				15.5	15.4	15.4	15.3	16.4	15.6
BH 8	12.378	15.2	15.2	15.2				15.4	15.3	15.5	15.4	15.2	15.5

BH = Borehole

LW = Low Water

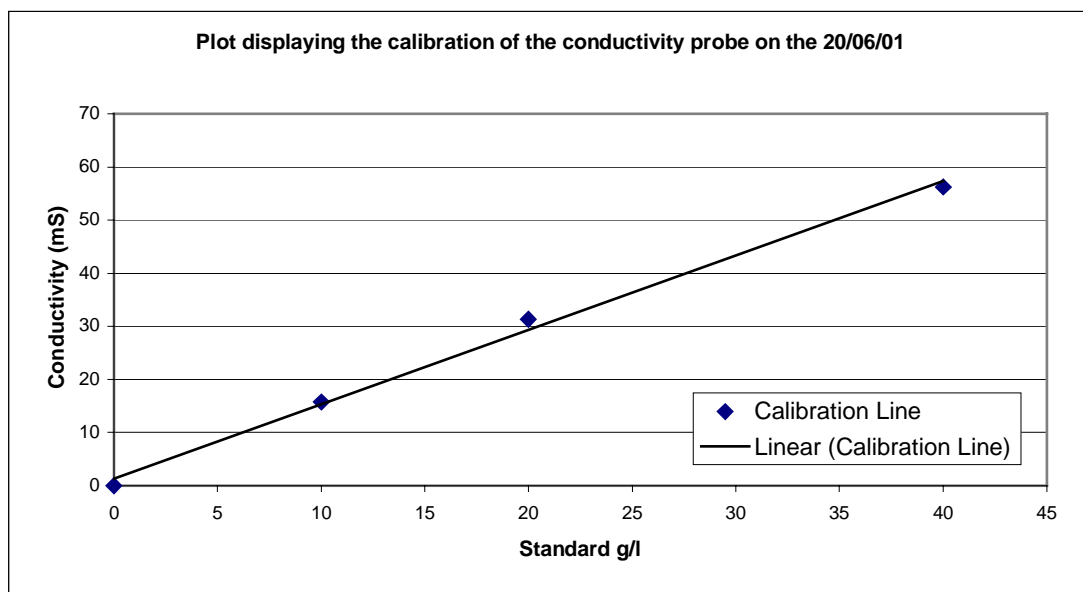
Δ = Horizontal Distance

Figure A2.15: Tidal heights and sine wave for Rossall Beach 20/06/01

Time	Vertical Distance	Sine	Sum			
08:15	-4.286	-4.90	0.376996			
08:40	-3.294	-4.03	0.547958			
09:50	-1.14	-1.95	0.657544			
10:50	-0.866	-0.99	0.016594		to	08:15
11:50	-1.385	-1.09	0.089921		Time	12
12:50	-2.839	-2.20	0.411344		Amplitude	4
13:50	-4.872	-4.03	0.701839		Offset	-4.9
14:50	-6.278	-6.10	0.030687			
15:50	-7.714	-7.85	0.018255		Solver	3.219302
16:50	-8.482	-8.81	0.104448			
17:50	-8.778	-8.71	0.003986			
18:50	-8.112	-7.60	0.259732			
19:50	-6.394	-5.77	0.394687			
20:50	-4.287	-3.70	0.347891			
21:33	-2.564	-2.38	0.032863			

The table above displays the calculations for of the tidal heights and the sine wave to fit the tidal data for the data produced at Rossall Beach on the 20th June 2001.

Figure A2.16: Calibration of the Conductivity Probe on 20/06/01 at Rossall Beach



Standard (g/l)	Conductivity (mS)
0	0.001018
10	15.72
20	31.3
40	56.2

Data produced at Rossall Beach on the 20th June 2001 from calibrating the conductivity probe.

Figure A2.17: Measurements made of the Tide level at Rossall Beach on 20/06/01

Time	Hz	V	$\underline{\Delta}$	ΔI
08:15	297.497	95.356	45.705	-5.636
08:40	297.649	96.771	27.746	-4.644
09:50	296.336	99.568	6.761	-2.49
10:50	312.923	99.893	4.965	-2.216
11:50	315.451	99.016	8.731	-2.735
12:50	302.686	97.196	22.484	-4.189
13:50	296.618	93.581	77.846	-6.222
14:50	295.987	92.361	152.299	-7.628
15:50	296.056	91.682	262.885	-9.064
16:50	295.809	91.487	327.075	-9.832
17:50	295.819	91.398	360.071	-10.128
18:50	295.695	91.575	295.202	-9.462
19:50	296.568	92.356	155.423	-7.744
20:50	299.437	95.354	45.741	-5.637
21:33	301.644	97.334	19.922	-3.914

Hz = Compass Bearing

V = Vertical Angle

$\underline{\Delta}$ = Horizontal Distance

ΔI = Height from the vertical

The table above is displaying measurements made using the theodolite at Rossall Beach on 20th June 2001. Measurements were taken of the tide levels approximately every hour.

Figure A2.18: Measurements made of the Boreholes at Rossall Beach on 20/06/01

	Hz	V	$\underline{\Delta}$	ΔI	Notes
BH 0	295.868	91.761	232.212	-8.484	Bored at 16:53
BH 1	0	0	0	0	Covered by incoming tide before reading, missing when tide receded
BH 1b	296.658	92.363	148.591	-7.481	Bored at 15:50
BH 2	0	0	0	0	Missing when tide receded
BH 2b	296.348	92.807	110.185	-6.751	Bored after 13:50 reading
BH 2c	296.355	92.816	110.2	-6.77	Reset at 15:50
BH 3	295.974	93.438	82.324	-6.296	Was under water at first surveying, was surveyed in at 13:50
BH 3b	295.866	93.429	83.35	-6.284	Reset due to bunged at 15:50
BH 3c	296.02	93.421	82.371	-6.274	Bored again at 17:26 because borehole went dry
BH 4	0	0	0	0	Was under water at first surveying, was missing when tide receded
BH 4b	298.425	94.239	63.444	-6.053	Missing with receding tide, 4b was surveyed in at 13:50
BH 4c	298.386	94.264	63.396	-6.076	Bored at 17:26 because borehole went dry
BH 5	0	0	0	0	Was underwater at first surveying
BH 5b	300.021	95.573	43.268	-5.57	Re-bored due to silted up pipe - 13:50
BH 6	302.757	96.753	27.958	-4.661	Measured before removing silted up pipe and re-boring 6b
BH 6b	303.119	96.897	27.253	-4.646	Re-bored 13:50
BH 7-CB	306.088	97.919	21.587	-4.353	Pipe silted up pipe - 13:50
BH 7-GL	307.276	97.04	21.717	-4.032	Pipe silted up pipe - 13:50
BH 7b-CB	306.176	97.587	19.905	-4.001	Re-bored 13:50
BH 7b-GL	308.253	97.176	20.2	-3.893	Re-bored 13:50

Hz = Compass Bearing

$\underline{\Delta}$ = Horizontal Distance

ΔI = Height from the vertical

V = Vertical Angle

CB = Bottom of Casing

GL = Ground level as close to the borehole as possible

The table above is displaying measurements made using the theodolite at Rossall Beach on 20th June 2001.

Figure A2.19: Calculations of the ground and water levels for the boreholes at Rossall

Beach on 20/06/01

	Δ	ΔI	Height above LW	Reading 17:50	C	Corrected Height of the water level 17:50
Water level	360.071	-10.128	0			0
BH 1b	148.591	-7.481	2.647	0.619	0.275	2.303
BH 2c	110.2	-6.77	3.358	0.45	0.112	3.02
BH 3c	82.371	-6.274	3.854	0.365	0.042	3.531
BH 4c	63.396	-6.076	4.052	0.466	0.444	4.03
BH 5b	43.268	-5.57	4.558	0.61	0.615	4.563
BH 6	27.253	-4.646	5.482	0.447	0.25	5.285
BH 7-GL	20.2	-3.893	6.235	0.53	0.51	6.215

BH = Borehole

LW = Low Water

Δ = Horizontal Distance

ΔI = Vertical Distance

C = Height of the borehole casing above ground level

Gaps have been left where no reading has been taken

The calculation that is made to get the Corrected height of the water level uses the following formula:

Corrected Height of Water level = (height of BH above LW + casing height (C) – reading)

Figure A2.20: Electrical conductivity variations at Rossall Beach on 20/06/01

		Readings (mS)														
	Δ	07:40	08:40	13:50	14:50	15:50	16:50	17:50	18:50	19:50	20:18	20:30	20:40	20:50	21:10	21:33
LW	360.071															
BH 1b	148.591	38.4				27.3	37.5	38.1	38.8	38.6						
BH 2c	110.2	40			33.4	36	37.4	36.6	37.2	37.3	40.2					
BH 3c	82.371	38.6		36.2	33.1	30.1		36.1	37.7	36		40				
BH 4c	63.396	27.6		38.3	39.5	38.7		34	41.6	40.1			43.6			
BH 5b	43.268	38.1		34.4	39.6	38.5	35.7	38.1	38.3	38.1				37.4		
BH 6	27.253	40	41.5	41.7	43.2	40.1	39.2	39.5	39.3	39.1				40.7	40.5	
BH 7-GL	20.2	41.4	40.9	42.6	42.1	39	28.2	38.3								40

Figure A2.21: Temperature variations in the boreholes at Rossall Beach on 20/06/01

		Readings (mS)														
	Δ	07:40	08:40	13:50	14:50	15:50	16:50	17:50	18:50	19:50	20:18	20:30	20:40	20:50	21:10	21:33
LW	360.071															
BH 1b	148.591	16.2				18.6	16.5	17.6	16.6	17						
BH 2c	110.2	16.3			19.3	16.1	15.7	16.7	16.7	16.7	17.3					
BH 3c	82.371	16.5		20.6	17.7	16.4		16.7	16.5	16.3		17.4				
BH 4c	63.396	16		19.8	21	21.3		19.8	19.2	18.6			17.2			
BH 5b	43.268	16.3		18.1	17	17.2	17	16.7	16.7	16.5				16.2		
BH 6	27.253	15.8	16.4	18	17.9	18	18.2	18.5	18.4	17.8				16.9	17.2	
BH 7-GL	20.2	16.1	16.2	18.7	17.9	18.3	18.1	18.2								17.1

BH = Borehole

Readings made after 19:50 are as each of the boreholes is about to be inundated with water

LW = Low Water

Δ = Horizontal Distance

Appendix 3

Figure A3.1: Table displaying tide tables

	First High		Second High		First Low		Second Low	
14 th June 2001	05:26	7.6m	17:59	7.2m	12:09	2.8m	00:32	3.2m
20 th June 2001	11:07	8.9m	23:28	9.1m	05:24	1.6m	17:45	1.3m
21 st June 2001	11:53	9.2m	00:13	9.3m	06:13	1.2m	18:30	1.1m

The data displayed in the table above was supplied by Her Majesties Coastguard Liverpool. It shows both high tides and both low tides experienced on the days that measurements were made as well as the respective heights. Times are in British Summer Time.

	High Tide	Low Tide
14 th June 2001	18:10	-
20 th June 2001	10:50	17:50
21 st June 2001	11:30	18:30

The table displayed above shows the readings of high and low tide that were measured on the individual days.

Figure A3.2: Heights of the Sea defences at Rossall

	Height sea wall (m AOD)	Ht intermediate wall (m AOD)	Ht rear splash wall (m AOD)	Typical level of hinterland
Cleveleys	8.10	N/A	9.40	6.10
Rossall	7.80	9.20	11.0	5.20
Fleetwood	7.20	N/A	N/A	9.10

AOD = Above Ordinance Datum

Table from Wyre Borough Council

<http://www.wyrebc.gov.uk/coastaledufigures.htm>

Time	SW2	Tide Levels
11:30	1.78	1.64
11:50	1.78	1.63
12:10	1.78	1.59
12:28	1.78	1.52
12:48	1.78	1.42
13:07	1.78	1.28
13:27	1.78	1.11
13:45	1.76	0.94
14:05	1.76	0.74
14:25	1.76	0.52
14:43	1.74	0.3
15:03	1.74	0.05
15:23	1.74	-0.15
15:41	1.72	-0.34
16:00	1.72	-0.5
16:20	1.72	-0.6
16:38	1.72	-0.66
16:58	1.71	-0.63
17:17	1.71	-0.59
17:37	1.71	-0.46
17:54	1.71	-0.32
18:14	1.71	-0.14
18:34	1.71	0.05
18:54	1.71	0.26
19:13	1.71	0.47
19:33	1.71	0.65
19:52	1.71	0.82
20:13	1.7	0.97
20:33	1.7	1.11
20:52	1.7	1.25
21:12	1.71	1.38
21:32	1.72	1.49
21:52	1.73	1.6
22:12	1.74	1.69
22:32	1.75	1.77
22:52	1.76	1.81
23:12	1.76	1.83
23:32	1.77	1.83
23:52	1.78	1.77
00:12	1.78	1.67
00:32	1.78	1.54
00:52	1.78	1.41
01:12	1.78	1.23
01:32	1.78	1.02
01:52	1.78	0.79
02:12	1.78	0.54
02:32	1.78	0.29
02:52	1.77	0.02
03:12	1.76	-0.22

Figure A3.3: Table displaying a set of data collected at the ICI Ardeer site on the 26-27.8.92. Data was supplied by Andrew Binley.

Continued...

Time	SW2	Tide Levels
03:32	1.76	-0.46
03:52	1.75	-0.69
04:12	1.75	-0.84
04:32	1.75	-0.97
04:52	1.75	-1.06
05:12	1.75	-1.04
05:32	1.75	-0.97
05:52	1.75	-0.86
06:12	1.75	-0.72
06:32	1.75	-0.5
06:52	1.75	-0.27
07:12	1.75	-0.02
07:32	1.75	0.2
07:52	1.75	0.4
08:12	1.75	0.57
08:32	1.74	0.74
08:52	1.74	0.89
09:12	1.74	1.01
09:32	1.74	1.14
09:52	1.74	1.26
10:12	1.74	1.38
10:32	1.74	1.51
10:52	1.73	1.61
11:12	1.73	1.71
11:32	1.75	1.81
11:52	1.76	1.88
12:12	1.76	
12:30	1.77	