A Study of Changes in High Water Levels and Tides at Liverpool during the Last Two Hundred and Thirty Years with Some Historical Background

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The original POL Report 56 was constructed in 1999 using Wordperfect for the text in the body of the report. Printouts of that and the separate figures were then combined and the whole report printed by a commercial printer (copies may still be available from the POL Library). Unfortunately, no pdf was made at the time.

In order to make this pdf now, and because POL does not use Wordperfect any longer, I have had to read the old Wordperfect file with Word, with the result that sections and footnotes etc. are not always laid out as before (and look a little messy in places). Apologies for that but I think no information has been lost.

P.L. Woodworth

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<tr><td colspan="3">ABSTRACT

This report describes changes in the tides and sea levels observed at the port of Liverpool since the second half of the eighteenth century, when the UK's first systematic measurements of high water heights and times were begun by Captain William Hutchinson. The resulting Liverpool tidal record is one of the longest of its type in the world and is shown to be of great importance to studies of long term changes in sea level as a result of climate change.

A proper interpretation of information obtained in ‘data archaeology’ exercises such as this is only possible given some understanding of the reasons for which measurements were made and the methods used. Therefore, the report contains a number of historical references discovered during the course of the research which may help to place the information within its proper context. The report also attempts to give proper credit to some of the remarkable individuals involved in tidal measurements at Liverpool.</td></tr>
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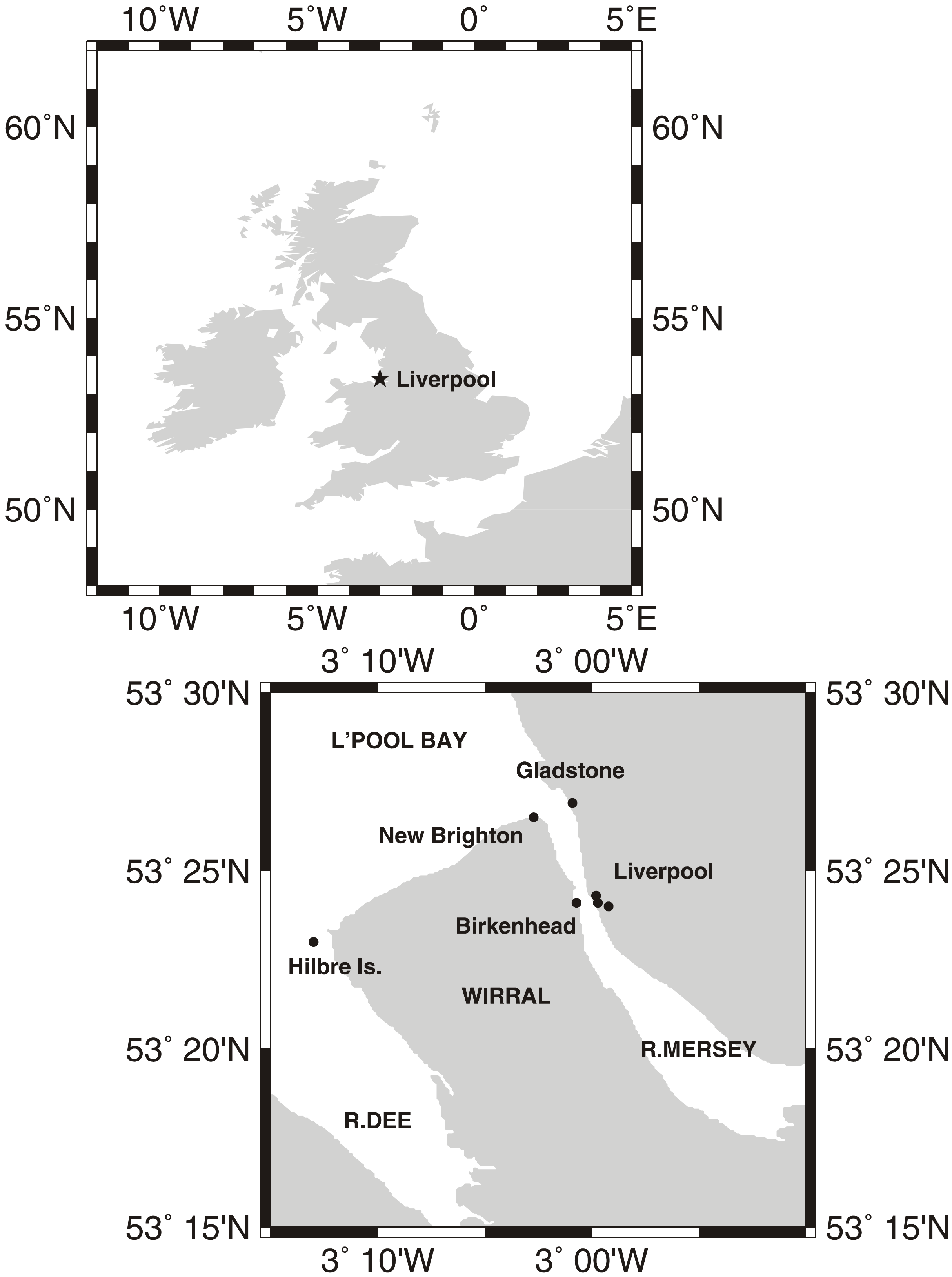

Tide Gauges Near Liverpool Mentioned in the Text

A Study of Changes in High Water Levels and Tides at Liverpool during the Last Two Hundred and Thirty Years with Some Historical Background

1. Introduction

This report is concerned with the historical record of high waters, and with early measurements of the ocean tide, at Liverpool in northwest England. These data sets span approximately 230 years, and together comprise the longest, near-continuous set of tidal information in the UK, and one of the longest in the world.

The second section of the report provides some of the historical background to the measurements. These took place as Liverpool expanded from being a small medieval town with a sheltered river anchorage (the 'Pool' of Liverpool) to become one of the greatest ports in the world. The efforts of some interesting individuals, such as William Hutchinson, in collecting tidal information are particularly notable during the eighteenth and early nineteenth centuries.

The third section describes the various data sets of tidal measurements at Liverpool, including those which we have assembled in the course of this analysis. From the middle of the nineteenth century, the Mersey Docks and Harbour Board (MDHB) and, more recently, the Proudman Oceanographic Laboratory (POL), operated a succession of different tide gauges at Liverpool. However, their data have never been processed and archived in a systematic fashion. Consequently, the construction of a composite time series of high waters, and the study of associated tidal changes, has been much more difficult than envisaged.

The fourth section presents a number of scientific analyses of the data sets, including investigations of Hutchinson's high water heights and times, long term changes in the principal ocean tide constituents, secular trends in mean high water (MHW), mean tidal range (MTR) and mean sea level (MSL), and long term variations in high water extremes. In order to study trends in MHW and MSL, as much geological information as possible is required concerning the land upon which the sea level measurements have been made, particularly with regard to its stability. Consequently, this section also contains results of geodetic levellings carried out during 1996-98 between historical benchmarks, including those installed in the last century by the MDHB and the Ordnance Survey.

Finally, the significance of the findings is discussed within the overall context of research into UK, European and global sea level changes, and conclusions of the entire study are summarised.

2. Historical Background

2.1 The First Docks

A history of the first docks of the port of Liverpool, from the opening of the 'Old Dock' in 1715, can be found in the excellent book by Nancy Ritchie-Noakes (1984), referred to hereafter as R-N (1984). It is not our intention to reproduce here the history of the many Liverpool and

Birkenhead docks themselves, but only to provide sufficient background for a proper appreciation of the locations at which sea level measurements have been made during the last two and a half centuries. Any reader interested in the history of the docks cannot do better than start with R-N (1984), with Jarvis (1991a) which concentrates on the nineteenth century dock expansion, and with McCarron (1998) which reviews the history of Birkenhead docks.

The Old Dock

The upper panel of Figure 1 presents a map of the town around 1700 (Merseyside Archaeological Society, 1981), and shows schematically the location of the construction of the Old Dock below the high water mark in the mouth of the Pool. It was constructed between 1710 and 1715 by the engineer Thomas Steers behind a coffer dam set into the bed of the River Mersey (Peet, 1930). Details of its construction, such as the number of men employed and the methods used to circumvent the difficulties of working in such a dangerous river, are sparse. Few records survive, and most of our knowledge of the way it was built comes from archaeological excavations.

The honour of being the 'first commercial dock in the world' is disputed between the Old Dock at Liverpool (1715), and the Blackwall Dock (c1660) and Great Howland Dock at Rotherhithe (1699) in London. Steers also worked on the latter. If a 'dock' is defined as having gates which point inwards to keep water in at low tide (i.e. a 'wet dock'), and as having interior quays against which ships can moor, load and unload, then the Old Dock wins, the London docks having both been built as lying-up and refitting basins without quays, rather than as working docks in the modern sense.

The construction of the Old Dock, with its associated quaysides, warehouses etc. hastened the complete reclamation of the shallow Pool (Stewart-Brown, 1930), as can be seen by comparison of the two maps of Figure 1. However, the topography of central Liverpool remains essentially unchanged to the present day. For example, if one walks east along Lord Street, it is clear one is walking downhill to what was once the Lord Street bridge over the Pool to Church Street which rises gently towards Bold Street.

The Old Dock was used intensively for over a century until it was considered too small (approximately 200 yards long, 90 yards wide at the western end, 70 yards wide at the eastern end), and too inconveniently inland (other docks having been constructed riverwards), to persevere with. It was closed in 1826 and filled in. Canning Place, named after the Liverpool Member of Parliament and Prime Minister, with its fine Customs House badly damaged in the bombing of the second world war and later demolished, was constructed in its place.

For sea level studies, however, some aspects of the Old Dock's construction remain of great importance. Figure 2 presents a cross-section through its entrance, showing the relationship of the sill, which is the stonework of the base of the entrance, to approximate MSL and to the top of the gates, based on information from Peet (1930). A well-constructed sill, masonry to support the gates and gates themselves were obviously vital to a 'wet dock', if too much water was not to be lost at low tide. In addition, it was clearly important to mariners to know the depth of water over the sill when entering or leaving the dock. The level of the 'Old Dock Sill (ODS)', therefore, became the working datum for the dock area, then for the whole port, and eventually for all of

Liverpool Bay, 'Liverpool Bay Datum (LBD)' being defined as 10 feet below the ODS. [1]

It is probable that the masonry of the ODS itself still exists. The sill certainly survived the 1829 enlargement of Canning Dock (see below) including its excavation to 2 feet below ODS (R-N, 1984), as we know that it existed in 1843 when the dock was drained and the sill was included in geodetic measurements of the area (Close, 1922). These measurements are discussed further in Section 4.4. It probably also survived the further deepening of Canning to 9 feet below ODS during the 1840s (R-N, 1984). Nevertheless, knowledge of the level of the ODS is preserved in terms of benchmarks throughout the area. Figure 3 shows the most impressive of these benchmarks, comprising a 'tide gauge' established in 1845 on the Canning Island entrance to the dock system. Geodetic levellings between these benchmarks are also discussed in detail in Section 4.4.

Two further observations about the Old Dock entrance can be made from Figure 2. An excellent feature was the width of the gates (34 feet according to Peet, 1930), which could accommodate almost all ships using the port even 100 years later. For example, Captain James Cook's famous mid-eighteenth century ship the Endeavour, a replica of which visited Liverpool in 1997, was a roomy 500 ton ex-collier and was 29 feet wide. Similar sizeable vessels would have had no difficulty using the Old Dock. [2]

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[1] Page xii of R-N (1984) states 'ODS lies 25 feet below high water of ordinary spring tides, 11 ½ feet below high water at neaps'. The former should be approximately 18 ½ feet, the latter is approximately correct. However, MHW, MHWS(N) etc. are time-dependent, see below.

[2] The exact date the dock was opened for commerce is not known for certain. Wardle (1941a) discusses which vessels might have been the first to use the dock and quotes Peet's finding of a document claiming that the 'Marlborough' entered the dock on 8 June 1715. Wardle points out that the HMS Marlborough of the time was a second rate, 680 men, 96 guns, and could have been the 'Great Ship' referred to by a Liverpool diarist. However, a second rate would have been about 50 feet wide and could not have squeezed through the gates, and possibly the ship was anchored in the river while smaller craft entered the new dock. Equally likely is that

A less ideal feature was the depth of the sill below MSL (approximately 5 feet or 1.5 m). With a mean tidal range of 6.5 m, it is clear that many heavily-loaded ships would not have been able to use the dock except close to high tide itself, severely limiting its hours of operation. It seems that Liverpool was slow to learn from this experience. The sill of the second wet dock (South or Salthouse Dock, opened 1753), the construction of which was started by Steers, was made at almost the same level as the ODS. Later docks had much lower sills and/or were equipped with 'half-tide basins' with lower sills, at the expense of increased sediment inflow from the river and consequent increased need for dredging.[3]

Salthouse and Canning Docks

'Marlborough' was confused with 'Mulberry'. Chandler (1957) and other authors state that the 'Mulberry', 'Bachelor' and 'Robert', all owned by Captain Bryan Blundell, were reputedly the first to use the dock.

[3] One of the principal grounds for support of docks on the Birkenhead side of the river was the opinion of the time that sills could be constructed deeper there (Baines, 1859).

Figure 4 shows a detail from John Eyes' map of Liverpool in 1765, at approximately the time that the first tidal records discussed below were acquired. By this time, the Old Dock had been joined by South (Salthouse) Dock, with entrances of both opening into a 'dry pier' or 'dry basin' [4] which was open to the river. This basin, which provided a shelter to ships entering or leaving the two wet docks, was later (1829) enlarged and acquired gates of its own, thereby converting into a further wet dock, renamed Canning Dock in 1832 (Macleod, 1982). The 'Intended Dock' to the north of the dry basin became the third Liverpool 'wet dock', George's Dock, in 1771 with its own dry basin.

Several locations can be pointed to in Figure 4. Steers lived in Strand Street and owned an anchor smithy in a short alley called Steers Wient to the north (left) of the Old Dock Gates. The gates were the location at which William Hutchinson recorded the heights and times of high waters throughout 1764-1793, as discussed in detail below. Hutchinson lived at 'No.1 on the north side of the Old Dock Gates' (Williams, 1897), convenient for his extended twice-daily duties.

A detail from another map over a century later (1900) is shown in Figure 5. Comparison to Figure 4 shows that the Old Dock has disappeared (1826), Salthouse is still entered from Canning in the north, although it now has two other entrances via the Albert Dock (1845) and Wapping Basin (1855) to the west and south respectively, and Canning exits into another small dock called the Canning Half-Tide Basin (1844). The addition of half-tide basins to working wet docks, thereby enabling more efficient working with the tide, was a feature of the work of Jesse Hartley, the Victorian engineer who built or re-built most of the Liverpool dock system (R-N, 1980, 1984; Jarvis, 1996).

The Salthouse, Canning and connected docks, including Hartley's impressive Albert Dock, survive essentially unchanged. Significant changes from Figure 5 since 1900 include the redevelopment of the Old Dock/Canning Place rectangle, and the widening of the 'Strand Street' and 'Wapping' main road alongside Canning and Salthouse Docks, including the demolition in 1957 of the Liverpool Overhead Railway which ran parallel to the road (Bolger, 1992). 'The Strand' and Strand Street continue to remind that the high water mark of the river was much further inland before dock construction began (compare Figure 5 to Figure 1).

George's and Prince's Docks and Piers

Figure 5 also shows the area between the Goree Piazzas and George's Pier Head occupied by George's Dock, which was closed in 1900 and filled in. The Port of Liverpool building ('Dock Offices') is shown under construction. This was shortly joined to the north (left on the map) by

[4] A 'dry dock' in Liverpool jargon can mean a 'dry basin' such as that shown, as well as having its usual meaning of a dock from which water can be pumped to service hulls of vessels, the latter having gates which point outwards to the river. A glossary of terms associated with docks can be found in McCarron and Jarvis (1992).

the Cunard and Royal Liver buildings which mark the Liverpool waterfront today. At the Pier Head can be seen the George's landing stage constructed in 1847, which, as described below, itself functioned as a tide gauge from 1854 until approximately 1925.

To the north can be seen Prince's Dock (1821), the first of the 'North Docks' (i.e. north of St.Nicholas's church) (Jarvis, 1991b). When the George's and Prince's stages were connected, they formed a floating structure half a mile long, the longest in the world, alongside which Atlantic liners berthed. Gauge operations were interrupted when the George's stage was destroyed by fire in July 1874 and rebuilt by the end of 1875. At some point in the mid-1920s, the tide gauge apparatus was moved from George's landing stage to form part of a conventional stilling well tide gauge at No.2 Baggage Rooms on Prince's Pier (adjacent to the 'Refreshment Rooms' of Figure 5) until the closure of the Prince's area in 1984. Thereafter, several temporary gauges were operated by POL at Waterloo and other docks. In 1991, an 'A Class' national network bubbler gauge was installed at Gladstone Dock 3 miles down-river. [5]

Importance of the Distances Between the Docks

When one undertakes studies of tides and sea levels using data which have been acquired from several sites, it is important to consider the systematic errors which may be involved by switching from one location to another. [6]

With regard to the studies of changes in the tide at Liverpool discussed below, the distances between each of the first docks can be considered 'small', and we are confident that the changes in measurement location would not in themselves have introduced major biases into the calculations. In the River Mersey, the amplitude of the M2 tidal constituent (the main lunar

[5] Gladstone Dock was not named after William Ewart Gladstone, the Liverpool-born Prime Minister, as is sometimes assumed, but after his second cousin Robert Gladstone. The latter was an important Liverpool merchant, Chairman of the Mersey Docks and Harbour Board, freeman of the city and a founder of Liverpool University. He had five daughters and four sons, one of whom was also called Robert (see below), and died in 1919. A pictorial history of Gladstone Dock can be found in Longbottom (1995).

[6] Excellent introductions to the study of tides can be found in Pugh (1987) and Open University (1989).

semidiurnal tide) is over 3 m, and increases by approximately 6 percent going up-river from Gladstone Dock near the mouth to Eastham, as shown by tidal constants available from the POL data banks and by a numerical ocean tide model of Liverpool Bay (D.Prandle, private communication). From the Old Dock gates, or Salthouse gates, to George's Pier measured along-river, is approximately 480 m and from the Old Dock gates to Prince's Pier is approximately 800 m. By inspection of the model in the vicinity of the measurements, we conclude that the shifts in recording location could have resulted in an approximately 0.2 percent reduction in measured M2 amplitude from the Old Dock to George's, and a similar reduction from George's to Prince's.[7] It will be seen that these differences are small compared to those reported to have taken place in the Liverpool tide during the last two centuries.

A major exception to this conclusion concerns the transfer of measurements from Prince's Pier in 1984 to Gladstone Dock commencing in 1991. The amplitude of M2 at Gladstone is 2.5 percent lower than at Prince's and correction terms have to be applied to the Gladstone tidal measurements in order to present the data in a comparable way.

In the study of time series of MSL, the main factor to be considered concerns the reliability of the transfer of datum from one location to another. In the case of the earlier docks, the datum used was either the ODS (for the Old Dock and George's), or was expressed in terms of other dock levels (e.g. level of Salthouse Dock sill) or benchmark heights (for Prince's) which could in turn be related to the ODS. The distances which are involved in transferring a geodetic level from one of these sites to another would be considered short by modern standards, and very small uncertainties would be obtained in making the levelling connections. In addition, they would have been considered small in the last century by people who were expert in the field (e.g. the Ordnance Survey). Of course, the uncertainties involved in, for example, the MDHB's transfer of the ODS datum to the tide gauge at George's more than a century ago will never be properly known, and the stated level connections have to be taken at face value.

A major exception again concerns the latest data from the gauge at Gladstone Dock. The distance from the older docks is too large for us to have undertaken a levelling connection of our own, and we have relied for datum transfer on the results of connections of the benchmarks at each site to the national geodetic network by the Ordnance Survey, and expressed in terms of Ordnance Datum Newlyn (ODN). Uncertainties in that datum transfer are probably centimetric rather than millimetric.

A further factor to be considered in MSL time series studies concerns the stability of the land upon which the measurements are made. All land, whether at the coast or in the middle of continents, experiences either uplift or submergence from a number of geodynamic processes, of which Post-Glacial Rebound (PGR) is the most well understood (Lambeck, 1990), and of which rapid vertical movements caused by earthquakes are the most dramatic. In some estuaries, in areas subject to ground water extraction, and at locations where land reclamation has taken place, then variations in the rate of vertical land movement can be expected over small distances

[7] Woodworth et al. (1991) estimated a possible 0.4 percent change in amplitude during the transfer from George's to Prince's. This is now considered to be an over-estimate.

(Emery and Aubrey, 1991). A full appreciation of the importance of short wavelength vertical land movements at Liverpool and other ports will not become available until some years of measurements by advanced geodetic techniques become available (Neilan et al., 1998). In the meantime, we are forced to consider the data as stemming from the one site, although remaining aware that, for example, submergence might be more likely on areas of reclaimed land, which includes most of the present-day Liverpool waterfront.

In principle, MSL measured at more than one site should also be corrected for the slope of the real sea surface associated with 'steric' water properties (especially salinity in a river estuary) and the meterological forces which operate on the surface (air pressures and wind stress). In principle,
a numerical model, controlled by each of the different forcings, is required to perform such computations properly. However, because of the small distances involved, even between Gladstone and the other docks, we have not considered these factors in detail.

Time series of MHW (or Mean Low Water, MLW), or of high water extremes, have to take into account all the factors associated with tidal as well as mean level changes, and, therefore, they are in some ways the most difficult to investigate. However, they are, of course, the time series of most interest to people who live by the coast.

2.2 The First Dockmasters

Thomas Steers, who constructed the Old Dock, appears to have automatically become Dockmaster thereafter (1717). Steers combined this position with many other functions, including Dock Engineer (1710-1750) and mayor of Liverpool (1739). Aside from docks (Old Dock, Salthouse Dock, earlier contributions to Rotherhithe Dock), he built a number of Liverpool's major buildings (e.g. St.George's church on the site of the Castle, the Old Ropery Theatre, and plans for a new Exchange). He culverted the remains of the Pool underground and worked on Liverpool's first fresh water supply system. In addition, he surveyed the Mersey and its tributaries, and the River Boyne in Ireland, and built the Newry Canal. He undertook various consultancies regarding land purchase and owned an anchor smithy near to the Dock.

Peet (1930) suggests that Steers had as multi-faceted a career as William Hutchinson, but oriented more towards civil engineering, surveying and construction. Most of the men who became Dockmasters were pilots or master mariners. The position was a responsible one, with duties extending to all hours of the day and night. It does not seem possible that Steers, who was away from the town for extended periods, would have had the time or interest to undertake the Dockmaster's duties as diligently as Hutchinson did.

In particular, no tidal measurements are known to have been made during Steers' period as Dockmaster, or at least none survive. Occasional mentions of people whose occupations might have been affected by the tide can be found in histories of the period, although none of them are accompanied by useful tidal data. For example, in 1745 the Corporation raised a regiment, the 'Liverpool Blues', to defend against the approaching Jacobite army. The Captain of the Fourth Company, Francis Stewart, was a 'tide surveyor' (Higham, 1995). However, this misleading term refers to the Customs Officer in charge of surveying the cargos of ships arriving on each tide (Jarvis, 1954). Steers himself was made responsible for strengthening the town's defences during the '45 rebellion.

After Thomas Steers' death in 1750, aged about 80, the post of Dock Engineer was assigned to Henry Berry who had been his clerk (Harris, 1937). The ancient position of Water Bailiff was allocated to his son, Spencer Steers, who became mayor in 1755-56. By 1759 the Dockmaster was an Alderman Bird. At a Council meeting on 7 February, Steers offered his resignation, on account of a report at a previous meeting that the docks had not been properly attended, on condition that Bird also resigned. Bird promptly did so, nominally on health grounds. Captain William Hutchinson was offered both positions with a Robert Linaker as Under-Dockmaster (Touzeau, 1910).

Hutchinson was a remarkable man, who rose from being a common sailor to become a privateer captain alongside Fortunatus Wright, the most famous of the Liverpool privateers. He was also at various times a ship-owner, boat-builder, commercial trader, inventor, author and philanthropist. His character is said to have been more like that of the Puritan seventeenth than the eighteenth centuries, combining the aggression of privateering with strict religious adherence. For example, he abhorred swearing, which must have made life difficult aboard ship. Annex 1 provides a list of some of his many accomplishments.

Two aspects of Hutchinson's life provide a connection to our tidal studies. First, Hutchinson is known to have had an interest in mirrors and illumination mechanisms for lighthouses. He experimented with the construction of large one-piece mirrors up to 12 feet diameter, and large mirrors made from smaller sections of looking-glass fixed to a wooden backing frame (Williams, 1897). He also developed oil-fired light apparatus, lighthouses at this time usually being lit by 'firebaskets' containing wood or coal. The Liverpool Council Minutes record that in 1763 he experimented with his reflectors at the Bidston Hill signal station, which became Bidston Observatory (POL), and at which the first Bidston lighthouse was constructed in 1771 (Hockey, 1994). One can imagine that Hutchinson, a canny businessman as well as an inventor, saw the possibility of providing the Bidston lighthouse, and others at Leasowe (1763) and Hoylake (1764) along the Wirral coast established by the 1761 Dock Act, with lights and mirrors. [8]

The second aspect of interest is, of course, his unstinting efforts of measuring the heights and times of high waters, and meteorological parameters, for almost 30 years (1764-93) at the Old Dock gates. High waters were measured at all times of day and night and in all weathers with

[8] The Bidston signal station had been assembled out of wood after the Council had given approval in 1763 to a design of Lightholler. Hutchinson was, therefore, prompt in making use of it as a platform for his reflectors. Plate 10 of Hutchinson (1777) shows a drawing of them. It is not known how his design differed from that of a William Holden who in 1772 was awarded 20 guineas by the Council for an improved version (Woods, 1944). Also it is not known if this Holden was related to those discussed below.

very few gaps. He noted occasional trips to Lancaster or London whenever he was away from Liverpool, when the recordings were made by the Under-Dockmaster. At the start of the first bound book of surviving records covering 1768 to 1772, one reads the following, presumably added in 1790:

"Hutchinson's MSS Journal from 1st January 1768 to the 31st of December 1772. These five years observations upon the tides were made from solar time, and the winds from the true meridian, and their velocity judged according to Mr. Smeaton's rules, our great storms going at the rate of 60 miles an hour, the thermometer kept in doors, at the head of a staircase four stories high, by Wm. Hutchinson, at the Old Dock gates, Liverpool. The first sheets [9] cut out to give Mr. Richard Holden to make out the 3000 observations mentioned in the preface of his tide table, by which he found theory from natural causes to agree with them, and his brother George Holden [10] continues the author of our tide tables to August 23 1790."

Some obvious questions arise such as 'Why did he make the high waters measurements?', and 'Why did he not measure low waters as well?'. The 'Treatise on Practical Seamanship' (Hutchinson, 1777) provides the answers.

The answer to the first is that he had an interest in understanding more about tidal elevations and currents, as the common methods then used for tidal prediction often proved inadequate, especially at neaps. He had personal experience of the consequences of these defective methods: "... I was in a West Indies ship running for a bar harbour in Ireland by this erroneous rule, when we beat off our gripe, rudder, and a great deal of the stern port, and an after part of the keel upon the bar, and had seven feet water in the hold when we got into the harbour, and was obliged to

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[9] These first sheets presumably covered 1764-67 but they have not survived. They would have included less than 3000 observations which is clearly a round number. Hutchinson does not seem to have expressed regret at their loss (e.g. in Hutchinson, 1777), perhaps because they were not lost at the time, but still in the possession of the Holdens. When the 'grandson' George Holden died in 1865 (see below), his extensive library, which conceivably might have contained the missing 3000 observations, was transferred to the Bishop's Palace of Ripon Cathedral from where it was transferred some years ago to the Special Collections of the Brotherton Library of Leeds University. I am grateful to the Dean of Ripon, The Very Revd. John Methuen, and the Leeds Librarian for making searches for them.

[10] This 'original' George Holden is not to be confused with his son and grandson of the same name who were also ordained and produced the tables in their turn. The son was Vicar and Headmaster of the Free Grammar School at Horton, near Settle, Yorkshire. The grandson (1783-1865) was Perpetual Curate at Maghull, near Liverpool. He was also known nationally as a writer on Biblical matters (Dictionary of National Biography, 1885). Holden's tables date from 1770 and were printed annually in booklet form and weekly in the Liverpool Advertiser and Mercantile Chronicle. The earliest set to be found in a Liverpool library is from 1795.They were published until the 1970s when they were replaced by Laver's. Other early sets of predictions included those of Elliot (1798-1807) continued by Wolfenden (1808 onwards). Copies of various tables can be found in the Liverpool Central, University and Athenaeum Libraries, Maritime Museum Archive Section and some are held by the Mersey Docks and Harbour Company and POL.

run on shore to prevent sinking. At Leverpool I have observed ships coming in at neap tides about the quarters of the moon, when instead of meeting with high water, as expected by the common way of reckoning, they have found it about a quarter ebb, that for want of water enough they have often struck or come aground and laid upon the bar, when lots of great damage has often been the consequence ...".

Moreover, he was ideally placed to make such measurements: "... And as I live fronting, and but 14 yards from the dock gates aforementioned, which opens with the flood and shuts on high water, whilst I am able and willing would be glad of any directions, rules, or hints, that might improve observations on the tides, to make them more useful to seamen, pilots, mathematicians, astronomers or philosophers ...".

However, the work was not entirely his own idea: "... For these reasons, and being requested by my friend Mr.Ferguson [11], the astronomer, who with great labour and pains furnished me with large schemes, tables, plans etc. relating to the tides in the year 1764, when I began, and have continued to make observations on the time and height of the tides flowing at the old dock gates ...".

The apparently good relationships between astronomers, mathematicians (e.g. Richard Holden), and mariners such as Hutchinson were no doubt aided by these being times of cultural renaissance in the town. Liverpool had always had a tradition of support for mathematics and related subjects (Chandler, 1957). However, many new societies were being formed, including a 'Ship Club' to which Holden and Hutchinson belonged. The Liverpool (later Lyceum) Library, 'the first gentlemen's subscription library in England', was established in 1758.[12] More comprehensive tidal studies would, therefore, have been of philosophical as well as practical interest.

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[11] David Cartwright kindly researched that this refers to James Ferguson, elected Fellow of the Royal Society in 1763, who wrote, among other astronomical treatises, 'Select mechanical exercises shewing how to construct clocks, orreries and sun dials on plain and easy principles' (London, 1773, 272pp.). A copy of this book, which includes a partial autobiography, is in the Royal Society library. One 'exercise' was a tidal clock (Cartwright, 1999). A biography of Ferguson was written by Henderson (1870). This describes Ferguson's stay at Hutchinson's house in March-April 1764 during which he gave a course of lectures at the Golden Lion Inn, Dale St., and observed a solar eclipse on 1 April. For accurate timing Ferguson had a meridian line drawn on the lead roof of Hutchinson's house with the aid of Mr.Holden, 'master of a mathematical school'. Hutchinson provided a good reflecting telescope for viewing the eclipse and Holden used his own instrument. Henderson quotes Ferguson: "In the year 1764 .... I contrived a clock for Mr.Hutchinson ... for showing the age and phases of the Moon, and the time of High and Low Water at Liverpool every day of the year, with the state of the tides at any time of the day; by looking at the clock." From Hutchinson's own description of this clock in the 'Treatise' it was not at all accurate at Quarter Moons as is understandable. One wonders what happened to this interesting clock which is described and illustrated by Henderson.

[12] The Lyceum Library closed in 1941. The building it occupied from 1802, built by Thomas Harrison of Chester, remains well preserved at the bottom of Bold Street.

All this evidence confirms that the reasons for Hutchinson's measurements were partly 'scientific', and partly 'practical' with regard to the needs of navigation, and were not directly related to his duties as Dockmaster. After all, the Old Dock had been in operation for over 50 years before Hutchinson began recording, and probably an *ad hoc* management scheme incorporating some kind of predictions of the times of high water would have been in operation for many years.

One might enquire as to why he did not start before 1764, as he had been appointed Dockmaster five years previously. Perhaps he had not met Ferguson by then. However, the answer might also be that during these first years he may have had other interests following on from his previous activities. His schemes for supplying fresh fish to the town, the reason he had been made a freeman *gratis* in 1755, seem to have ended around 1758 [13] (Touzeau, 1910) or 1760 (Williams, 1897). Touzeau suggests that lack of further Council support for his schemes led to his taking the Dockmaster position. However, he had many other interests and his development of lighthouse reflectors, for example, suggests that he was not idle in between his Dockmaster's duties in the period up to 1764.
As for there being no routine measurements of low tides in the surviving records for 1768-93, two factors would have conspired: the fact that the heights and times of low waters would have been less important for dock operations (no ship could have entered the Old Dock on any low water so there would have been less interest in measuring and predicting them); and the fact that to measure low waters would have required extra resources in the form of a second tide pole on a pier or other structure at a point in the river that did not dry out.

[13] This would have coincided with the end of a 400 pounds interest-free loan for three years by the Council to fit out a second cod smack. It seems that at this time Liverpool fishermen did not go after cod (Touzeau, 1910).

Hutchinson was, however, very interested in the possibility of recording low tides, if the measurements could be performed easily. In the 'Treatise', one reads: "... I have reason to conclude in moderate weather, that in proportion as the tides commonly rise above the nine feet mark at the gates, they fall the same below the sill of the gates, and that the four feet and a half mark is near the half flood mark let the rise be what it will [14] , though it does not agree with half the time of flowing nor ebbing of the tides. But to observe more exactly the whole rise of our middling tides, I had a board fixed upright at low water in the river, marked with six inch marks each foot, high enough to observe by, till the tide reached the dock gates, and remarked the time it flowed to each foot the rise of the whole tide ...".

In 1793, he was forced to abandon his measurements with the following note:

"Having resigned my place as Dockmaster [15], this journal ceases by me, William Hutchinson. These observations, made from the beginning of 1768 to August 10, 1793, makes twenty-five years, seven months and ten days, which I have given to our Library, exclusive of the 3000 observations given to Messrs.Holdens, to make their tide tables, as mentioned in the preface to them. I could not continue any longer to make observations, for want of the command of our dock gate men and gauge rod to take the night tides. "

[14] In other words, the four feet and a half mark is approximately MSL (Figure 2).

[15] Touzeau (1910) and R-N (1984) give 1801, the year of his death, as the end of his period as Dockmaster.

To anyone familiar with present day requests for resources for research, his exasperation has a familiar ring. Several years of his high water data had already been employed by the Holdens in the development of the first Liverpool tide prediction tables, and it is clear from Hutchinson (1777) that he was very proud that his measurements had been used in this way. It became an offence (5 pounds fine) for a Mersey pilot to be without the tables and a watch. Hutchinson must have known that extensions to his data set would be valuable. [16] He presented his records to the Liverpool (Lyceum) Library from which they were transferred in 1936 by Robert Gladstone to the archives of the Liverpool Central Library. [17] At some point they have been carefully bound, thereby preserving them in good condition. A manuscript copy of the records made in 1814 by J.Lang [18] is preserved in the Liverpool Athenaeum Library.

Possibly the only disappointing aspect of Hutchinson's work, given his enormous efforts in collecting his data set, is the relatively little scientific use he was able to make of it. For example, the nodal variation of MHW (Section 4.1) would have been straightforward to identify if he had been able to manipulate the information. He observed correctly: "... Notwithstanding gales of winds affect the tides, I observe it is more in the height than in the time ..." and computed approximate relationships between wind speed and direction and water level. However, he missed entirely the 'inverse barometer' relationship whereby sea level is depressed by approximately 1 cm given an increase of 1 mb in air pressure: "... I cannot perceive, as has been imagined, that the tides are affected ... by the different weight of our atmosphere, as shewn by the barometer ...". The study of the 'inverse barometer effect' in Hutchinson's data had to wait until later (e.g. Lubbock, 1836). [19]

3. Data Sets of Tidal Measurements at Liverpool

[16] A letter of 12 September 1835 from David Wylie (President of the Liverpool Library and Secretary of the Philosophical Society of Liverpool) to John Lubbock at the Royal Society reads "Mr.Cummins (?), the intelligent head clerk in Mr.Hartley's office, tells me that his father who succeeded Mr.Hutchinson as Dockmaster continued the observations. I presume they will be found among the papers of the office." Such records have not been referred to elsewhere.

[17] This Robert Gladstone (1870-1940) was the son of the aforementioned RG after whom Gladstone Dock was named. Although he trained as a solicitor, he was also a respected historian and collector and writer of an incomplete history of Liverpool. Many of his records are now held in the Robert Gladstone Collection in the Athenaeum Library. The Liverpool Central Library is the successor to the 'Free Library' or 'Brown Library'.

[18] Lang was a Liverpool printer who printed the Holden's and other tide tables.

[19] The discovery of the 'inverse barometer effect' is often credited to Sir James Clark Ross (1854) based on observations at Port Leopold, Canada in 1848-49. However, research by Daussy and Lubbock using data from Brest and Liverpool respectively had already demonstrated the effect many years previously, as Ross acknowledged in a postscript to his paper. Close (1918) provided an interesting review of nineteenth century research on the topic, while the interested reader should see Wunsch and Stammer (1997) for a modern review. Recently, the Swedish scientist Nils Gissler has been credited with one of the earliest recorded observations of the inverse barometer effect in a 1747 article (Roden and Rossby, 1999).

3.1 The First Tidal Measurements (Before Hutchinson)

Measurements of the heights and times of the tides were made at many locations around the UK coast before the first known recordings at Liverpool. Cartwright (1999) has provided a historical review of tidal measurements in different parts of the world, from antiquity through to modern times, and of parallel developments in tidal theory. Chapter 6 of Cartwright's book describes the earliest serious attempts to measure and compile tidal data in the UK, spanning the period 1650-1825. Most important of these in the seventeenth century were the observations for the Royal Society of London, culminating in the work of John Flamsteed, the first Astronomer Royal, and others. Much improved tide tables for the Thames (for high water times only) resulted from Flamsteed's observations of only a small number of high waters in 1681-82, interpreted in the context of his knowledge of the ephemerides of the Moon and Sun.
Liverpool can, however, claim to be the UK location at which the first systematic tidal measurements were made, Flamsteed's research in the Thames, for example, being based on an extremely small data set by Hutchinson's standards. It is even possible that extended recordings were in progress at Liverpool much before Flamsteed. Deacon (1971) refers to the work of the astronomer Jeremiah Horrocks, who was making measurements at Toxteth, slightly upstream of Liverpool, in 1640. Horrocks's letters imply that he made some kind of tidal measurements for at least three months, and was intending to record for a year. Deacon assumes that the records were lost in the Civil War or the Fire of London. [20]

Some kind of extended recording of the heights of high waters at the start of the eighteenth century can perhaps be inferred from the design of the gates of the Old Dock. Peet (1930) has described how these were "... of iron ... well and ingeniously constructed ... containing also sluices which would open below ..." and were 23 feet high (Figure 2). Therefore, they would have prevented the dock from flooding by any high tide less than 23 feet above ODS, overtopping from waves aside. This choice of height of the gates was almost perfect given the statistics of high tides in the Mersey.

Figure 6(a) shows the distribution of over 18000 high waters from the Hutchinson data set; Figure 6(b) shows the upper part of the distribution in greater detail. The number of high waters above a given threshold can be seen to increase considerably as the threshold is lowered below 23 feet (276 inches). There is only one high tide measured above that level (aside from two very large values which we believe to be errors, see below). That was 23 feet 6 inches in the afternoon of 1 November 1772. If the gates had been chosen to be, say, 20 feet high (240 inches), there

[20] I am grateful to my colleague Chris Hughes for referring me to this section of Margaret Deacons's book. Horrocks (or Horrox) was the first astronomer to observe the transit of Venus. He was born in Toxteth and died in 1641, shortly after the tidal measurements, aged less than 22 years (Anon, 1876; Chapman, 1990). He is commemorated in two churches in Toxteth: the Ancient Chapel of Toxteth, where Horrocks worshipped, and St.Michael's which was constructed in 1815. The latter contains a plaque presented in 1826 by a Moses Holden, author of a book on astronomy for young people. There is no evidence, and it seems unlikely, that this Holden was related to the aforementioned. Unlike his tidal measurements, some of Horrocks's astronomical records survived and were inspected by Flamsteed at Towneley Hall near Burnley in 1672 (Howse, 1980).

would have been 370 occasions when the tide rose over the top of the gates, and the dock would have been flooded every few weeks.

Therefore, it is tempting to speculate that at some point, perhaps during the six years it took to construct the Old Dock but before the gates had been designed and installed, someone had conducted a respectable survey of at least high spring tides. No Old Dock records survive to confirm this suggestion. [21]

3.2 William Hutchinson's Records

So far as we know, Hutchinson's records have never been computerised comprehensively, although some of the meteorological information has been used by climatologists (e.g. Craddock, 1976), and therefore must have been computerised or documented partially on an *ad hoc* basis. They form a very large data set and we have been able so far to enter into computer files only the heights of high water for all years 1768-1793, and the times of high water for seven years (1768-69, 72, 77, 82, 87 and 92). We have not computerised any of the meteorological data, except to note the barometer and wind information when exceptionally high tides were recorded.

In principle, it would be ideal to obtain photographic or optically-scanned digital copies of the complete collection for wider circulation. However, the type of binding used makes such copying a difficult task, and Liverpool Central Library has refused to consider the suggestion. In the short term, where that means almost two centuries so far, loss of the originals is guarded by Lang's copy in the Athenaeum Library.

[21] Peet (1930) suggests that Steers' role at Rotherhithe might have been the design of the gates. In addition, he may well have been aware of tidal characteristics from his experiences in Holland, where he may have lived, arriving with William of Orange and fighting at the Battle of the Boyne. Gates to hold the water in connection with inland navigation had been in use in Holland for many years, and their design principles would have been familiar to an engineer. However, his origins are not known conclusively. Picton (1875) describes him as a 'native of Kent'.

A second copy of part of the records, for the years 1774-1792 only, exists in the archives of the Royal Society of London. This version consists of a rearrangement of Hutchinson's original measurements from their chronological order into tables of heights and times ranked in terms of parameters such as the 'Age of the Moon'. The data reduction for this work was performed by Joseph Dessiou from the Hydrographic Office and others, on behalf of John Lubbock, vice-President of the Royal Society. [22] These investigations, like others of tides at the time, were stimulated by the recently-formed British Association for the Advancement of Science (BAAS) (Cartwright, 1999). Lubbock made extensive use of the Hutchinson-Dessiou tables in his development of a non-harmonic method of tidal prediction. In particular, he calculated tables from which improved tidal predictions could be made at Liverpool. [23]

In one paper (1835), Lubbock made a seemingly ungracious criticism of Hutchinson for not having defined clearly whether the recorded 'solar times' of high water were 'apparent solar' or 'mean solar' time. He remarked that 'this point ought not to have been left in doubt'. However, it is a very important point for tidal analysis, as we describe below. The 'Treatise on Practical Seamanship' (Hutchinson, 1777) provides no further guide on this point, referring only to 'times' of high water, and to the tide clock constructed in association with Ferguson which was maintained 'as near as I could to solar time'.

As mentioned above, knowledge of the datum of sea level measurements is important if they are to be employed in long term mean sea level time series studies. However, nowhere in the 1768-93 records does he state explicitly what datum his high water levels were measured relative to. Fortunately, in the 'Treatise' one reads: "... sill of the gates, from whence is marks in the stone work upward to twenty-two feet and a half, from which the heights of the tides are taken, ...". Therefore, the datum of his measurements must indeed have been ODS. Uncertainties between what Hutchinson may have understood as ODS, and what later surveyors have assumed to be ODS, are discussed in Section 4.4.

One concern is that neither the 1768-93 records nor the 'Treatise' describe exactly how he made the routine measurements of the heights and times of high water. The heights are not so much a problem, as the level changes only slowly near high water. However, the method of determining the high water time is more problematical.

[22] If the two Liverpool copies of Hutchinson's records were to be lost, the information in the Dessiou tables could be restored to chronological order using computer programs of lunar ephemerides.

[23] A copy of 'Smith's 1841 Liverpool Commercial Almanack and Tide Table. Calculated by Alex Brown, A.M.' based on Lubbock's tables is kept by the Mersey Docks and Harbour Company.

The above quotation tells us he made visual observations using what was then called a ‘tide gauge’. These would have been six-inch high letters inscribed every foot into the stone of the wall of the entrance to the Old Dock showing the depth of water over the sill. (His ‘board fixed at low water’ would nowadays be called a ‘tide pole’. Also his reference to night-time ‘gauge rods’ in his 1793 resignation remarks implies some sort of ‘tide pole’.) By the middle of the eighteenth century, it was well understood that one should measure at least three levels around high water and their times from which the real high water and time could be computed by quadratic interpolation (D.Cartwright, 1972a and private communication). However, there is no evidence that Hutchinson actually worked this complicated way for almost 30 years, rather than simply ‘guestimate’ the high water level time. There are no surviving rough workings which would give a clue. [24] Amin (1983) notes that, even in the early nineteenth century, different methods were used to define the time of high water in London: the ‘interpolation’ method used at St.Katherine Docks, but the time when the level appeared to begin to fall used at the London Docks.

Two plots can be shown to demonstrate the uncertainties in the measurements. Figure 7 shows the distribution of ‘inch’ values of the feet and inch measurements for the entire data set. The number of measurements with a round number of feet can be seen to be approximately twice the number with 1-11 inches; this results in the spikiness evident in Figure 6(a). Three and six inch values, but not nine, are also more likely than others. It is not easy to measure levels with an accuracy much better than inches, especially by lantern light in the middle of a stormy night. The temptation then is to round one’s estimate of high water, even to the nearest foot in really bad conditions.

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[24] Some kind of ready ‘guestimate’ of the time of high water could perhaps have been concocted by Hutchinson using predictions from the Holden’s tide tables. However, Hutchinson’s ‘measured’ times cannot be simple copies of the tide table predictions as the comparisons to predictions based on modern tidal constants (e.g. Figure 10) would in that case demonstrate a strong residual tidal time-difference signal, probably containing especially strong spring-neap components. Such signals are indeed present at a low level in Figure 10 and in corresponding figures for other years. However, they are by no means the main features of the time series, which appear to contain also a component originating from normally-distributed measurement errors (in addition to the ‘equation of time’). Small tidal time-difference signals would also be expected in the figures if the real tides of the eighteenth century were not identical to those described by modern tidal constants.

With regard to the recorded times of high water, Figure 8 shows the ‘minutes’ values of the hours and minutes. The vast majority of the timings have been rounded into units of five minutes.

The rounding of the heights and times implies uncertainties in measurement from this effect alone of the order of 1-2 inches and 3 minutes respectively, assuming that each direction of rounding is equally likely.

3.3 Royal Society Records

(i) The Royal Society possesses a handwritten page, enclosed within archives numbered MA331-333, which was sent to Lubbock in 1835 by Jesse Hartley. The page includes a statement of the levels of mean spring and neap high waters above datum (ODS) for the years 1816 and 1819-21 i.e. two values, each averaged over the four years. Values for spring and neap low waters are given averaged over only 1819-21. Included with the page are interesting tables of the heights of the sills and areas of each Liverpool dock. The page does not state who actually made the measurements in this period, which was before Hartley’s appointment. However, it is approximately the same time as the survey of the Mersey by Francis Giles.

Ideally, it would be useful to average the high water spring (MHWS) and neap (MHWN) values to provide an estimate of mean high water for the period. There are three problems associated with such a computation. First, it is not clear how the observers at the time defined MHWS(N); there are alternative definitions. Second, any estimate of MHWS(N) will necessarily be based only on the tides around springs and neaps, which are a small subset of the full 700-odd high tides per year. Third, the average of MHWS and MHWN will usually be smaller than MHW owing to the way that the different harmonic constituents combine and to shallow water effects.

In spite of these reservations, we describe in Section 4.5 how an estimate of MHW for 1816-21 has been derived from these records.

(ii) Archive MA331-333 also contains tables of measured heights and predicted times (i.e. predicted from the tide tables then in use) of high waters, together with meteorological data (wind direction, air pressure and temperature and general remarks), at Prince’s, Salthouse and Queen’s Half Tide Dock (QHTD) in the north, centre and south respectively from July 1827 to August 1835. These were also sent to Lubbock by Hartley in 1835. We have computerised all the high waters for Salthouse together with a month at the beginning and end of the records for the other two docks.

The datums of the high water measurements were not explicitly noted. However, from analysis of the data from all three sites, it is clear that measurements must have been made with respect to the sills of the individual docks. These are known both from the information in (i) and from tables in R-N (1984). Fortunately, the question as to whether the Salthouse data were measured with respect to the ODS or to Salthouse’s own sill is not a major one, Salthouse’s sill being only 1 inch lower than that of the Old Dock. Measurements at Salthouse are known to have continued beyond this period. For example, Lubbock (1837) refers to data from May 1836. However, the records have not survived.

At some point, someone has written ‘Brunswick?’ alongside the ‘Queen’s Half Tide Dock’ on the header page to the tables. This query is understandable as the QHTD, as formally named, did not exist until 1852. However, Queen's did have an entrance dry basin which was later converted into the QHTD, and we believe this is just a case of incorrect terminology. Moreover, a map enclosed with the records, and signed by Hartley, shows where the measurements were made: the southern site was the Queen's entrance basin.

(iii) Lieutenant (later Admiral) Henry Mangles Denham spent seven years from 1833 in undertaking the most comprehensive survey to date of the Mersey and its approaches (Denham, 1835; Mountfield, 1953; R-N, 1984). He was elected Fellow of the Royal Society in 1839. During March-October 1834, he made tidal recordings with what must have been one of the first self-registering gauges. Lubbock and others had been encouraging the development of such automatic recording for several years, and self-registering gauges similar in principle to one described by Palmer (1831) had already been constructed by various designers and installed at Sheerness, Bristol and other locations (Cartwright, 1999).

Denham was able to record values of sea level every half hour, on the hour and half hour, together with measurements of the times and heights of high and low waters and of half-tide level. In addition, he noted the time of the turn of the tidal stream and a set of meteorological parameters including wind speed and direction, air pressure and temperature, and gave a general statement of weather conditions. The data were entered into a fine leather-bound book and presented to Lubbock (Royal Society Archive MA156). Lubbock himself appears not to have made use of them, although a subset was used by Whewell (1840).

The half-hourly sea level data have been entered into computer files and analysed. They appear to be of good quality, as discussed further below, except for a period spanning 10-23 June when there was a 'tape slipping'. [25]

Denham did not record in the leather-bound book either the exact location of the measurements, their datum or the time zone used. For a professional hydrographer, these are serious omissions, if we adopt the standards of criticism that Lubbock used for Hutchinson. From Denham (1840) one gathers that the location was the Rock Lighthouse, New Brighton [26] and that the datum was 'low water level of equinoctial spring tides'. [27] Tidal analysis has shown that the time zone used

[25] My colleague Ian Vassie has pointed out that this may refer to a slippage of the tape, or wire to which the float and counterweight are connected, around the driver wheel of the chart recorder of the tide gauge.

[26] For a history of Fort Perch Rock and its lighthouse, see McCarron (1991).

[27] Denham (1840) includes an account of his presentation to Section C of the BAAS in 1837 only part of which is included in Denham (1837).

must have been local ‘mean time’ (Section 4.2).

Denham had a theory, implied in the book presented to Lubbock and as he described at the Dublin meeting of the BAAS (Denham, 1835), that the tidal curve went through the same mid-tide point each cycle, as did other researchers in the 1830s (e.g. William Walker at Plymouth, see Deacon, 1971). This theory, although of course approximately correct and important for ‘mean sea level’ datum transfer, was later selected for special criticism by Shoolbred (1875).

(iv) Archives MA193-194 include Dessiou’s reworkings of part of Hutchinson’s data referred to above. Letters from Whewell to Lubbock, also kept at the Royal Society, document their tussle to borrow Hutchinson’s records from the Liverpool Library for Dessiou to analyse.

3.4 Ordnance Survey Measurements 1844

Tide pole measurements at the entrance to Victoria Dock (approximately 1 mile down-river from Prince’s) were made every five minutes for one hour periods around high and low waters for 10 days in March 1844 by the Ordnance Survey (OS), in order to define Ordnance Datum Liverpool (ODL) at approximate mean sea level (Close, 1922). This followed the OS’s decision, as a result of Airy’s analysis of tidal observations around Ireland in 1842, to adopt mean sea level as the datum plane to which all heights shown on OS maps of Great Britain should be referred. The ODL datum is not commemorated in one special benchmark, although heights of several ancillary marks in the area are known in terms of ODL.

A mark labelled ‘Ordnance Trigl. Survey’ at Victoria Dock entrance was employed in the 1844 measurements and would be of historical interest if found. However, that entrance to Victoria was later closed and redeveloped and, more recently, Victoria itself has been filled in. [28]

Close (1922) states that levelling from Victoria Dock to the George’s gauge established that the tide gauge zero, which the operators considered as being the ODS, was 4.670 feet below ODL. This levelling must have been performed after 1853 when the gauge was installed. The significance of this result is discussed further in Sections 4.4 and 4.5.

ODL is no longer used as a national datum, having been replaced by ‘Ordnance Datum Newlyn’ (ODN), which is defined in terms of sea level measured at Newlyn in Cornwall during 1915-21 (Close, 1922; Pugh, 1987).

3.5 MDHB Records from George’s and Prince’s Piers

[28] It is just possible that the mark survives on the river side of the river wall; it was said to be ‘5.20 feet below the coping at the old entrance to Victoria Dock from the River Mersey’. However, a search by boat in May 1998 failed to find it. No mark survives on the landward side of the old entrance.

The gauge at George's Pier was installed in 1853 and began operations in mid-January 1854. It made use of the floatation of the landing stage rather than of a conventional float in a stilling well, and provided one of the earliest long records in the UK of sea level variations throughout the complete tidal cycle (Lord, 1855; Parks, 1857). [29] The gauge itself was a chart recorder manufactured by Newman (Anon, 1860) driven by a 'chain' to the landing stage. A similar system was installed at almost the same time at Hilbre Island, in the mouth of the estuary of the River Dee, using the same tide gauge hardware but with a conventional float arrangement. [30] Sea level, measured relative to the ODS, was noted every 15 minutes and was recorded in red notebooks. The books for 1857 onwards are now kept in the POL tidal archive. From these records, values of annual mean sea level have been computed (Spencer and Woodworth, 1993), along with mean tidal range (Woodworth et al., 1991) and mean high waters for this analysis. However, the 15 minute values themselves spanning half a century remain uncomputerised.

The use of the landing stage as a tide gauge must imply that the measurements were fairly crude, although subsets of data analysed in the last century did provide acceptable tidal information (Roberts, 1871; Thomson, 1876). In particular, the stage was liable to ground at low spring tides, resulting in the loss of low water data (see below). In addition, loading of the stage in the early years clearly affected its effective datum and introduced considerable variability into the time series (Roberts, 1871). The 15 minute values were not recorded after 1903, although high and low waters were noted in separate ledgers until 1912.

The transfer of the gauge to Prince's Pier in the 1920s until the closure of Prince's in 1984 is a period with many gaps in the record. We know that the gauge was now a conventional stilling well with a Bailey recorder up to July 1957, a Kent gauge from December 1957 to January 1984, and a Legé gauge from October 1956 to December 1974. The available notes suggest that there may have been two wells as there is an overlap of some records but this is not clear. The MDHB appears not to have been good at keeping documentation during these years, and many charts and associated information were lost in the bombing of the second world war. Until this analysis, the longest subset of surviving Prince's data in the form of hourly (or similar) values of sea level spanned the last two decades of operations from 1963 onwards. These data were archived by the

[29] This installation took place while Lt.William Lord was Marine Surveyor. Lord also devised an efficient vocabulary for the semaphore telegraph between Liverpool and Holyhead (Large, 1998).

[30] Hilbre was evidently established as 'open ocean' gauge by the MDHB, and also no doubt for surveying purposes along the Wirral coast. It is of historical instrumental interest with a siphon water conduit to the open sea (Thomson, 1876). A float gauge with electronic potentiometer readout is still operated there as part of the local port network.

British Oceanographic Data Centre (BODC).

In the course of this analysis, we have discovered 11 further years of Prince's data in the form of hand-written tabulations of hourly sea levels. The tables contain numerous comments in the handwriting of A.T.Doodson, former Director of Bidston Observatory (POL), and were used to compute tidal constants. [31] These tables have been computerised, and from them we have computed mean high waters. In addition, we have found additional ledgers of high and low waters for the period 1941-70 which have also been computerised for the years for which we did not already possess hourly values (Table 1). It is unlikely that further Prince's data will be discovered.

After 1984, the Prince's Pier area, including the Baggage Rooms in which the gauge was installed, was abandoned by the MDHB and became derelict. Since 1991, an 'A Class' bubbler tide gauge has been operated at Gladstone Dock by POL as part of the UK national network.

It is important to realise that many tide gauges were operated by the MDHB at various times in different parts of the River Mersey and surrounding area. The POL chart archive can provide a partial list for anyone interested. The conventional float gauge installed at Hilbre Island at the same time as the George's Pier landing stage gauge is a special example. Most of the early Hilbre Island records are now stored in the POL chart archive and could provide the basis for further study; none of them have so far been transferred into computer form. [32] A gauge was operated at Alfred Dock, Birkenhead from at least 1935 with MSL data available for 1955-1991. Many other gauges were installed for short periods for river engineering purposes or for legal (e.g. high water mark) considerations.

4. Scientific Analyses of the Data Sets

4.1 Annual Mean High Waters from the Hutchinson Data

Figure 9 shows the annual mean values of high water (MHW) from Hutchinson's data. The data set is virtually complete from the start of 1768 to August 1793, and no further special data selection criteria have been required.

The MHW values exhibit a nodal (18.6 years) variation with an amplitude of approximately 10 cm consistent with later data, and with maximum and minimum MHW years consistent with Equilibrium Tide expectations of 1773.8, 1783.1 and 1792.4. A perfect cycle with 18.6 years period cannot be expected from real MHW values, as, like values of MSL, they vary from year to year depending on variations in meteorological and oceanographic forcings e.g. interannual

[31] In 1931, Doodson published averaged tidal constants for Liverpool using the seven years of data between 1857-69 reported by Thomson (1876) together with data from 1918, 20, 22 and 24 in the International Hydrographic Bureau, Special Publication No.26, sheet 12.

[32] Thomson (1876) and Baird and Darwin (1885) contain harmonic constants from 1858-67 from the Hilbre Island gauge (then written 'Helbre') which demonstrate that the leading tidal constituents are very similar to those of Liverpool, but that the shallow-water terms are significantly smaller.

storm surge activity and interdecadal steric variations in the adjacent North Atlantic.

One concludes from this important initial inspection that the height information at least in the Hutchinson data set has the time dependence one would expect, and that the MHW values can probably be combined with confidence with later data as long as the datum information in the different data sets is adequate. MHW changes since Hutchinson's era to the present are discussed in Section 4.5.

4.2 Hutchinson's Times of High Water: What Clock Did He Use?

In an attempt to determine the exact form of 'solar time' employed by Hutchinson, we have first made use of his data alone, by comparing his recorded times of high water to those predicted on the basis of observations of more recent measurements of the tide at Liverpool. Tidal prediction software of the POL Applications Group was used, together with an accurate set of tidal constants for Prince's computed by Amin (1982). This software provides predictions in Greenwich Mean Time (GMT).

Figure 10 (a) shows the difference between Hutchinson (H) and predicted (P) times of high water for 1777; data for each year studied have similar characteristics. The difference has a spread of +/- 20 minutes, which was initially disappointing as it could have implied that Hutchinson's accuracy of measurement of high water times was poor. The tide at Liverpool is so large, compared to normal surge magnitude, that the times of the real high waters should not usually differ from predictions by more than about 10 minutes. This can be demonstrated using a year of recent data from Prince's (Figure 11) wherein both the data and the predictions are measured in GMT.

A partial solution is obtained when the H-P difference is plotted throughout the year as shown in Figure 10 (b). This can be seen to have the same shape as the 'Equation of Time', the variation of the time of noon through the year from the 'mean noon' owing to the small eccentricity of the Earth's orbit. A similar curve would be obtained if at every noon the difference between the time recorded on a sun dial situated on the Meridian and that from the Greenwich time signal was plotted.

If one corrects Hutchinson's data for the 'Equation of Time', one obtains Figures 12 (a,b). The difference now has a spread of +/- 10 minutes, similar to that of the Prince's data, and no remaining seasonal dependence. A systematic time difference of approximately 4.5 minutes remains in the data for 1777: differences of 3.9, 6.0, 4.8, 4.5, 4.0, 5.6 and 6.9 minutes are obtained for 1768, 69, 72, 82, 87 and 92 respectively.

It is tempting to leap to a conclusion that these mean differences cannot be considered significantly different from zero because:

(i) Hutchinson's times were anyway rounded in units of 5 minutes. Consequently, if he tended to round his times upwards always, one might expect a systematic H-P offset of around 2.5 minutes from this effect alone,

and (ii) in 5 minutes at high water the water level changes only by a few millimetres and Hutchinson would not have been able to detect such changes by visual methods. Moreover, as we do not know whether he used a 'quadratic interpolation method' or whether his data would have contained a possible bias towards recording later times as he waited for the tidal curve to 'turn over', a further discussion of possible differences from zero would appear to be a rather esoteric one.

Therefore, one might argue that, if the Liverpool tides have not undergone significant change since the late eighteenth century and the present, then Hutchinson's clock must have recorded some approximation of GMT but without the 'equation of time' correction.

However, this interpretation of the data is not plausible. It is clear that Hutchinson must have had some kind of mechanical clock so that he could record the night-time tides. In addition, it was common practice to regularly calibrate clocks with the use of a sun dial or, more precisely, with a small transit telescope (Stott and Hughes, 1987). [33] That would have introduced the 'equation of time' effect into his data. However, is it likely that he would then have applied a 12 minute correction to his times in order to adjust from Liverpool to Greenwich time zones (Liverpool's longitude being 3 degrees west), leaving his recorded times in an 'apparent but with a mean adjustment to Greenwich' system?

This seems most unlikely. However, there is alternative deduction which is much more attractive. This stems from the fact that during the last two centuries large morphological changes took place in the River Mersey and Liverpool Bay. These included the dredging of the Mersey Bar, the construction of deep water navigation channels, and the canalisation of the river banks (Section 4.3). These changes could have resulted in high tides occurring earlier now than during the eighteenth century as obstructions to the tidal flow were removed.

This second interpretation, therefore, would suggest that Hutchinson recorded simply in (local) apparent solar time as was the practice in England until approximately 1792 when 'mean time' (but still local mean time) became established (Howse, 1980). Hutchinson (1777) makes clear that, as a former mariner, he certainly had the fullest appreciation of the importance of Greenwich to the determination of longitude, using either lunar distances or the 'new' method of reference of local time (noon) to the Greenwich time kept by ships' chronometers. However, on land, Hutchinson would almost certainly have used the same local time as everyone else.

The 5 minute mean difference of Figures 12 (a,b) would correspond then to a mean difference of 17 (= 5 + 12) minutes if both the measurements and the predictions are to be considered in GMT. Consequently, the ocean tide would have arrived approximately 17 minutes later (or about 8.5 degrees of semi-diurnal phase) during Hutchinson's era than today.

Copies of Holden's tide prediction tables support this conclusion. In the preface of the 1773 edition (reproduced in Hutchinson, 1777) through to at least the 1805 edition, all of which were derived from Hutchinson's first set of measurements, one reads "... If any person shall think proper to compare this table with his own observations, he ought always to set his watch right, immediately before, by some good sun-dial; for these observations are made according to solar time...". In other words, the Holden predictions for the times of high water were still in 1805 referred to (local) apparent solar time and not to local (and certainly not Greenwich) mean time.

This second scenario is far more plausible than the first. However, one might still enquire that, if

[33] The transit telescope was used to record meridian passages of the Sun or stars to a few seconds precision. Such an instrument was used as a time base for the historic tide records at Brest, 1711-15 (Cartwright, 1972a,b) and was used at all major ports to set ships' chronometers.

the tides had changed their character so much as to cause significant changes in the times of high water between the late 1700s and now, how could it be that as good agreement should be obtained between Hutchinson's times and modern predictions in Figure 12 (typically +/- 10 minutes) as between modern data and modern predictions in Figure 11? Surely, one might have expected a larger standard deviation of the time difference in Figure 12 (a), aside from consideration of any mean offset?

An answer to this question has been obtained with the use of tidal prediction software based on the Amin (1982) set of tidal constants. This set provides the amplitudes and phase lags of over 100 diurnal, semi-diurnal, long period and shallow water tidal constituents. However, it happens that at Liverpool, the semi-diurnal tides are so predominant that the times of high water can be predicted from only the 10 largest semi-diurnal constituents to within 3.5 minutes (standard deviation) of the times predicted from the complete set. (Of course, for high water tidal elevations the full set is required).

Any modifications to the morphology of Liverpool Bay which result in changes to the 'tidal admittance' of the dominant M2 constituent can be assumed to result in corresponding changes to the admittances across the relatively narrow semi-diurnal frequency band, including those of the 10 major semi-diurnal terms. This will result in approximately uniform changes in phase lag across the band, and the prediction software has been used to demonstrate that such a uniform change of phase lag will result effectively in a straightforward shift of the time of high waters.

Therefore, to attempt a final answer to Lubbock (1835), Hutchinson's 'solar time' was certainly (local) apparent solar time. [34]

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[34] However, by the time his paper was published Lubbock would have been in no doubt that the 'solar time' was 'apparent'. The Royal Society contains an extensive collection of letters received by him around 1835, including those from Thomas Bywater (a tidalist with special interest in diurnal inequality), David Wylie (see previous footnote) and Jos.Brooks Yates (in whose special care Hutchinson's records were placed by the Liverpool Library) who all insisted that Hutchinson used apparent solar time. Amongst other points, Bywater stressed that '... if he [Hutchinson] had meant mean time, he would not have admitted into his own work [the Treatises] Mr.Holden's explanations that solar time meant sun dial time...". Wylie commented on the good quality sun dials in St.Nicholas's church yard and at the bottom of Pool Lane, adjacent

4.3 Tidal Changes from Hutchinson to the Present

In order to consider the tidal changes which have taken place at Liverpool since Hutchinson's era, we first consider the relatively small changes between the mid-nineteenth and twentieth centuries. These have been studied previously by several authors. We then consider the evidence from the earlier nineteenth century provided by the newly-computerised Denham data set. Finally, we return to an analysis of Hutchinson's data studied in combination with the later information. The main points to be considered are the changes in the arrival times of high waters, and in the tidal amplitudes.

George's and Prince's Data

Figure 13 shows a plot of long term change in annual Mean Tidal Range (MTR), which is equal to Mean High Water (MHW) minus Mean Low Water (MLW), derived from the George's and Prince's data sets. This plot extends that presented in Figure 2(i) of Woodworth et al. (1991) by means of the extra information acquired in the course of the present research. However, in spite of the greater amount of data (59 years rather than 36) the observed long term trend in MTR over the period 1858-1983 is almost the same (1.27 +/- 0.18 compared to 1.30 +/- 0.18 mm/year obtained previously).

The extra data has to some extent removed a major concern of the 1991 analysis with reaching a definite conclusion of an increasing MTR. The concern was that a possibility existed of a small systematic difference in tides measured at the two sites which, although close, had different tide gauge equipment. Even though increasing MTR was evident in the George's data alone, the absence of a complete set of annual MTR values from Prince's in the first half of the twentieth century reduced confidence in the validity of the MTR trend estimate. The extra data, although patchy, from the first half and middle of the century has removed that concern somewhat.

However, a second concern remains, which stems from the fact that, while the MHW record from George's was largely complete, many years of MLW were not, owing to the landing stage grounding at low spring tides. Even in the years accepted for the investigation, the number of acceptable high waters in the year usually exceeded the number of low waters, thereby introducing a possible under-estimate of MTR in the first part of the record.

These objections aside, the observed long term trend in MTR over the period 1858-1983 of 1.3

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to the Old Dock. Yates claimed to have consulted Hutchinson's surviving relations (a nephew and niece who lived with him) who told him that Hutchinson's house had "... an excellent sun dial of large dimensions [by] which minutes (and they add seconds) could be read ...". A good sun dial could certainly read to minutes but clearly not to seconds. I am very grateful to Michael Reidy (University of Minnesota) for referring me to this section of the Lubbock correspondence.

mm/year was considered to be probably correct by Woodworth et al. (1991), and certainly to be 'large' compared to MTR trends observed elsewhere in the UK. MTR is determined largely by the amplitude of M2 (the main lunar semidiurnal tide) times 2, although there are also small contributions from all tidal components (Doodson and Warburg, 1941; Woodworth et al., 1991). If MTR is increasing, then the amplitude of M2 must also be increasing.

The fact that the George's Pier 15 minute values have not so far been computerised has hindered a complete tidal analysis of the data. However, subsets of the data were investigated during the last century as part of the BAAS studies of tides. The 1871 BAAS report (Roberts, 1871) contains one-year analyses for seven years between 1857 and 1870, which were summarised in the 1876 report (Thomson, 1876), yielding an average amplitude for M2 of 10.0259 feet (305.6 cm) and for S2 of 3.1605 feet (96.3 cm). These calculations were made by Edward Roberts of the 'Nautical Almanac' Office and almost certainly were not corrected for nodal effects, as can be inferred from the table on page 202 of the 1871 report. The data were reanalysed by Baird and Darwin (1885), who certainly took nodal terms into account, obtaining similar average amplitudes (9.975 and 3.161 feet, or 304.0 and 96.4 cm, for M2 and S2 respectively) with average Greenwich phase lags of 326.7 and 11.7 degrees respectively (Table 2). These two analyses suggest that M2 amplitudes in the latter half of the last century were approximately 6.5 - 8.1 cm (order 2-2.5 percent) smaller than those of today, consistent with the change in MTR between the George's and Prince's data sets (13 cm/century) observed in Figure 13. In addition, at face value, the main semi-diurnal phase lags appear to have been about 3 degrees larger in the last century than today (Table 2), implying that high tides would have arrived about 6 minutes later.

Later, the 1904 BAAS report (Shoolbred, 1904) listed values for M2 and S2 during 1902 of 10.091 and 3.188 feet (307.6 and 97.2 cm) respectively. These values were also computed by Roberts and, therefore, may not have been corrected for nodal terms, although Roberts was a keen follower of Darwin's (1883) tidal procedures and his methods would probably have been updated by this time. However, the Shoolbred publication is not clear on this point. This study of one year of data was undertaken to see if tidal amplitudes had increased significantly since the dredging of the Mersey bar had begun. The conclusion was that the amplitudes had not increased.

Denham Data from 1834

An even earlier estimate of the ocean tide at Liverpool can be obtained from the six months of half hourly data obtained by Denham in 1834. These have been computerised and tidally analysed. Although it would have been preferable to have had several years of data at our disposal, these six months, if one has to have only six months, are ideal for the following reasons.

First, a tidal analysis of a limited amount of data, such as 6 months, has to assume a form for the nodal variations of the lunar components, and these are usually based upon the characteristics of the Equilibrium Tide (Doodson and Warburg, 1941; Pugh, 1987). However, at many ports, the amplitude of the nodal variations departs significantly from its equilibrium value. This is the case for M2 at Liverpool, for which the amplitude of its nodal variation is nearer 3 percent than the 3.7 percent in the Equilibrium Tide owing to non-linear frictional effects (Amin, 1985; Woodworth et al., 1991). Fortunately, 1834 is near to a mid-point of the nodal cycle.

Consequently, this complicating factor is not important.

Second, the amplitude of M2 is observed to vary through the year at many ports around the UK (Pugh and Vassie, 1976; Amin, 1985). At Liverpool, the amplitude of M2 varies by approximately by 1 percent and is a maximum in mid-May (Amin, 1985; Woodworth et al., 1991). This is an average statement, as the seasonal dependence may vary from year to year. Nevertheless, if one has to choose a limited period of approximately six months, then mid-March to mid-October, spanning approximately the periods of maximum to minimum amplitude, is better than other possible choices.

Table 2 lists the amplitudes and phase lags of the main tidal constituents determined from Denham's data alongside recent values from Gladstone Dock; we believe Denham made his measurements at New Brighton, which is at the mouth of the Mersey on the west bank opposite to Gladstone Dock. The two sets are shown separately to those of Baird and Darwin (1885) and Amin (1985) which are from George's and Prince's Piers respectively, both near to the Liverpool Pier Head approximately 3 miles upstream of the mouth.

The first point to note is that the MSL (Z0) of the Denham data is computed to be 16.251 feet. (Z0 values from the other data sets are not relevant to this discussion). This MSL value would correspond to a Mean Tide Level (MTL) of 16 feet 5 inches above datum, after small corrections are applied for shallow water tidal effects at Liverpool. From a map opposite page 135 of Denham (1840), one reads that his working datum was not ODS or LBD but his definition of 'Low Water of Equinoctial Spring Tides', and that 'half tide level' was 16 feet 6 inches above that datum. Therefore, our MTL is consistent with his stated 'half tide level' value. His choice of datum can also be seen to lie, as might be anticipated, between what is now defined to be 'Mean Low Water Springs' (MLWS), which is approximately 13.8 feet (4.2 m) below MSL, and 'Lowest Astronomical Tide' (LAT), which is approximately 17.1 feet (5.2 m) below MSL. Consequently, it is clear that we have interpreted Denham's data set in essentially the same way that he did himself. Unfortunately, however, as he did not document precisely his working datum in terms of surviving nearby benchmarks on land, or even in terms of the ODS datum transferred from Liverpool, the MSL of the data set has little value for surveyors or with regard to the study of secular sea level changes.

The second point to be noted in Table 2 is that the amplitudes of most of Denham's constituents, including that of the major semi-diurnal tide (M2), are systematically lower than those obtained recently from Gladstone Dock. In the case of M2, the amplitude is 3.5 percent smaller. The question arises, therefore, as to whether Denham's gauge might have had some kind of systematic scale error.

This question can be tested by making use of the Royal Society data set of high waters obtained from Salthouse Dock which includes data from 1834, and by comparing these values to high waters derived from the half hourly values of sea level from Denham's gauge. As the range of high waters is similar to the amplitude of M2 (approximately 3 m), a comparison of high waters measured at the two sites should infer how well Denham could measure M2.

Figure 14 shows that the two sets of high water values are highly correlated, with the solid line demonstrating what would be a proportionality (Salthouse/Denham) of exactly 1.0. A linear regression fit between them, using the Denham data as the independent variable, determines a slope of 1.012 +/- 0.007. In fact, one might have anticipated a value around 1.026, which is the ratio of the amplitudes of M2 at Prince's and Gladstone, Prince's Pier being at almost the same location as Salthouse Dock and Gladstone being adjacent to New Brighton. Therefore, the available evidence suggests that Denham's gauge if anything recorded slightly larger amplitudes than one would have expected. Overall, one can infer a possible scale factor between the two data sets of order 1 percent. From that, one can conclude that the amplitudes of the Denham data set are also accurate to about 1 percent, and that a change in amplitudes of order 3.5 percent between his epoch and the present has taken place (and possibly a slightly larger change if Denham's gauge did indeed measure slightly larger amplitudes than expected).

The third point from Table 2 concerns a comparison of the phase lags obtained from the Denham and recent Gladstone Dock analyses. However, it is important first to consider whether Denham made use of Liverpool or Greenwich mean times. There is no doubt that he used some kind of mean time as the 'time' columns in his tables are clearly labelled 'Mean Time' and as his data demonstrate no 'equation of time' effect as Hutchinson's did.

All experts consulted are of the opinion that 'Mean Time' in this period should almost certainly be interpreted as local mean time. The use of local mean time was now standard throughout the country and it was to be some years before GMT came to be commonly used (Howse, 1980). In 1845, the newly established Liverpool Observatory (the predecessor of Bidston Observatory) installed a time ball at Waterloo Dock to enable ships' chronometers to be set to a good approximation of GMT. GMT was introduced by the North Western Railway at their Liverpool and Manchester termini in 1846, and in 1856 Liverpool was one of the first locations at which precise time signals were received by electric telegraph from Greenwich. However, these developments considerably post-date the Denham measurements.

To attempt to resolve completely the mean time ambiguity, we attempted once again to compare Denham's data to those provided by Hartley from Salthouse Dock, with the assumption that, even if Denham had been 'progressive' enough to record in GMT, the dockyard would almost certainly have used local mean time. Unfortunately, a major difficulty with performing this comparison arose from the discovery of a letter written by Hartley to Lubbock at the Royal Society dated 19 September 1835, in which he pointed out that of the three sets of measurements at Liverpool in this period, Salthouse indeed "... will be most correct because the gauge is in still water ...". However, while the high water levels in the tables are as observed, the high water times were taken from the common tide tables then in use as the recording of times, in addition to heights and meteorological parameters, would have been too much for the Dockmasters. A subsequent letter of 30 November 1835 shows that for about 2 months from 12 October onwards, Hartley did ask observers to record real high water times, but these records have not survived. Hartley's reaction to Lubbock's disappointment at not having real times to analyse was that "... if the time of high waters happens to be before or after the time in the common tide tables such has not been noticed (allow a heavy gale will make +/- 10 minutes either way) ...". Consequently, for the present analysis, all one can do is assume that Hartley was correct, and that the predicted times from the tide tables were, on average, a reasonable representation of the real times of high water measured in local mean time. [35]

[35] By 1826 the Holden's tables provided an 'equation of time' column for ready adjustment of 'solar time' (i.e. apparent solar time) into 'mean time' (i.e. local Liverpool mean time) although the predicted times of high water were still tabulated in 'solar time'. The 1834

Inspection of the times of high waters from the two data sets for April-October 1834 gives a Salthouse minus Denham median time difference of 2.4 minutes with spring-neap fluctuations of +/- 10 minutes, presumably as a result of the errors in the tide table predictions. If one ignores those fluctuations and considers only the median time difference, one has next to recall that New Brighton (Denham) is 'upstream' of Salthouse with regard to the incoming tide. From modern measurements, we know that there is an M2 phase lag difference of 2.3 degrees between Gladstone and Prince's (Table 2), indicating that the high waters arrive at Liverpool itself 4.6 minutes later than at the river mouth. If the tide table predictions were in local mean time and Denham measured in GMT, one would have expected an average (S-D) difference of 4.6 - 12 = -7.4 minutes. Therefore, subject to the several major assumptions discussed above, one can conclude that the Denham measured and Salthouse predicted times used the same time system, and that Denham is more likely to have recorded in Liverpool and not Greenwich mean time.

Denham's M2 phase lag, assumed to be defined now with respect to local mean time, can be seen to be 0.55 degrees larger than that for recent Gladstone Dock, defined with respect to GMT. Consequently, the tide in 1834 must have arrived approximately 2 x 0.55 + 12 = 13 minutes later than today, roughly mid-way between the timings of the Hutchinson and current eras but closer to Hutchinson's. (A similar calculation based on the use of Prince's tidal constants rather than Gladstone's leads to the same conclusion). Some of Denham's smaller constituents have phase lags significantly different to those of the more recent data, even with allowance for the timing differences. However, instrumental errors, which contribute particularly to the higher tidal harmonics, might be expected to play a part in the early measurements.

In summary, the Denham data are consistent with an increasing lag in the arrival of high waters the further back in time we look, varying from 6 minutes from the Baird and Darwin data, to 13 minutes from Denham's to 17 minutes from Hutchinson's. However, it can be seen that these findings are dependent critically upon the validity of our assumptions on the form of 'time' used in the historical tidal data.

Poor Man's Tidal Analyses of Hutchinson, Salthouse and Denham High Water Data

For a complete tidal analysis, one requires hourly or similarly sampled sea level data, rather than high and low waters, or just high waters alone. If both highs and lows are available, then a form of harmonic analysis can be performed (Darwin, 1890; Doodson, 1951; Amin, 1977). However, if only highs are known, as is the case for the Hutchinson and Salthouse data sets, then only a

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Salthouse predicted times in Hartley's data set could, therefore, have been in either local form of time; we do not have a copy of Holden's tables for 1834 to check directly. However, the absence of any 'equation of time' signal in the S-D time differences and the knowledge that Denham's data were themselves in 'mean time' infers that Hartley's Salthouse tabulations also employed local Liverpool mean time.

coarse investigation can be attempted.

We have constructed two *ad hoc* methods for testing for changes in tidal amplitudes, one of which makes use of both the high water height and time information, and the other of which uses just the heights. Both methods examine the modulation of high water levels through the year, including the spring-neap cycle caused by the combination of M2 and S2, and the tendency for the semi-diurnal tide to be larger at the equinoxes. Consequently, they each test primarily the magnitude of the S2, N2, K2, MA2/MB2 and other tidal components (Pugh, 1987). However, if one assumes that the 'admittance curves' of the tidal bands do not change shape significantly with time (i.e. if one assumes that, if S2 experiences a lower amplitude and/or a change of phase lag, then M2 will experience corresponding changes), then variations in these modulations can be inferred to be similar to those in M2 itself, which, as explained above, determines the variations in Mean Tidal Range.

In the first method, we have made use of predictions for the heights and times of high water for the Hutchinson and Denham eras based on tidal constants from Prince's Pier. In addition, we have also made use of Prince's real and predicted high water values for 1967 to use as a control. The year 1967 was chosen as that is in the middle of the period 1963-71 over which the constants were computed (Amin, 1982). Figures 15 (a-c) show the differences for each high tide of predicted minus recorded high water level plotted as a function of predicted level. If tidal amplitudes for any epoch studied were generally larger (smaller) than during the Prince's period, then one would expect there to be a trend in the distribution, with a negative (positive) slope, as the difference between predictions and measurements would simply be proportional to the tidal signal.

From the control for 1967 in Figure 15 (a), one can see that the distribution is essentially flat (slope of -0.010 +/- 0.009), as is to be expected, with the predictions on average reproducing the measured levels. However, for the Denham data in Figure 15 (b), a positive trend is apparent with a slope of 0.092 +/- 0.009, indicating that the tidal amplitudes in the Denham measurements are smaller than those of the Prince's predictions by about 9 percent. If we recall that Denham's measurements were at New Brighton rather than Prince's Pier, the Denham amplitudes can be inferred to be about 6 percent lower than those of the present day. This reduction is qualitatively consistent with, although slightly larger than, that obtained from the more sophisticated tidal analysis discussed above. Some discrepancy is to be expected in view of the simple assumptions of the method.

Hutchinson's data from 1769, which is also near to a mid-point of the nodal cycle, can be seen from Figure 15 (c) to show a similar behaviour with a slope of 0.084 +/- 0.010 obtained. Similar results are obtained from the other 6 years of Hutchinson's data for which we have both high water height and time information, although the magnitude of the slope varies considerably from year to year. Similar results are also obtained if the data are band-pass filtered to focus particularly on the fortnightly spring-neap oscillations in the measured and predicted data sets. On average, this implies that tidal amplitudes were 8 percent lower in Hutchinson's era than today.

In the second 'poor man's method', we have investigated simply the standard deviation of the distribution of high waters measured in each year. This simple method has the advantage of allowing the analysis of years of data for which we have high water levels only and not times (or for which the times are considered unreliable). If tidal amplitudes fluctuate from year to year, then we should expect the standard deviation to fluctuate similarly, apart from small variations owing to storm surge activity.

Figure 16 shows the root-mean square (rms) of high waters for each year of data in the entire Liverpool data set. Only years of data which are essentially complete can be used for this test, as data gaps (e.g. at the equinoxes) can result in significant changes to the computed rms values. The earliest points are from the Hutchinson and Salthouse measurements, which are also the most complete, and indicate similar values for rms of around 73 cm. These increase significantly between 1835 and 1860 to values of around 76 cm, and maintain that value, with some scatter, until the present day. (Several large values around 1860 can be accounted for by the variability of the loading of the landing stage at that time). Recent data from the 1990s from Gladstone show rms values a couple of percent lower than at Prince's, as might be anticipated from the smaller semi-diurnal amplitudes at that site.

Two particular features of Figure 16 can be pointed out. First, the rms values from Hutchinson's data, which show considerable variation, reflect the variations in slope obtained in the first poor man's method. Therefore, the two methods are clearly testing the same features of the tide. Second, the year 1834 (the period of Denham's data but note that the Denham data themselves are not part of the Salthouse data set) has a relatively large rms value of 76.4 cm compared to lower values for the preceding few years. Consequently, our estimate of approximately 3.5 percent lower tidal amplitudes in Denham's era than today, obtained above, may need revision to a larger percentage if it is to reflect more correctly the tidal amplitudes of the Salthouse period as a whole.

Summary of Evidence of Tidal Amplitude Changes

In spite of the small number of rigorous tidal analyses performed on the historical data sets, and, in particular, of the simplicity of the 'poor man's methods', the evidence suggests that the tidal changes observed during the middle of the last century were as large or larger than any which have taken place subsequently. We can summarise the information as follows:

(1) There is no evidence (from the second poor man's method, Figure 16) that amplitudes changed significantly between the Hutchinson and Salthouse periods.

(2) The magnitude of the reduction of amplitudes during the Hutchinson to Salthouse eras, relative to the predictions based on Prince's data, can be estimated as 3.5 precent from the tidal analysis of Denham's data (which may be an underestimate); 6 percent from the first poor man's method applied to Denham's data; approximately 8 percent from the first method applied to Hutchinson's data; and around 4 percent from the second poor man's method. There is considerable scatter in the last two estimates for individual years.

(3) The increase in amplitudes between the 1850s and the present day corresponds to that derived from change in MTR over the period (Figure 13).

From this summary, we can define a simple 'tidal amplitude history model' as:

- For the period 1768-1835, amplitudes may be assumed to have been 6 +/- 3 percent (18

+/- 9 cm) lower than those of the present day.

- For 1850 to the present, amplitudes may be assumed to have increased at a rate of 0.635 mm/year (i.e. half of the 1.27 mm/year secular trend in MTR) giving an overall increase of approximately 8 cm in this period.

This model will be used in Section 5 in order to provide correction terms to time series of observed Mean High Waters in order to derive ‘Adjusted Mean High Waters’ which will be employed as if they were ‘Proxy Mean Sea Level’.

Why Should the High Tide Now Arrive Earlier and Larger?

This is the first time to our knowledge that the evidence for tidal changes in the mid-nineteenth century has been presented quantitatively. However, there is a considerable amount of evidence that people were certainly aware of possible changes at the time. In the book ‘Liverpool in 1859’ by Baines (1859), the author compares the survey of the Mersey published in 1857 by James Walker and John B.Hartley (Jesse Hartley’s son) to that conducted in 1822 by Francis Giles. The Denham survey is not referred to. The point is made that most of the tidal flow in the approaches to the port ‘now’ runs via the Queen’s and Victoria Channels, rather than over and through the sandbanks and narrower channels of Liverpool Bay, and that the heights of the banks themselves have increased. In addition, from the Narrows to the upper estuary past Dingle Point there has been an increase of typically 7-10 feet in the depths of the navigable channels, with the result that the main tidal currents take place ‘straight and more direct’ and have increased. In addition, the area (although not necessarily the volume) of the upper estuary has increased by six percent. To understand these changes in greater detail, one has to appreciate the environment of the Mersey and some of the history of its engineering changes.

A major point is that the Mersey estuary, like most estuaries, is a complicated dynamical system in which sediment (mostly sand in this case) is constantly reworked by tidal currents and, to a lesser extent, by the fresh water inflow from the rivers. Modification to one area sooner or later affects other areas. It took many years to realise that the volume of the upper estuary affects the extent of ‘scour’ through the Narrows and the maintenance of deep water channels in the approaches. Conversely, changes to the morphology of Liverpool Bay, either naturally through variations in sediment transport along the Lancashire and North Wales coasts or from the Irish Sea, or anthropogenically through processes such as dredging, can affect the channels of the upper estuary by altering the quantity of sediment available for redistribution. Price and Kendrick (1963) describe a set of experiments using physical models of the estuary which demonstrate these interactions clearly.

The time at which serious consideration began to be given to modification of the approaches can be dated from Denham’s arrival in Liverpool in 1833 as the first Marine Surveyor, although his hydrographic survey was the sixth major one to be made of the area. A recurring subject of concern throughout Liverpool’s history has been the possibility that the routes through the approaches could seriously deteriorate and that the major investments in docks could potentially be wasted (Mountfield, 1953; McCarron, 1998). Any Liverpool resident is well aware of the history of the port of Chester and of the Dee estuary only twenty miles away to the south, and of the port of Preston and the Ribble estuary a similar distance to the north. Denham’s appointment resulted from a new wave of concern about the historical routes through the Rock and Formby

Channels. [36]

[36] It is known that as far back as 1755 and 1758 Hutchinson urged the Corporation to take steps to preserve the navigation from possible decay, as well as to develop the breeding of oysters and other forms of fishing for the town's benefit (Mountfield, 1953).

Within a year, Denham had conducted a first survey of Liverpool Bay, and discovered the 'New Channel' (Denham, 1835, 1837), becoming a freeman of the town for his efforts. [37] The New Channel followed almost the same course as the later Victoria (1846) and Queen's (1857) Channels, of which the latter defines the deep water route to the port today. However, Denham realised that any channel would need constant maintenance to keep safe for navigation, and devised a means of 'harrowing' to maintain the depth. This was eventually replaced around 1890 when Lyster's scheme for dredging the bar was introduced (Wheeler, 1893; R-N, 1984). The 'bar' is a horseshoe-shaped accumulation of sand which tends to occur at the seaward end of the deep channels. Lyster's scheme removed about 80 million tons of sand, and provided about 16 feet of additional depth over the bar for navigation. From 1909, 'training walls' were added to the Queen's Channel in an attempt to stabilise channels and maintain depth by keeping sand outside the walls on the sandbanks, 'where it belonged'. Perversely, as always, this seems to have had the effect of increasing the availability of sediment for transport to the upper estuary which has decreased in volume by 10 percent since the start of this century (Price and Kendrick, 1963).

To this set of complicated estuarine processes must be added the fact that unprecedented changes were made to both banks of the narrow part of the river at Liverpool from about 1820 onwards. A section from Baines' book from 1859 can be quoted:

"In considering the causes [for increasing tidal currents] .... it appears that in 1822, the embanked or walled side of the river on the east, or Liverpool side, was confined to the space between the south side of what is now Coburg Dock, and the north side of Prince's Basin, in length about 3000 yards, or less than two miles. This walled or embanked side now extends from the Herculaneum Estate on the south, to the middle of Bootle Bay on the north, a length of about 9700 yards, or upwards of five miles.... Over this space the tide had at that time full action. On the west, or Cheshire side, also, the water has been excluded from Wallasey Pool, and a river wall 800 yards in length has been built for the Birkenhead Docks."

These changes, engineered primarily by Jesse Hartley on the Liverpool side and by a series of other engineers on the Birkenhead side of the river (McCarron, 1998), are almost certainly responsible for the changes in tidal timings and amplitudes observed between the Hutchinson-Salthouse-Denham data sets and those from George's Pier onwards. If one simply deepens a river (by dredging, for example), one might expect low waters to become lower more so than high waters become higher. Either way, the tidal amplitudes will increase. The canalisation of the

[37] Denham's 1833 map is reproduced in Mountfield (1953), Price and Kendrick (1963) and Pugh (1987). Relations between Denham and the Dock Trustees were down-hill from this point, until he resigned in a battle over resources in January 1839 following the 'Great Storm' (see below). His election to Fellow of the Royal Society the next month must have been some compensation. He continued to publish reports based on his Liverpool data. For example, Denham (1840) summarised much of his work in the Mersey and contained 'proposals for a better port' with a permanent self-registering tide gauge and a meteorological and astronomical observatory (established under John Hartnup four years later). The Mersey Conservancy Act of 1842 was largely based on his findings. His concerns on practical matters, such as the safety of river steamers (Kavanagh, 1998), led to major local improvements. His work at Liverpool formed only the start of a distinguished naval career in which he rose to the rank of Admiral (Mountfield, 1953).

Mersey, on the other hand, might have affected high waters to a relatively greater extent, although this is difficult to prove conclusively without a detailed numerical model.

The tidal change in the middle of last century suggested by Figure 16 is larger than any fluctuations which might have accompanied the changes to the river due to the bar dredging or the training walls or the continued expansion of the docks through the nineteenth and early twentieth century. [38] As mentioned above, the BAAS tides committee (Shoolbred, 1904) found no evidence for major tidal changes since their earlier studies which might have been caused by the bar dredging. In addition, the mid-nineteenth century changes are approximately 2 or 3 times larger than those reported for the nineteenth to twentieth centuries by Woodworth et al. (1991). For these reasons, we agree with Baines' suspicions that the canalisation of the river banks, including the closure of Wallasey Pool, around 1835-55 will have caused the largest changes to the tide in the last two centuries.

4.4 Geodetic Levellings and Checks on Datum Relationships

Background

Inspection of geological maps of Merseyside (British Geological Survey, 1975) shows the underlying Permo-Triassic sandstones on both the Lancashire and Cheshire sides of the river superimposed upon which are the various 'drift' deposits. On the Liverpool side, including the dock areas and the old Pool, the surface layers are simply described as 'alluvium'. This consists of sands, silts and muds with clay grades dominant and with mud forming an important layer on the bed of the estuary. The thickness is about 1-2 m, although up to 20 m in some places. At Liverpool, these overlay the Chester Pebble Beds formation several 100 m thick. The Queensway (Birkenhead) Mersey Road Tunnel was driven through the Chester Pebble Beds formation with a buried glacial channel filled with boulder clay discovered on the Liverpool side (Ion, 1996).

Much of what is known about the near-surface three-dimensional geological structure of Liverpool is derived from enormous number of tunnels and cuttings which permeate the city (Moore, 1998). Knowledge of the area of the docks comes from the excavations for the docks themselves, and from the digging of the Mersey Tunnels and of the foundations of the buildings at the Pier Head. For example, R-N (1984) reports that the construction of Salthouse Dock was slow, being hampered by the site's deep sand and muddy gravel. In addition, when the George's and Albert Docks were constructed, considerable elm, beech and oak pilings were required in the 'quicksand' on their river sides, sandstone outcrops providing firmer foundations nearer to the shore. Baines (1852) states: "...the whole of the river wall in front [of the Albert and Canning Docks], and the piers in the double entrance from the river into the Half-Tide Basin, are on quicksand, and have been built upon 13792 piles of beech timber, the aggregate length of which would amount to over 48 miles...". The choice of Canning Island for the master ODS benchmark (Figure 3) was, therefore, rather an illogical one. More recently, Ion (1996) has described how the flooding being experienced recently in the basement of the Cunard Building, but not in the

[38] The final length of river occupied by Liverpool docks stretched to about 7 miles after the construction of the Royal Seaforth Dock in 1972.

Port of Liverpool Building next door, may be due to the latter being underlain by a higher porosity sandstone and/or by a marl band which is impeding the rise in ground water level.

These sets of evidence suggest that the area around the Old, George's and Prince's Docks is far from being geologically uniform. In addition, at least part of the area has been subject to submergence as a result of Mersey Tunnel excavations. R-N (1984) reports that the area around Manchester Dock and Chester Basin (small docks used for river traffic situated between the Canning Half-Tide Basin and the Pier Head and filled in by 1936) was 'settling dangerously' before their closure, as a result of the Mersey Tunnel (Queensway) works. [39] Therefore, it is clear that localised rates of vertical land movement could be experienced in the area, in addition to that from long-wavelength geological processes such as PGR. These differential movements may result over long periods in different determinations of level-differences between benchmarks.

Tide Gauge X

Approximately 15 m north of the south-east corner of Canning Dock, on its east wall, can be found a traditional 'tide gauge' of six inch high Latin numerals inscribed every foot into a vertical concave channel in the stone blocks of the dock wall (Figure 17). The highest level marked is XXII, which one will recall was the highest level marked on Hutchinson's gauge (i.e. the twenty-two feet and a half mark which is indicated by the top of the XXII numerals). The adjacent pavement, which slightly overlaps the concave channel, would correspond approximately to the 24 foot level, and, at first sight, one would guess that the zero level would correspond to the ODS.

By superimposing Eyes' map (Figure 4) onto those post-dating Hartley's 1829 reconstruction of Canning Dock (Figure 5 is adequate although Bennison's map of 1835 is more suitable), it is clear that the gauge is situated very close to where the centre of the riverward end of the narrow part of the entrance to the Old Dock would have been and, therefore, close to the start of the sill. This is consistent with the Ordnance Survey surveyors in 1843 having been able to readily perform levellings from the 22 foot mark on the gauge to the sill itself (Close, 1922 and see below). Eyes' map shows the gates to be close to the narrow part of the entrance, others (e.g. Okill's Plan No.3 which is reproduced by Stewart-Brown, 1930 and which is similar in almost all respects to Eyes') show the gates to be more towards the middle of the narrow passage (or 10-20 m east of the entrance). Clearly, the gates would have to have been installed over part of the sill but there is no record of the sill's horizontal dimensions.

It is intriguing to wonder if the gauge could have been the one used by Hutchinson. However, it cannot have been, or at least it cannot have been the same gauge in exactly the same position, because:

(i) as mentioned above, it seems to be located close to the centre of where the narrow fairway into the Dock would have been, although the relative positions are not known with complete

[39] This is a little surprising as the Queensway road tunnel actually passes to the north of the two docks and approximately beneath the Port of Liverpool and Cunard buildings. It is the 1886 railway tunnel which passes underneath the two docks. It is conceivable, however, that the Queensway workings also affected the adjacent area.

certainty.

(ii) the stone blocks of the gauge show evidence of having been moved. For example, the XXI numerals, which are at the bottom of a block, are approximately one inch too short, consistent with the bottom of the block having been re-trimmed at some point. (Alternatively, the block beneath, which would have contained the base of the XXI together with the XX numerals, could have been replaced at some point with one containing only XX).

and (iii) if it had been the original gauge at the Old Dock gates, it would probably have faced north or south, rather than west as it does now (Figure 4).

The most likely date for the installation of the gauge is 1829, during Hartley's extension of the east wall of Canning Dock towards Strand Street, following the closure of the Old Dock in 1826. The many changes made by Hartley to Canning in this period are listed in Hartley (1836) and, aside from deepening, Canning has remained much the same since. Certainly, the gauge existed before 1832 as the Holden's tables for that year refer to 'the Old Dock Sill, the datum of which is still preserved on the eastern wall of the Dry Dock [Canning Dock]'. Similarly, Lubbock (1837) refers to 'the datum in the east wall of the Canning Dock' which is almost certainly the same thing.

There seem to be two possibilities for the origin of 'Tide Gauge X' [40]:

(i) It is indeed Hutchinson's original Old Dock gauge but the stone blocks were repositioned by Hartley in 1829 to form part of the new Canning east wall. This suggestion would be consistent with Hutchinson's description of the Old Dock gauge and with the evident re-trimming of the block containing the XXI numerals.

(ii) It is a 'new' gauge, which had not been in use at the time of the Old Dock, and which was installed by Hartley simply to preserve the datum. The re-trimming of the XXI block tends to disfavour this explanation as any 'new' gauge on a dock wall would probably have been carved

[40] The Liverpool Central Library lost a number of important archives during the second world war including early nineteenth century oil paintings of the Old Dock entrance in the Binns Collection referred to by Peet (1930). In addition, no photographic copies of the paintings seem to have survived. These paintings may have been useful in resolving this issue. The South Docks were surveyed in great detail before renovation began in the 1980s (Moss and Stammers, 1980) with the position of every bollard, shed and railway line noted. However, tide gauges on the dock walls seem not to have interested the organisers, even one as impressive as Canning Island's. So far as we know, no-one has researched this topic already.

in situ.

Consequently, the first possibility is the most likely. Either way, by 1826 the datum of the ODS would have become an important reference for the docks. Hartley would have wanted the datum preserved adjacent to the original location of the sill, as the note in the Holden's tables for 1832 indicate. In this scenario, the datum would then have been transferred, also by Hartley, to the gauge on Canning Island in 1845.

The problem with this rather neat explanation is the fact, discussed below, that 'Tide Gauge X' indicates values of water level about half a foot lower than the Canning Island 1845 ODS gauge. This discrepancy is of considerable importance with regard to the systematic errors involved in connecting Hutchinson's time series of MHW to the later ones. As Hartley seems to have left no proper record of how 'Tide Gauge X' came to be installed where it is, or, even more surprisingly, of how the Canning Island gauge was constructed, it is probable that we shall never fully understand the histories of these two important sets of marks. [41]

Even though we have not been able to determine fully how 'Tide Gauge X' was established, it is of great importance in providing a link between the geodetic datums used at Liverpool since the middle of the nineteenth century. Close (1922) reported that in 1843, when the sill was exposed during drainage of Canning Dock as part of the development of the Albert Dock area, geodetic levellings were made by the Ordnance Survey between the bottom of the 22 foot mark on the gauge (i.e. the 22 foot level), the granite stone of the Old Dock Sill, and Ordnance Datum Liverpool (ODL). Their findings, which were not published, are reproduced in Figure 18, showing the discrepancies between the height of the stone sill itself, the height of the 22 foot level on the gauge above the sill, and what was assumed to be ODS datum at that time.

Geodetic Levelling Exercises at Liverpool

In order to understand further the relationships between the heights of various benchmarks in the area, particularly with regard to their long term stability, a new set of geodetic levellings was carried out by POL during 1996-98. Details of the exercises are given in Annex 2. At Prince's Pier, the work was just in time, as the area began to be redeveloped. In the case of the Canning Island gauge (Figure 3), an elegant new technique was devised to enable levelling to be made with the aid of an observer from a boat.

The main conclusion from the exercise is that the OS marks E and F (on the south side of the Albert Dock buildings), Tide Gauge X, and Canning Island can be inferred to have, to within centimetric accuracy, relative levels now as were obtained in the 1840s i.e. when the

[41] A letter from Jos. Brooks Yates (see previous footnote) to Lubbock dated 24 September 1835 reads "... Mr.Hutchinson's house at the Old Dock gates and the tide gauge are long since removed. The datum with the register above it are proposed to be removed to an exterior wall about half a mile to the northward, but on examining this datum the other day I find it has given away...". This could perhaps explain the half a foot discrepancy, if the dock wall containing the gauge had not been rebuilt exactly as before. The 'half a mile to the northward' would imply that it was intended to re-establish the datum in either George's or possibly Prince's docks.

measurements of ‘Tide Gauge X’ described by Close (1922) were made, and when the Canning Island ODS gauge was established. Moreover, the Canning Island ODS gauge indeed indicates levels with respect to the ODS datum, as presently understood, as it claims to do, and its relationships to ODL and ODN are as documented. These facts enable us to construct with confidence one composite Liverpool sea level record from the combined George’s and Prince’s data. From the 1840s at least, no matter what the level of the real granite sill might have been, surveyors defined the ODS datum to be as described in Figures 2 and 18 and as represented on the fine stonework of Canning Island.

A second major conclusion follows from our confirmation of the relationship of the markings of ‘Tide Gauge X’ to ODL as reported by Close (1922) and as shown in Figure 18. The markings do not show levels with respect to the ODS datum, as that datum was understood from at least the 1840s, but indicate values approximately half a foot smaller (e.g. water level at the 22 foot marker level would have been 22.48 feet above ODS as defined at Canning Island). The difference can be seen to be suspiciously close to 6 inches which would have been the height of the gauge markings themselves.

Consequently, one might ask if sea levels measured by Hutchinson’s gauge at the Old Dock entrance would have been the same as levels measured with respect to either:

(i) the ODS datum as we understand it to be from the 1840s,

or (ii) the physical ODS as observed by the Ordnance Survey in 1843 and as indicated by the granite stone in Figure 18,

or (iii) if the scale of his gauge was aligned with the upper markings on ‘Tide Gauge X’.

In case (i), we may simply include Hutchinson's high water values in our data set as if they were measured with respect to the ODS datum as understood from the 1840s.

In case (ii), we would have to add 0.22 feet (7 cm) to his recorded high water values to be consistent with the later data.

In case (iii), we would have to add 0.48 feet (15 cm) to be consistent.

In the analyses of the next Sections, we have assumed case (i) to apply. It is the simplest assumption to make in the absence of a proper understanding of the histories of ‘Tide Gauge X’ and of the Canning Island gauge. Also it is consistent with Hutchinson's statement in the ‘Treatise’ that “... the four feet and a half mark is near the half flood mark let the rise be what it will ...” (or, in other words, that MSL at that time was approximately 4.5 feet above his definition of ODS). From knowledge of long term change in MSL at Liverpool (Section 4.5), one would expect MSL during Hutchinson’s era to be slightly lower than the 4.82 feet of the 1860s (Figure 2), which was measured relative to ODS as then understood. Therefore, Hutchinson’s 4.5 feet above ODS is more plausible than 5 feet (i.e. 4.5 + 0.48) if case (iii) applied. Of course, this evidence is hardly conclusive.

Cases (ii-iii) can also be assigned lower probability than case (i) if we recall that a single capable engineer, Jesse Hartley, was Dock Engineer throughout 1824-1860 and was responsible for all works in this period, including the datum transfers. The relatively good datum transfer from the granite Old Dock Sill to Canning Island in 1845 (Figure 18) can be taken as evidence that Hartley 'knew what he was doing'; the discrepancy of 0.22 feet can be explained by Hartley's use of a different part of the sill to define the datum to that used by the Ordnance Survey in 1843. 'Tide Gauge X' can then be regarded as providing only a rough representation of levels above the ODS datum, which Hartley would have known about, the gauge numerals having been vertically offset during the Canning east wall redevelopment or at some period later. It is inconceivable that Hartley would not have been aware of the different levels shown by the two gauges.

However, it is clear that cases (ii-iii) cannot be completely ruled out from providing an estimate of the systematic error in the assumption that case (i) applies. It will be seen below that datum uncertainties of the order of 7 or 15 cm would be major considerations.

4.5 MHW and MSL Secular Trends

Figure 19 shows the values of annual MHW obtained from the data sets described in Section 3 and summarised in Table 1. The MHW values have been derived in different ways for each period of recording, as the data have allowed. The simplest method is the computerisation of tabulations of high water observations, and the computation of annual averages, from the Hutchinson, Salthouse, and part of the George's and Prince's data sets. Probably the most computationally precise method is the use of 'turning points', cubic-spline interpolations of regularly sampled (e.g. hourly) levels around each high tide in order to determine the high water level. Much of the Prince's data, and all of the Gladstone data, are in the form of hourly values of sea level, and have been analysed in this way. For most of the George's data, we have used the largest documented 15-minute value around a high tide to define the high water level. This implies a maximum 7.5 minute timing error, or 3.75 degrees phase error from the real high tide to the closest 15-minute sampling, which corresponds to a negligible change in high water (Woodworth et al., 1991). As the amplitude of the tide at Gladstone is lower than that at Liverpool itself, an additional correction of 7.9 cm, the difference in the amplitude of M2 at the two sites, has been applied so as to obtain comparable MHW values.

The point spanning 1816-21 was calculated as the average of the reported MHWS and MHWN values in Section 3.3(i) together with an additional 10 cm which accounts for the systematic difference between MHW and (MHWS+MHWN)/2 arising from contributions from all tidal constituents, but especially from S2 and N2 and other large semi-diurnals (Doodson and Warburg, 1941; Woodworth et al., 1991), and from shallow water constituents (e.g. 2SM2). The additional amount, or 'bias', was estimated in two ways, with similar results. In the first method, tidal predictions based on modern tidal constants (Amin, 1985) were used, with the assumption that the tidal regime was not significantly different in the earlier era. Two different definitions of MHWS(N) were tested: the modern way, in which the highest (lowest) high tide is selected each fortnight together with the next high tide, in order to remove diurnal effects; and the historical way (Amin, 1983), in which simply the highest (lowest) high tides are used. The two definitions yield biases differing by about 1 cm. In the second method, use was made of tables of MHW, MHWS and MHWN for 1854-56 by Parks (1857), with the assumption that Parks computed the spring and neap mean levels by the same method as for the earlier data. This is the only table we know of from that era which lists all three parameters. In spite of our confidence in the accuracy of the bias estimated in an 'average year' (10 cm), the estimate of MHW for 1816-21 is still necessarily less certain than those for other years because of the significantly smaller sampling implied in using data only from springs and neaps rather than from the complete high water record.

The MHW values display an essentially linear trend of 1.76 +/- 0.06 mm/year over the whole period with little 'acceleration' (0.16 +/- 0.11 mm/year/century). Figure 19 also shows a simple linear trend plus nodal parameterisation to guide the eye through the 'nodal noise' of the data points. The rise of MHW since Hutchinson's era has been noted before. Shoolbred (1877,1878) performed a cursory analysis using only a few years of Hutchinson's data, and without being apparently aware of nodal variations, and yet arrived at the correct conclusion that levels had risen between the late-eighteenth and late-nineteenth centuries. He also assigned the cause to increasing tidal range and to the canalisation of the river (Shoolbred, 1877). The present investigation shows that the increasing MHW has persisted into the present century.
The MHW secular trend (1.72 +/- 0.13 mm/year) for the George's-Prince's-Gladstone (GPG) era can be compared to that for MSL over a similar period presented by Woodworth et al. (1999). The MSL trend is 1.23 +/- 0.12 mm/year (Figure 20). Therefore, the MHW trend for the GPG period at least can be understood as being determined by a change in the mean level, superimposed upon which is a tidal change approximately that of the change in M2 (i.e. half of the 1.27 mm/year trend in MTR). Possible further contributing factors to the observed MHW variations throughout the entire record are discussed below.

4.6 Changes in Extreme High Waters Since Hutchinson

Annual maxima of high waters, whether originating either from the ocean tide or from individual storm surges or from several factors in combination, can be used to compute probabilities of exceedence of particular levels, or 'return periods' (Pugh, 1987). Conventional extreme level analysis uses each annual maximum only (i.e. one value per year); more sophisticated algorithms employ N-largest methods (Coles and Tawn, 1990). Both methods, but especially the former, are sensitive to incorrectly measured large values of high water contaminating the data set.

In Hutchinson's data, there are two very large values of high water: (i) 28 feet 9 inches on the evening of 8 October 1771, and (ii) 28 feet 8 inches on the evening of 27 October 1776.

In the case of (i), the entry in the records is accompanied by a note that the weather was 'mostly cloudy with some rain overflowed our dock gates' and the barometer showed 29.23 inches (990 mb) at noon. Therefore, it seems likely that the high water could have been over the 23 feet of the gates, although probably not as large as that reported. It is possible that the value could also be a badly written 22 feet 9 inches.

In the case of (ii), the weather is stated to be 'mostly cloudy above red clouds in the evening' and the barometer at noon was 30.0 inches (1016 mb). There is no ambiguity about the 28 feet 8 inches value actually written down, but, if it had been real, we might have expected an accompanying note commenting on the exceptionally high tide. The mild-sounding weather conditions, together with the fact that searches in newspapers of the period failed to discover a report of an anomalous tide, leads us to conclude that this second value is probably a simple error.

As these two values are more than five feet larger than the next largest value of 23 feet 6 inches (Figure 6), and as they would significantly distort any extreme level analysis, we have not considered them within a study of extremes during this period. Figure 21 shows the 1-largest extreme level curve computed from the Hutchinson data, compared to the results of a similar analysis of George's data for 1857-1903 and Prince's data for 1941-77 by Coles and Tawn (1990). The three can be seen to be similar apart from an offset of approximately 40 cm, which can be accounted for largely by the secular change in MHW, discussed above. One concludes that there is no evidence for a significant change in meteorological conditions ('storminess') between the different epochs which would have resulted in more frequent large high waters.

One might ask 'what is the greatest high water level recorded at Liverpool?'. This is, of course, difficult to answer with certainty because of the many gaps in the data. However, if one excludes the two large values reported in Hutchinson's data set, and confines discussion to levels of 23 feet 6 inches and above, then several occasions may be mentioned:

(i) In the page of tidal information sent by Hartley to Lubbock, described in Section 3.3(i), there is mention of an extraordinary equinoctial spring tide in April 1821 (date not given) of 23 feet above datum (assumed to be ODS). This is not so extraordinary, except that mention is also made of a level of 25 feet above datum at the Leasowe lighthouse, not necessarily for the same storm.[42] However, in view of the uncertainties in defining the water level on a lighthouse and also in transferring the ODS datum across the river to Leasowe, this might be discounted.

(ii) In the George's Pier recording there are at least two examples of 23 feet 6 inch tides, comparable to Hutchinson's maximum, exceeded by one of 23 feet 9 inches in 1863 (mentioned by Wheeler, 1893) and one of 24 feet 6 inches on 26 November 1905. The former is confirmed as not being a simple typographical error by the adjacent 15 minute values. The latter, however, is a simple tabulation without comment.

In addition, in the records of the Marine Surveyor, archived at the Merseyside Maritime Museum, there is a memo dated 13 February 1899 'on that afternoon tide rose to 24 feet above Old Dock Sill and on previous afternoon to about 23 feet 6 inches - the latter not recorded as George's gauge did not act'. There are gaps in the data for both these tides in the 15-minute ledgers.

(iii) In more recent years (to December 1996), high tides of 24 feet 1 inch, 24 feet 5 inches and 23 feet 7 inches above ODS occurred in 1976, 77 and 81 respectively. One of 24 feet 4 inches

[42] Shoolbred (1878) also refers to 'an extraordinary high tide, as marked on the Leasowe lighthouse' of 25 feet above datum (ODS) with no mention of its date. It seems that this tide might have been part of local folk-lore. The mark would have been about 20 ½ feet above ODN (Figure 2) or about 4 ½ feet above an OS benchmark (4.88 m ODN) on the north side of the present lighthouse which replaced the original 1763 light in 1824 (Brownbill, 1928), or did not replace it (Woods, 1944), depending which historian you believe. (The present lighthouse has a 1763 date stone above its entrance which Brownbill considers was taken from the original). There is no tidal mark on the present lighthouse. A likely date for high tidal flooding at the site would have been 1771 when the Leasowe defences were breached and the lower lighthouse of the two at Leasowe was destroyed. Its destruction provided the impetus to upgrade the Bidston Hill signal station to a proper lighthouse for the Horse and Rock Channels (Woods, 1944, Hockey, 1994).

was recorded in February 1990 by a MDHB gauge at Gladstone. [43] That tide was estimated by the MDHB themselves as 24 feet 9 inches, although the measurement may have been made elsewhere in the river. It has been referred to as 'the highest ever' in some reports.

[43] BODC holds data from this gauge for 1989-90. In 1991 the 'A Class' bubbler gauge was installed alongside it.

If one high tide has to be chosen, then the 1905 value wins on face value. However, it can be seen that uncertainties in measurements, and the data gaps, preclude the definite identification of the 'largest ever high tide' at Liverpool. Missing from our data set are high water levels associated with some of the town's most famous storms, such as the flooding of 1721 which resulted in the congregation of St.Peter's having to be rescued by boat and the ship 'Tabitha Priscilla' to be carried over the pier into the Old Dock, the 'hurricane' of January 1802 in which the tide rose 6 feet above its calculated level and did enormous damage, and the 'Great Storm' several days before and after 8 January 1839. [44] It is clear that levels at around 24 feet above ODS have occurred from time to time throughout the last two centuries, even if Figure 21 suggests that such high levels are now occurring more frequently. [45]

5. Significance of Changes in the Tide, MHW and High Water Extremes at Liverpool in the Context of Climate Research

The changes in tidal amplitude demonstrated by Figure 16 require primarily local explanation. They are too large to have been caused by changes in the deep ocean tides over the same period, and, consequently, are not of great interest to researchers concerned with global ocean tides. However, they are of potential great interest to studies of river engineering and of coastal processes. The tidal changes are also of importance to our ability to use the long time series of MHW of Figure 19 as if it were a time series of 'Proxy Mean Sea Level' within studies of long term sea level changes due to climate change. We show below how the MHW record can be corrected for the tidal changes to provide a proxy-MSL time series with a much longer record than is available for true-MSL from Liverpool and from most other locations in Europe.

As mentioned above, Woodworth et al. (1999) have demonstrated that the available Liverpool MSL record, spanning the George's-Prince's-Gladstone (GPG) period, has an average trend of 1.23 +/- 0.12 mm/year. Using data from the twentieth century only, the trend is 1.39 +/- 0.19 mm/year, which compares to an 'anticipated' trend of 0.18 +/- 0.04 mm/year, based on extrapolations of parameterisations of Holocene geological information from the Mersey from the Durham University geological sea level data bank (Shennan and Woodworth, 1992; Woodworth et al., 1999). (See also Tooley (1978), Shennan (1989) and Lambeck (1996) for discussions of geological data in the region). This yields a 'net twentieth century trend' for Liverpool of approximately 1 mm/year, consistent with other data from the region (Shennan and Woodworth, 1992; Woodworth et al., 1999), and which can be accounted for by factors such as

[44] The effects of the storms of 1802 and 1839 on land and sea are described in detail by Picton (1875). Lamb (1991) gives a meteorologist's interpretation of the 1839 storms, while several paintings by the marine artist Samuel Walters commemorate the attempted rescue of ships in Liverpool Bay (see Davidson, 1992 which also contains descriptions of the 1839 'Great Storm'). The limited facilities available to Denham during this week of storms, especially with regard to the absence of a steamer under his constant control upon which he blamed a chain of casualties, was a major factor behind his resignation (Mountfield, 1953).

[45] The increasing frequency (or decreasing 'return period') of extreme high tides evident from Figure 21 is confirmed by anecdotal evidence. For example, Canning Island (Figure 3) is now regularly over-topped by waves, a situation which 150 years ago Hartley would have thought he had avoided (A.Jarvis, private communication).

global sea level change (Douglas, 1991; Warrick et al., 1996). [46]
However, important topics of study by groups such as the Intergovernmental Panel on Climate Change (IPCC) (Warrick et al., 1996) are concerned with when this apparent rise of regional and global level commenced, and with the variations (or 'accelerations') in this secular trend over longer timescales. Estimates of 'acceleration' of sea level during the last two or three centuries from the small number of very long European records are of the order 0.4-0.9 mm/year/century (Woodworth, 1990; Gornitz and Solow, 1991; Douglas, 1992), with Liverpool's MSL acceleration for the GPG period of 0.82 +/- 0.36 mm/year/century compatible with those estimates but not as accurately determined as one would wish.

The new time series of Liverpool MHW allows the study of trends and accelerations in proxy-MSL to be performed over a much longer time scale than the GPG period for which we have true-MSL data. However, a major difficulty in employing the observed MHW values as proxy-MSL directly is introduced by the local tidal changes. MHW would have been much larger in the first part of the record if the tidal amplitudes had been as large then as they have been in later years. In order to present values from each period on a more comparable basis for MSL studies, Figure 22 shows the same MHW information but with values adjusted according to the 'tidal amplitude history model' of Section 4.3.

Over the period up to 1880, the adjusted time series has only a small trend (0.39 +/- 0.17 mm/year). However, the time series gains a progressively positive gradient. A trend of 1.22 +/- 0.25 mm/year is obtained for the twentieth century, with a value of 0.83 +/- 0.06 mm/year for the overall record. The overall acceleration is 0.33 +/- 0.10 mm/year/century. The fact that the trend is small during the first half of the record, as anticipated from the geological information, suggests that most of the true acceleration in sea level began during the second half of the last century

Adjusted MHW can be accepted as a simulation of proxy-MSL only if it reproduces the main features of the true-MSL time series over the GPG period for which we have both sets of information. The linear trend in Adjusted MHW, 1.09 +/- 0.13 mm/year, corresponds well to the 1.23 +/- 0.12 mm/year trend in MSL. The acceleration of Adjusted MHW in the GPG period, 0.25 +/- 0.36 mm/year/century, is less than the 0.82 +/- 0.36 mm/year/century of MSL, although the two values are consistent within errors. Therefore, the tidal amplitude history model has been largely, although not completely, successful in reproducing MSL, as might have been

[46] Changes in both land and sea levels, and the inherent ambiguity between them in relative sea level measurements, have been discussed by Liverpool scientific societies for the last two centuries. For example, what appeared to be palaeo-tree trunks had been excavated during the reclamation of the Pool (of course without the benefit of carbon dating), and what is now known to be a palaeo-submarine forest of oak and other trees had been discovered at low tide at Leasowe, providing the basis for geological discussions (Picton, 1849).

anticipated.

Figure 22 also includes the values for MSL at Liverpool and at the three other sites in the region with very long MSL records. ‘Accelerations’ in each record are comparable at 0.82, 0.42, 0.44 and 0.84 mm/year/century for Liverpool, Amsterdam, Brest and Sheerness respectively (Woodworth, 1990; Woodworth et al., 1999). The ‘anticipated geological trends’ for each site are also comparable at 0-0.5 mm/year, except for Sheerness which has a larger value of 1.11 mm/year (Shennan and Woodworth, 1992; Woodworth et al., 1999). Therefore, to a good approximation, our conclusion as to the timing of the onset of the true acceleration in sea level obtained from the Adjusted MHW values from Liverpool is valid for these long MSL records also. However, it can be seen that the greater length of the Liverpool Adjusted MHW record, compared to the MSL time series from the same location, is of great importance in reaching such a conclusion.

The findings based on the Liverpool Adjusted MHW information have to be qualified by reservations concerning the accuracy of the local tidal corrections; the 3 percent error attached to the 6 percent tidal correction for pre-1835 would correspond to an uncertainty in computed acceleration of order 0.3 mm/year/century which has to be combined with the 0.10 mm/year/century statistical uncertainty. In addition, the datum uncertainties of cases (ii-iii) referred to in Section 4.4 have to be considered. However, it can be seen that, if the Adjusted MHW values for prior to 1850 were to be increased by an additional 7 or 15 cm compared to those of Figure 22, as would be the situation if cases (ii-iii) were to apply, then the Adjusted MHW values of the earlier part of the record would be significantly larger than those later, and the shape of the time series would be inconsistent with those of the other stations. This provides further indirect evidence for rejecting cases (ii-iii).

Conclusions with regard to regional sea level changes cannot usually be drawn using data from one station, or from one group of stations, only. However, the results do appear to verify findings of acceleration of European MSL derived from other long records from stations further afield (Woodworth, 1990; Gornitz and Solow, 1991). Stockholm in Sweden is the site with the longest continuous European MSL record and with a tide gauge which is still operational (Ekman, 1988). At Stockholm there is a large rate of ‘anticipated’ sea level change due to post-glacial rebound which is observed in the tide gauge record. This effect has been removed from the MSL data shown in Figure 22 by detrending the information over the period 1774-1873. The overall acceleration since 1774 is 0.45 mm/year/century.

These findings on ‘accelerations’ of European MSL, to which the Liverpool data contribute significantly, have recently been published in the scientific literature (Woodworth, 1999).

Long term changes in ‘storminess’ is also a topic of interest to climate researchers such as those of the IPCC. Our extreme level analysis has demonstrated that there is no evidence for significant changes in extreme sea level at Liverpool during the last two centuries, beyond what would be expected from the secular trend in MHW alone, thereby confirming that the statistics of extreme storm events during past and present epochs is essentially the same (see Lamb, 1995 for a review of this subject).

6. Scientific Conclusions

A data set of tidal information from the port of Liverpool spanning 1768 to the present has been collected by means of converting archived records held by several libraries into modern computer form. This data set constitutes the longest near-continuous time series of tidal information in the UK, and one of the longest in the world.

A number of scientific analyses of the various components of the data set have been performed with the following conclusions:

(i) Annual mean high water (MHW) at Liverpool has increased at an average rate of 1.76 +/- 0.06 mm/year between the late eighteenth century and the present, with little apparent ‘acceleration’ of the rate. This increase will have been caused partly by a rise in the Mean Sea Level (MSL) and partly by an increase in the amplitude of the ocean tide. In particular, in the post-1850 period, for which MHW, MSL and MTR data are all available, the trend of MHW of 1.72 mm/year is well represented as a trend in MSL of 1.23 mm/year superimposed upon which is a trend owing to changing tidal amplitudes of order 0.64 mm/year (i.e. half of the trend in MTR).

(ii) The amplitude of the tides increased significantly (order 6 +/- 3 per cent) between 1835-55, almost certainly as a consequence of the canalisation of the river banks and other modifications to the river and its approaches, and of ongoing dock developments. This compares to the period between the mid-nineteenth century and the present, wherein amplitudes increased by approximately 2 per cent.

(iii) The available evidence suggests that the timings of high waters by William Hutchinson between 1764-93 were in (local) apparent solar time and that the sea level measurements of Denham in 1834 were recorded in (local) mean time.

(iv) A consequence of the previous conclusion is that in the late eighteenth century, high waters would have occurred significantly later than at present (order 17 minutes). In the early nineteenth century, the lag compared to present was of order 13 minutes, and was approximately 6 minutes by the latter half of the century (although the accuracy of this last estimate is probably similar to the estimate itself).

(v) MSL has risen at an average rate of 1.23 +/- 0.12 mm/year between the mid-nineteenth century and the present, comparable to rates observed at tide gauges elsewhere in the UK and Europe. The ‘acceleration’ of MSL over the same period was 0.82 +/- 0.36 mm/year/century.

(vi) The observed MHW values can be adjusted to compensate for the changes in the amplitude of the ocean tide, with the values for Adjusted MHW employed as proxy-MSL over a much longer period than for which true MSL data are available. The data indicate an average rate of rise of Adjusted MHW between 1768 and the present of 0.83 +/- 0.06 mm/year with an acceleration of 0.33 +/- 0.10 mm/year/century. This record is arguably the second oldest proxy-MSL record in the world after Amsterdam’s record (1682, although the data held by Bidston Observatory are from 1700 only) and of comparable age to Stockholm’s (1774).

(vii) The Adjusted MHW values from Liverpool show a similar ‘acceleration’ to those seen in previous analyses of other long MSL records from Europe. In combination with longer term sea level information derived from geological sources, they suggest that the apparent rise of regional

MSL observed in the twentieth century of order 1 mm/year (Shennan and Woodworth, 1992), which is the subject of much debate in the context of climate change research, took place primarily as a consequence of an acceleration around the second half of the nineteenth century. Such observations could provide an additional constraint on interpretations of global climate change during the past few centuries.

(viii) Repeated geodetic levellings since the beginning of this century have indicated that marks E and F on the south side of the Albert Dock warehouses, 'Tide Gauge X' at Canning Dock, and the ODS gauge at Canning Island are relatively stable. The mark B on Canning Pilot House shows evidence for gradual submergence, and an anomalous recent value, suggesting submergence, was obtained for the Cunard Buildings. Mark G's level at Prince's Dock with respect to others in the area is consistent with documented values from earlier surveys, allowing combined George's-Prince's MSL and MHW records to be constructed with confidence.

(ix) Although many extremely large high tides have occurred from time to time at Liverpool throughout the last two and half centuries, and although the frequency of these large events is greater nowadays than in previous years, extreme level analysis of the high water levels from Hutchinson's era, together with values from the nineteenth and twentieth centuries suggests that the increase in frequency can be explained primarily by the overall increase in MHW, rather than by an increase in the frequency of storm surges.

7. Concluding Remarks

Several authors have commented that in some ways it is surprising how Liverpool should have developed as a major port at all. The approaches could be difficult to navigate with tidal currents exceeding 2 m/sec (4 knots) opposite Liverpool and 3.5 m/sec (7 knots) in some channels (Wheeler, 1893; Lane et al., 1997). Compounded by the large vertical tidal range, this made the river a difficult place to work for sailing ships. The historical record contains many references to ships run ashore, or grounded on the entrance sills of the docks, as the captains misjudged the tide. [47]

The relatively sheltered Birkenhead side of the Mersey with its own 'pool' was always preferable, as engineers such as Telford [48] and hydrographers such as Denham, pointed out many times (Mountfield, 1953; R-N, 1984; McCarron, 1998). The answer seems to have been that, of

[47] On the other hand, some people found romantic aspects in tall ships and tides; for example 'the call of the running tide' in 'Sea Fever'. John Masefield (1878-1967), the Poet Laureate, was a cadet on the training ship HMS Conway in the Mersey.

[48] Telford made his remarks standing on Bidston Hill near the site of the future Tidal Observatory (POL) (Meacock, 1911).

the established west coast ports, facing towards Ireland and America and relatively safe from attack by other European nations, Liverpool was better located than most. Bristol, for example, with its even larger tidal range and confined river access, could never have developed through the nineteenth century as Liverpool did. In addition, Liverpool's commercial community always somehow found the drive to keep the momentum going from the 'Old Dock' through to recent times.

It is fortunate that these port developments took place or we would not have at our disposal the tidal data sets discussed in this report. All the early records were connected in some way with either dock operations or hydrographic surveys of the Mersey. Rarely did 'science' enter into consideration until the Lubbock-Whewell and BAAS researches of the nineteenth century. The Liverpool records have provided an excellent example of 'data archaeology', and of the fact that good quality oceanographic and geophysical data, whatever their origin, may have an importance in scientific and practical applications not considered at the time.

Historical research into long term changes in ocean tides has been undertaken by other authors for other ports. For example, studies of changes in the River Thames by Rossiter (1969), Bowen (1972) and Amin (1983) have shown that Liverpool is not unique in experiencing large tidal changes over many years. Bowen (1972) investigated the many factors contributing to variations in tidal range and concluded that the changes to the Thames embankments play an important role in determining the height of the major surge events. Amin (1983) demonstrated that the tide now arrives at London Bridge about half an hour earlier than in the early nineteenth century, partly owing to man-made modifications to the estuary. Other studies of tidal changes have been made elsewhere in the UK (e.g. Woodworth et al., 1991), in Europe (Cartwright, 1972a,b) and further afield (Doodson, 1924; Cartwright, 1971). Research into long term changes in mean sea levels are, of course, studied intensively as part of investigations into natural and anthropogenic climate change. I am sure that further 'data archaeology' of tides and mean sea levels at other locations, by researchers knowledgeable about both tidal data and local histories, would repay the efforts involved.

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Annex 1

Some Aspects of the Life of William Hutchinson (*)

Born 1715 Newcastle-upon-Tyne. Early years as cook's cabin boy and 'beer drawer' through to forecastleman in small colliers in east coast coastal trade.

Sailed as forecastleman in East Indiaman to India and China in 1738-39. Served as mate of bomb's tender in Hyères Bay around 1743 during the Mediterranean war and by 1747 was in command of a privateer alongside Fortunatus Wright, the most famous of the Liverpool privateers 'whom he adored' (Muir) (**). Sailed with FW in the 'Leostoff' to West Indies in 1750 (Williams), or as master of the 'Lowestoft' frigate (Picton, Touzeau), or as commander of the 'Leostaffe' (Brooke). The 'Leostaff', as Hutchinson referred to her himself, was an old 20 gun frigate sold by the Navy to FW.

Observed a particular day each year for devotion for deliverance after loss of vessel. He and crew being without food on a barren coast had drawn lots to be put to death to feed remainder. Hutchinson lost but was saved when another vessel appeared (Brooke).

Freeman of Liverpool *gratis* 'in consideration of his efforts for the better supplying the town with sea fish by fitting out well boats (or cod smacks)' (1755).

Captain and part-owner of the 'Liverpool' privateer during the first part of the Seven Years War (1756-63) (***).

Two years of successful cruises in the 'Liverpool' in the Mediterranean and home waters in 1757-58. 'The ablest and boldest of the Liverpool privateers' (Muir).

Developed special method for making tea (quart bottle boiled in ship's kettle with the salt beef).

In 1758, an attempt by Hutchinson to 'curb the insolence' of the notable French privateer François Thurot in the Irish Sea by regaining command of the 'Liverpool' from Captain Ward, who had just replaced him. Attempt got nowhere. This was the last privateering adventure by Hutchinson. Thurot was killed in a battle between 3 British and 3 French frigates, which he commanded, off the Isle of Man in 1760.

Appointed Dock Master and Water Bailiff on 7 February 1759 (Picton incorrectly says 1760).

Survived through pistol misfire an attempted murder in 1759 (about 3 months after becoming Dockmaster) by seaman called Murphy from the 'New Anson' privateer. Murphy was sentenced to Navy for life.

Inventor of reflecting mirrors and oil burning apparatus for lighthouses. Mirrors tested at Bidston Signal Station in 1763. One of the original mirrors still exists at Trinity House Museum in London.

In 1779 improved on a quick-match priming mechanism for large guns developed originally by Henry Ross, another Liverpool inventor.

Measured heights and times of high waters and meteorological parameters at Old Dock 1764-1793 (data survive for 1768-1793).

Author of the 'Treatise on Practical Seamanship' 1777. Second version 1787.

Instrumental in the establishment of the world's first lifeboat station at Formby, and of Mersey pilotage services, and with Dr. Thomas Houlston of the Liverpool Infirmary developed early methods of artificial respiration (Cooper).

In April 1778 commanded the 'Queens Battery' in defence of the town against the American corsair John Paul Jones (who did not appear). The Bidston light was extinguished in this period.

Founded Liverpool Marine Society in 1789 for the benefit of masters of vessels, widows and children. 'Contributor to all the benevolent institutions of the town' (Picton). Also proposed, unsuccessfully, Maritime Academies at Liverpool, North Shields and Limehouse, London for students of seamanship.

Inventor of marine equipment (e.g. types of rudder) and commentator on ship design (ships at this time were being built too high with extra decks). Author of a 'Treatise on Naval Architecture' (Hutchinson, 1791). This treatise also contains a number of sections reprinted from Hutchinson (1777).

Ridge of rock and gravel near Fort Perch Rock, New Brighton named after him (****). Hutchinson cut away the rock and deepened the channel.

Died 7 February 1801 aged 85 and interred in St.Thomas's churchyard (*****). His will records that his estate was left to his sister and nephew (Dickinson) and makes no mention of a wife or children (******). In Hutchinson (1777) he described himself as 'a former cook of a collier .... and a seaman who had done his best' which provides an understated obituary. Williams writes that Bryan Blundell considered his life to be 'one unwearied scene of industrious usefulness'. Blundell was the mariner, ship owner (see earlier footnote), mayor (1721,1728) and founder of the Blue Coat Hospital who died in 1756.

(*) This annex is largely based on the references to Hutchinson in Wylie (1835), Brooke (1853), Picton (1875), Dictionary of National Biography (1885), Williams (1897), Muir (1907), Touzeau (1910), Dickinson (1950), Chandler (1957), Bridgwater (1963), Cooper (1997) and Woodworth (1998).

(**) Williams (1897) is particularly worth reading for a description of the exploits of FW and other Liverpool privateers. FW was born in Wallasey and was lost at sea in 1757 in command of the 'St.George' privateer.

(***) The 'Liverpool' was launched soon after the start of the war. She was a 22 gun frigate (18 of which 12 pounders) with 160-200 men. She was sold in April 1759 and used for the New York - Liverpool trade. There was also a King's ship at this time called the 'Liverpool' as there has been for over 250 years (Wardle, 1941b).

(****) So far as I know, there is no recognition in Liverpool itself of either Hutchinson or FW. Parts of the ugly post-war City Council offices in Canning Place were named 'Steers House', 'Foster House' (after John Foster who built the Customs House) and 'Mulberry House' (see earlier footnote). They are now under demolition.

(*****) All historians except Williams are incorrect in giving either 11 or 14 February as the date of his death. The Liverpool Advertiser of Monday 9 February refers to Hutchinson's death 'on Saturday' and gives an effusive obituary, and the parish records show he was buried on the 11th (microfiche records at Liverpool Central Library). St.Thomas's in Park Lane was demolished in 1885 as the building was unsafe and the graveyard is now a car park.

(******) Wylie's 1835 letter suggests that there was a daughter married to Lt.Browne, RN, agent for transport at Liverpool. This is an incorrect reference to his niece Nancy who was married to Lt.John Browne.

Postscript to Annex 1

The week of 12-16 April 1999 contained two important meetings in London organised by POL and concerned with ocean circulation, gravity measurements and sea level changes. During a break between the meetings, I was able to take the District Line to Tower Hill and visit Trinity House, an organisation founded by Henry VIII in 1514 to provide aids to the general navigation such as lighthouses, light vessels, buoys and beacons, and to provide other functions, such as a Deep Sea Pilotage Authority. Eventually, Trinity House built up an impressive network of lighthouses around England and Wales. Their present headquarters on Tower Hill date from 1794 and are in a very grand building next to the Tower of London. It has been extensively refurbished since being hit during the war.

Their main reception leads on to a small museum and pride of place goes to a concave reflector mirror of an early (1763) lighthouse. The mirror is quite small, about 2.5 feet in diameter overall, and is composed of small pieces of looking glass, each about 4 x 2 cm. In the centre, at its focus, is an oil-burning arrangement which provided the light, itself an important innovation, lighthouses at that time being lit by 'firebaskets' of coal or wood. At the back of the mirror is the oil reservoir.

You have probably guessed that this early 'lighthouse' was in fact the Bidston Hill Signal Station which had been constructed to the design of Lightholler the same year (see above) and the inventor of the mirror and burner was Captain William Hutchinson. Hutchinson's design, somewhat improved upon a few years later by William Holden, was subsequently used for the original purpose-built Bidston lighthouse constructed in 1771. This building lasted until the 1870s when the present lighthouse replaced it. It was most gratifying to see Hutchinson's mirrors and the historical importance of Bidston Hill celebrated in such prestigious surroundings in London.

Just about every object connected with Hutchinson has vanished (e.g. his house, his church, his tidal clock, maybe or maybe not his tide gauge) with the major exception, of course, of his tidal records in his own handwriting. Therefore, in spite of reading extensively about Hutchinson, I had always believed that his mirrors must have vanished as well, until the Liverpool University Librarian pointed out to me Jack Cooper's 'Liverpool Firsts' book, and this led me to Trinity House. I am very grateful to them both.

One remaining puzzle is concerned with how the mirrors came to be owned by Trinity House. The Bidston lighthouse, or the other Wirral lights for that matter, were never owned by Trinity House but were built and operated by the Corporation of Liverpool and then by the Mersey Docks and Harbour Board (Woods, 1944). One can only surmise that, at some point during the nineteenth century, someone (mostly likely the MDHB) donated the object to what it thought to be a good home. Someday, I hope to be able to do more research on this.

Liverpool Central Library possesses a poor photographic copy of a portrait of Hutchinson which is presumably lost. The copy is reproduced in Chandler (1957).

Annex 2:

Geodetic Levelling at Liverpool: Comparison of Historical and Recent Measurements

Part 1: Levelling in the Canning-Albert Dock Area and Pier Head

In this study we have made use of benchmark levels for the Canning-Albert Docks area measured by the Ordnance Survey since the beginning of this century and accessible from their data bank. In addition, we have used those for 'Tide Gauge X' reported by Close (1922) and have included the Canning Island (CI) ODS transfer level benchmark from 1845 shown in Figure 3. Each of the surviving marks was resurveyed during 1998 in order to search for evidence of anomalous vertical movement. The marks (mostly OS cut marks) in question are:

Mark A (NG ref. SJ 3439 8969). This was on a wall on the north side of Gower St. at the junction with Wapping, on the south side of Salthouse Dock, and no longer exists.

Mark B (NG ref. SJ 3391 8993). This is on a SW angle of the south face of the Pilotage Buildings on the north side of the entrance to the Canning Half Tide Basin. The Pilot Building is currently used for the Museum of Liverpool Life. At the time of writing the mark is behind a gate which provides access to the Albert Dock area from the river parade leading to the Pier Head.

Mark C (NG ref. SJ 3396 8975). This was on a wall on the NE side of the river parade. It may still exist but we were not able to find it. It is probably to the rear of the property of the Tate Gallery.

Mark D (NG ref. SJ 3385 9041). This is on a stone wall on the NW side of the entrance to the Cunard Buildings at Pier Head.

Mark E (NG ref. SJ 3414 8959). This is on an east angle of the SE wall of the Albert Dock building on the NW side of Gower St. As of 1998 it can be found near to an ATM cash dispenser about 20 metres from the entrance to the Beatles Exhibition.

Mark F (NG ref. SJ 3424 8964). This is on a stone gate post on the NW side of Gower St. on the SW side of the SE entrance to the buildings.

Mark X19f6. This refers to the 19 foot 6 inch level on 'Tide Gauge X' to be found approximately 15 m north of the SE corner of Canning Dock.

Mark X22. This refers to the 22 foot level on 'Tide Gauge X'.

Mark CI19f6. This refers to the 19 foot 6 inch level on the Canning Island ODS transfer level benchmark.

In the 1998 levelling, the closure of the circuit B-E-F-X-CI-B was 7 mm over a distance of about 1.5 km.

Comparisons of OS Marks to Mark E Levels

In this section we compare the levels of other marks to those of mark E because, as will become apparent, that mark exhibits greater relative stability. Level differences for each epoch are shown in the table below.

Difference	Epoch	Height Diff. (m)		
A-E	1906	7.25-7.07 ODL	=	+0.18
	1947	7.32-7.14 ODN	=	+0.18
	1959/60	7.31-7.13 ODN	=	+0.18
B-E	1906	7.47-7.07 ODL	=	+0.40
	1947	7.44-7.14 ODN	=	+0.30
	1960	7.42-7.13 ODN	=	+0.29
	1998	POL levelling	=	+0.26
D-E	1906	7.04-7.07 ODL	=	-0.03
	1947	7.10-7.14 ODN	=	-0.04
	1960	7.11-7.13 ODN	=	-0.02
	1996/98	POL levelling	=	-0.30
F-E	1906	6.98-7.07 ODL	=	-0.09
	1947	7.05-7.14 ODN	=	-0.09
	1960	7.04-7.13 ODN	=	-0.09
	1998	POL levelling	=	-0.08

Conclusions:

(i) Marks A, E and F exhibit relative stability through time.

(ii) Mark B on the Pilot Building shows evidence for ongoing relative submergence, especially between 1906 and 1947.

(iii) Mark D in recent levelling is approximately 27 cm lower relative to the others than in previous levellings. It is possible that the wall on which the mark is located has been rebuilt.

Comparison of Marks X and E

From Close (1922) we have a level for X22 of 17.81 ft. (5.43 m) above ODL in 1843 (Figure 18). The earliest measurement in the OS databank of mark E (which we are now considering 'stable') is 7.07 m above ODL in 1906. Consequently, we can compute a 'historical value' for (X22 -E) of -1.64 m.

From recent levellings (X19f6 - E) = -2.43 m. If one assumes that the 22 foot mark is 2.5 feet above the 19 foot 6 inch mark, then (X22 - E) = -1.67 m. (It was more convenient for us to use the 19 foot 6 inch mark in the recent survey because of the overhang of the concave vertical channel containing the gauge by the pavement above.)

Conclusions:
Marks E and X are relatively stable to centimetric accuracy and X22 has a similar level relative to ODL as in 1843 as reported by Close (1922).

Tide gauge X does not show levels relative to ODS but values approximately half a foot lower, as reported by Close (1922) and as shown in Figure 18.

Comparison of Marks E, B and CI

From recent levellings we have (CI19f6 - E) = -2.59 m.

Now, if E is indeed 7.07 m ODL as measured in 1906, then:
CI19f6 will be 4.48 m ODL or (4.48 m + 4.67 ft) ODS which is 19 ft 4 in. relative to ODS.

Alternatively, if E is 7.13 m ODN or 7.09 m ODL as measured in 1960, then:
CI19f6 will be 19 ft 5 in. relative to ODS.

From recent levellings we have (CI19f6 - B) = -2.85 m.

Therefore, if B is 7.42 m ODN or 7.38 m ODL as measured in 1960, then:
CI19f6 will be 19 ft 6 in. relative to ODS.

Conclusions:

(i) Whether levelled from the 'stable' E mark or from the 'subsiding' B mark (but using the most recent ODN value for the latter), the 19 ft 6 in. level recorded on the Canning Island transfer level benchmark is indeed consistent with recording to ODS to within approximately one inch.

(ii) The Canning Island site shows no evidence for submergence, unlike the Pilot Building (mark B) only a few 10s of metres to the north.

Part 2: Levelling Extension to Prince's Pier

Records at POL indicate that in 1956 an OS working party installed a mark G3979 (an OS flush bracket) at Prince's Pier only a few metres from the tide gauge. This mark still exists and we designate it 'Mark G'. The POL records indicate a height of 7.27 m ODN for this mark in 1956. However, for some reason the OS itself appears to have no record of it.

In 1996 a re-levelling of marks B-D-G (and return) was completed with closure of 1 mm over a distance of about 2 km. This new levelling was urgently required in order to confirm the level of mark G before the Prince's area was redeveloped.

The level difference G-B from the new levelling was -0.128 m to be compared to (7.27-7.42) = -0.15 m if one uses the 1956 and 1960 ODN values for marks G and B respectively. This is satisfactory agreement, and is consistent with the few cm sinking of B since 1960 evidenced by the B-E time series discussed above, and suggests that G has undergone no large change of level in the last few decades.

Conclusions:

The documented ODN value of the height of mark G is consistent with that from the new levelling to approximately cm accuracy. Consequently, the datum of the Prince's Pier gauge can be *connected with confidence to that from George's.*

Table 1

Mean High Water Data from Liverpool

Years	Data Set	Data Type
1768-93	Hutchinson	Tabulations of HW Observations
1816,19-21	RS Archive	Tabulation of Annual MHWS(N)
1827-35	RS Archive	Tabulations of HW Observations at three docks (N.B. Observations were made beyond this period at Salthouse but data not survived)
1834	Denham	HW turning points computed from half-hourly values of sea level
1854-56	Parks (1857)	Tabulations of Annual MHW, MHWS(N) from George's Pier
1858-1903	George's	HW determinations from nearest 15-minute value of sea level
1903-12	George's	Tabulations of HW Observations (These will have been obtained from the tide gauge chart)
1927,63-82	Prince's	HW turning points computed from hourly values of sea level (BODC data)
1920,22,24, 35,38,43-44, 46-49	Prince's	ditto (data acquired this analysis)
1941-42,45, 50-62	Prince's	Tabulations of HW Observations (N.B. these cover 1941 onwards. However, we have preferred to use turning points where hourly data are available)
1989-97	Gladstone	HW turning points computed from hourly values of sea level with a correction to compare to tidal data from the earlier data sets

Table 2

Amplitudes (H) and Phase Lags (G) of the Baird and Darwin, Amin (1985), Denham and Recent Gladstone Dock Tidal Constants where Denham amplitudes exceed 5 cm

Author:		**B&D**		**Amin (1985)**	
Data Span/Location:		**1857-70/George's**		**1963-81/Prince's**	
	Speed (deg/hr)	H (cm)	G (deg)	H (cm)	G (deg)
O1	13.9430356	11.3	40.9	11.4	41.07
K1	15.0410686	10.8	194.3	12.0	192.00
MU2	27.9682084	7.8	39.3	6.3	39.87
N2	28.4397295	58.0	305.6	58.9	300.94
NU2	28.5125831	16.1	291.9	13.6	298.77
M2	28.9841042	304.0	326.7	312.1	323.53
LAM2	29.4556253	7.0	336.3	6.4	321.63
L2	29.5284789	16.1	335.3	14.3	334.11
S2	30.0000000	96.4	11.7	100.8	7.87
K2	30.0821373	28.5	7.1	29.0	5.81
MN4	57.4238337	-	-	8.4	186.07
M4	57.9682084	21.1	222.7	22.1	214.21
MS4	58.9841042	12.4	270.0	12.6	256.92
M6	86.9523127	6.0	349.0	5.5	321.39
2MS6	87.9682084	-	-	5.3	2.65

Author:		**Denham/POL**		**POL Applications Group**	
Data Span/Location:		**1834/New Brighton**		**1991-94/G'stone Dock**	
	Speed (deg/hr)	H (cm)	G (deg)	H (cm)	G (deg)
ZO		495.32 (= 16.251 ft)			
O1	13.9430356	9.94	43.49	11.6	41.42
K1	15.0410686	9.94	184.02	12.2	190.92
MU2	27.9682084	6.96	74.39	5.0	29.39
N2	28.4397295	55.07	298.02	58.0	298.22
NU2	28.5125831	12.40	295.42	13.3	296.32
M2	28.9841042	294.05	321.78	304.2	321.23
LAM2	29.4556253	5.89	325.37	5.8	322.71
L2	29.5284789	17.54	337.20	7.9	341.45
S2	30.0000000	93.28	5.27	97.5	5.83
K2	30.0821373	25.43	4.73	27.8	4.25
MN4	57.4238337	8.08	198.15	9.6	175.77
M4	57.9682084	21.49	224.29	24.4	203.12
MS4	58.9841042	13.23	262.69	14.7	245.94
M6	86.9523127	6.29	327.51	5.3	348.15
2MS6	87.9682084	5.49	15.34	5.0	30.66

All phase lags are with respect to GMT, except Denham's which are probably with respect to Liverpool mean time (see text). To convert his phase lags to Greenwich add 3, 6, 12 and 18 degrees to the diurnal, semi-diurnal, quarter-diurnal and sixth-diurnal constituents respectively. Measurements used by Baird and Darwin and by Amin were made at George's and Prince's Piers respectively near to the Liverpool Pier Head. Denham's measurements were probably made at New Brighton at the mouth of the Mersey (see text) on the opposite bank of the river to Gladstone Dock.

Figure Captions

Inside front cover. Tide gauges near Liverpool mentioned in the text.

1. Upper map: schematic layout of Liverpool streets around 1700 (Merseyside Archaeological Society, 1981). North is to the top of the map. The intended Dock (point 28), Lord Street, Lord Street Bridge (point 49) and Church Street (indicated by St.Peter's church, point 9) are mentioned in the text. The dotted lines connecting the Old Dock to Townsend Bridge (point 46) along the inlet of the 'Pool' correspond approximately to the modern Paradise Street and Whitechapel. Lower map: layout of streets after construction of the Old Dock (point 27) and reclamation of the Pool.

2. Cross-section through the gates of the Old Dock showing relationship of the ODS to other datums used at Liverpool.

3. Canning Island tide gauge constructed in 1845 which provides a benchmark commemorating the level of the Old Dock Sill.

4. Detail from John Eyes' map of Liverpool in 1765. North is to the left of the map.

5. Map of part of Liverpool in 1900. North is to the left of the map.

6 (a). Distribution of high waters from the Hutchinson data set; (b) Upper part of the same distribution.

7. 'Inch' values from the entire Hutchinson data set.

8. 'Minutes' values from the Hutchinson data set for 1777.

9. Annual mean high waters from the Hutchinson data set.

10 (a). Differences between the times of high water observed by Hutchinson in 1777 and predicted times based on modern tidal constants; (b) Differences in times plotted through the year.

11. Differences between observed and predicted times of high water from Prince's Pier from 1967.

12 (a). Differences in times for 1777 shown in Figure 10 corrected for the 'Equation of Time'; (b) Corrected differences in times plotted through the year.

13. Annual mean tidal range at Liverpool. The curve is a linear trend plus nodal variation fit described by Woodworth et al. (1991).

14. High water levels measured at Salthouse Dock in 1834 plotted versus those derived from the Denham data set. The solid line indicates a proportionality of exactly 1.0. Data from the short

period of Denham 'slipping tape' have been excluded.

15 (a). Differences between predicted and observed high tide level plotted versus predicted level for Prince's data from 1967; (b) Denham's data from 1834; (c) Hutchinson's data from 1769.

16. Root mean square (rms) values of high water levels recorded each year at Liverpool. Most data are from the Central or South docks (Old Dock, Salthouse, George's, Prince's) except those from the 1990s which are from Gladstone Dock down-river (see text).

17. 'Tide Gauge X' on the east wall of Canning Dock. The gauge is in the vertical concave channel behind the surveying staff.

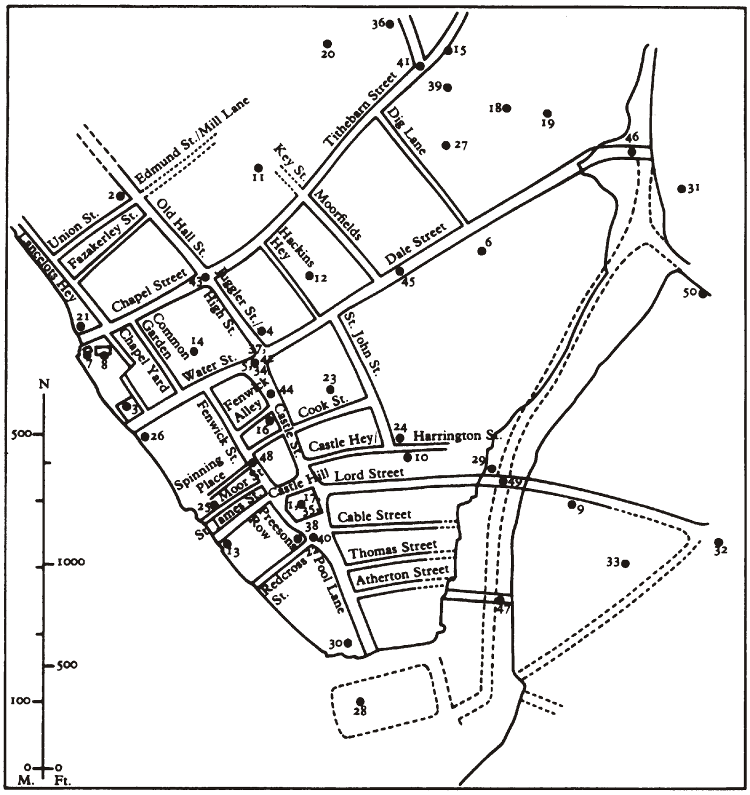
18. Geodetic levels measured in 1843 between the bottom of the 22 foot mark on 'Tide Gauge X', the granite stone of the Old Dock Sill, ODS datum as assumed for the George's Pier tide gauge and ODL (redrawn from Close, 1922).

19. Annual mean high water values at Liverpool from 1768 to the present. The curve is a linear trend plus nodal variation fit described in the text. Values from the 1990s from Gladstone Dock at the mouth of the Mersey have been adjusted to account for the lower tidal amplitudes there than at Liverpool itself where all the other measurements were made.

20. Annual mean sea level values at Liverpool from Woodworth et al. (1999). Dots, squares and triangles indicate data from George's Pier, Prince's Pier and Gladstone Dock respectively. The solid line indicates an average trend of 1.23 mm/year.

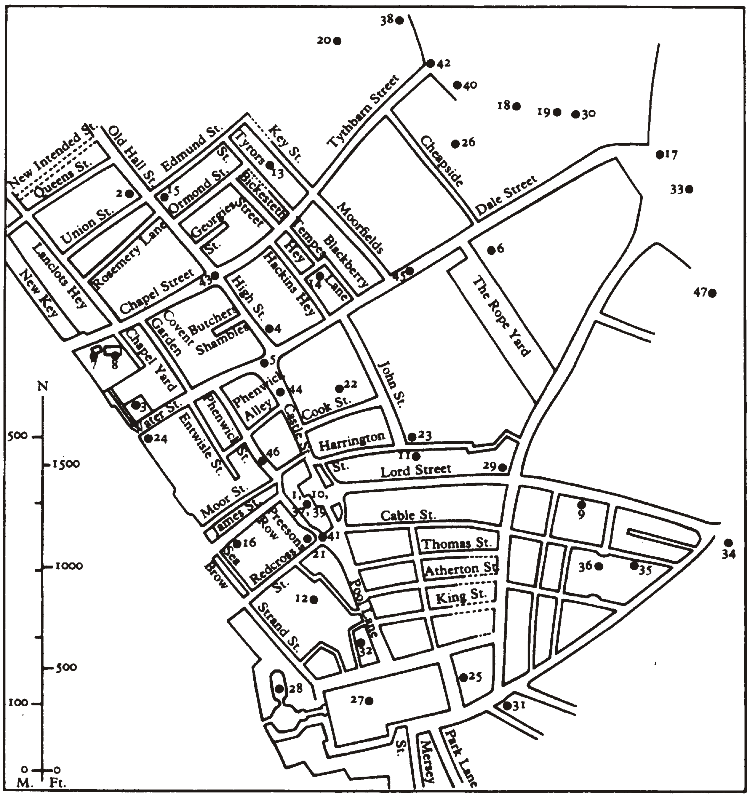
21. The 1-largest extreme level curve computed from the Hutchinson data set compared to that determined from George's and Prince's data by Coles and Tawn (1990).

22. Values of Adjusted MHW at Liverpool compared to the longer mean sea level records from the region and from Stockholm. An arbitrary offset has been added to each time series for presentation purposes. The Stockholm data from Ekman (1988) have been extended to 1997 using data from the Permanent Service for Mean Sea Level.



Later Stuart: 1660–1714

Castle		1
Old Hall		2
Tower		3
Town Hall a) 4;	b)	5
Crosse Hall		6
Places of Worship		
(St Mary del Key)		7
St Nicholas' Chapel/Church		8
St Peter's Church		9
Castle Hey Presbyterian Chapel		10
Key Street Presbyterian Chapel		11
Friends' Meeting House		12
Baptist Meeting House		13
Commerce and Industry		
Granary		14
Tithebarn		15
Horse Mill		16
Horse Mill		17
Middle Mill		18
Middle Mill		19
Paul's Mill		20
Salthouse		21
Sugar refinery		22
Sugar refinery		23
Sugar refinery		24
Custom House a) 25;	b)	26
Tannery		27
Dock		28
Pot Works		29
Charity		
Pool House		30
Almshouses:		
Poole's		31
Richmond's		31
Warbrick's		32
Charity School		33
Law and Order		
Stocks a) 34;	b)	35
Pinfold		36
Pillory a) 37;	b)	38
Ducking Stool		39
Cage		40
Crosses		
Wayside: St. Patrick's Cross		41
Town: High Cross		42
White Cross		43
Sanctuary Stones		
Castle Street		44
Dale Street		45
Bridges		
Townsend Bridge		46
Pool Bridge		47
Dry Bridge		48
Lord Street Bridge		49
Fall Well		50



George I: 1714–1727

Castle		1
Old Hall		2
Tower		3
Town Hall a) 4;	b)	5
Crosse Hall		6
Places of Worship		
(St Mary del Key)		7
St Nicholas' Church		8
St Peter's Church		9
St George's Church (site)		10
Castle Hey Presbyterian Chapel		11
Benn's Garden Presbyterian Chapel		12
Key Street Presbyterian Chapel		13
Friends' Meeting House		14
Roman Catholic Chapel		15
Baptist Meeting House		16
Baptist Chapel		17
Commerce and Industry		
Middle Mill		18
Middle Mill		19
Paul's Mill		20
Sugar refinery		21
Sugar refinery		22
Sugar refinery		23
Custom House a) 24;	b)	25
Tannery		26
Dock: Wet		27
Dock: Dry		28
Pot Works		29
Pot Works		30
Glass Works		31
Charity		
Pool House		32
Almshouses:		
Poole's		33
Richmond's		33
Scasbrick's		33
Warbrick's		34
Charity School		35
The Blue Coat School		36
Law and Order		
Stocks		37
Pinfold		38
Pillory		39
Ducking Stool		40
Cage		41
Crosses		
Wayside: St. Patrick's Cross		42
Town: White Cross		43
Sanctuary Stones		
Castle Street		44
Dale Street		45
Bridge		
Dry Bridge		46
Fall Well		47

Figure 1

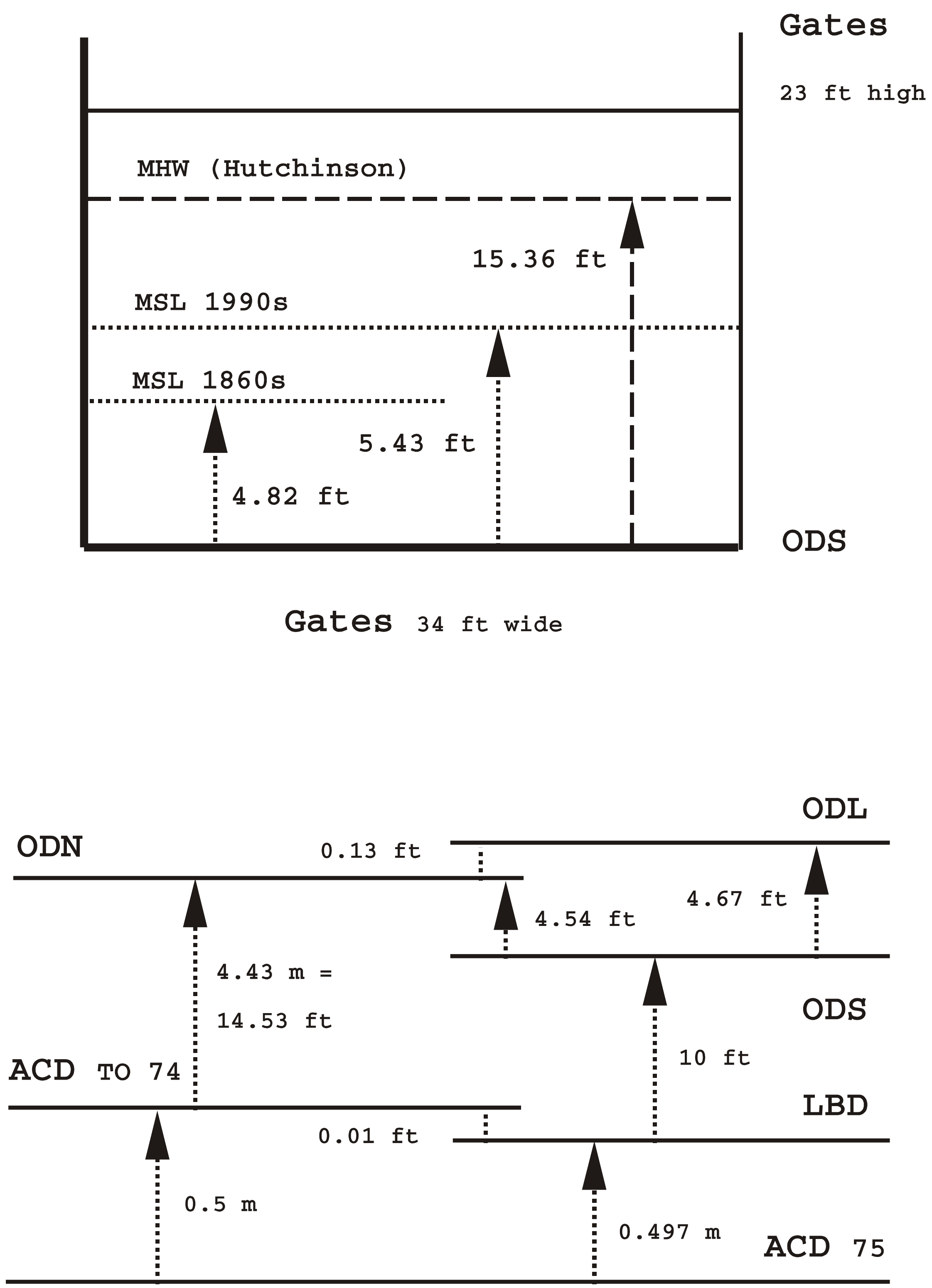

Gates
23 ft high
MHW (Hutchinson)
15.36 ft
MSL 1990s
MSL 1860s
5.43 ft
4.82 ft
ODS
Gates 34 ft wide
ODL
ODN
0.13 ft
4.54 ft
4.67 ft
4.43 m =
14.53 ft
ODS
10 ft
ACD TO 74
LBD
0.01 ft
0.5 m
0.497 m
ACD 75

Figure 2

Figure 3

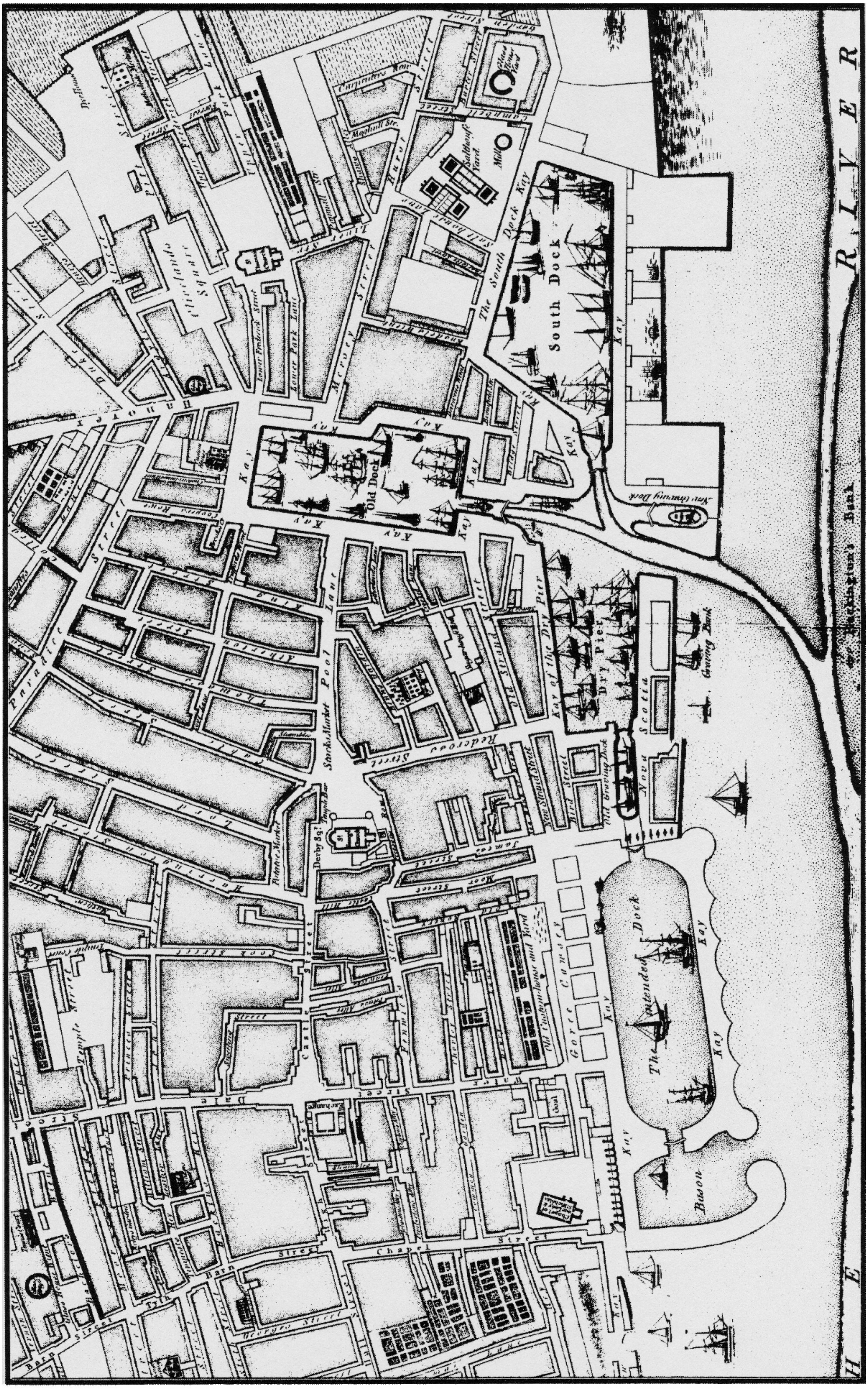

RIVER
South Dock
The South Dock Kay
Old Dock
Kay
Dry Pier
Kay of the Dry Pier
Nova Scotia
The intended Dock
Bason
Goree Causey
Hanover Street
Duke Street
Cleveland Square
Mersey Street
Lower Park Lane
Paradise Street
Atherton Street
Thomas Street
Lord Street
Harrington Street
Pool Lane
Redcross Street
Old Strand Street
James Street
Moor Street
Water Street
Castle Street
Dale Street
Temple Street
Chapel Street
Exchange
Derby Sq.

Figure 4

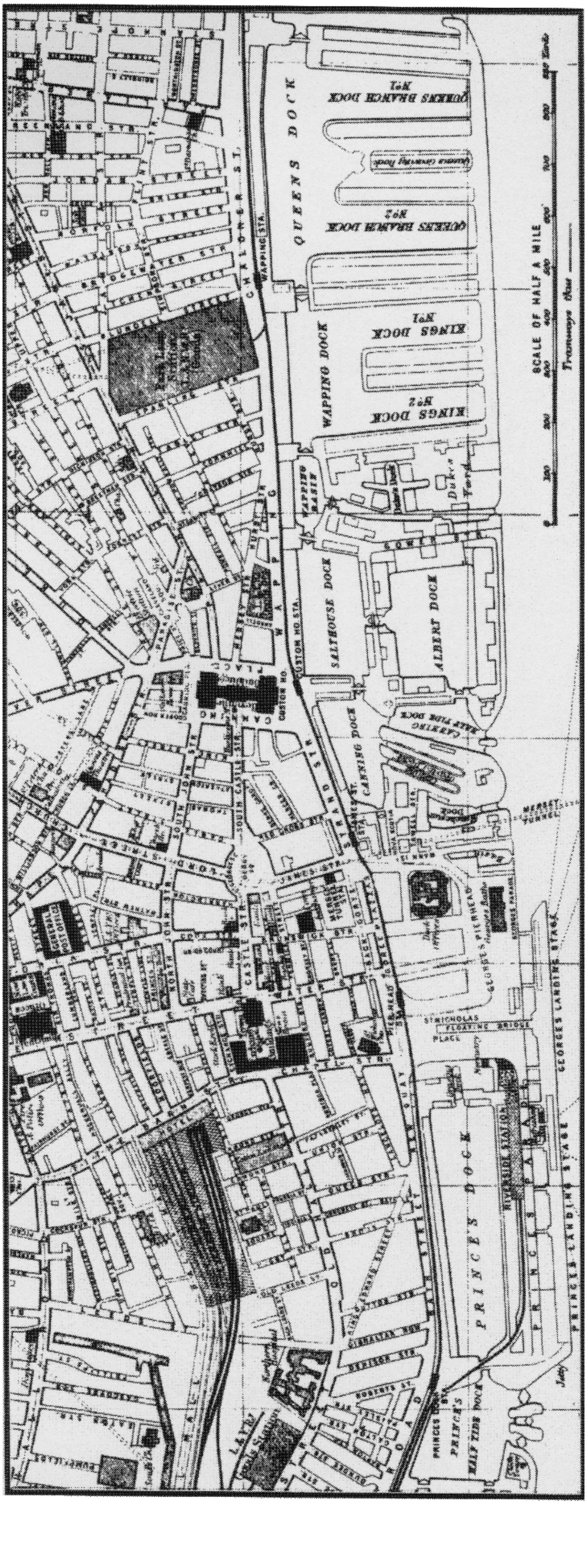
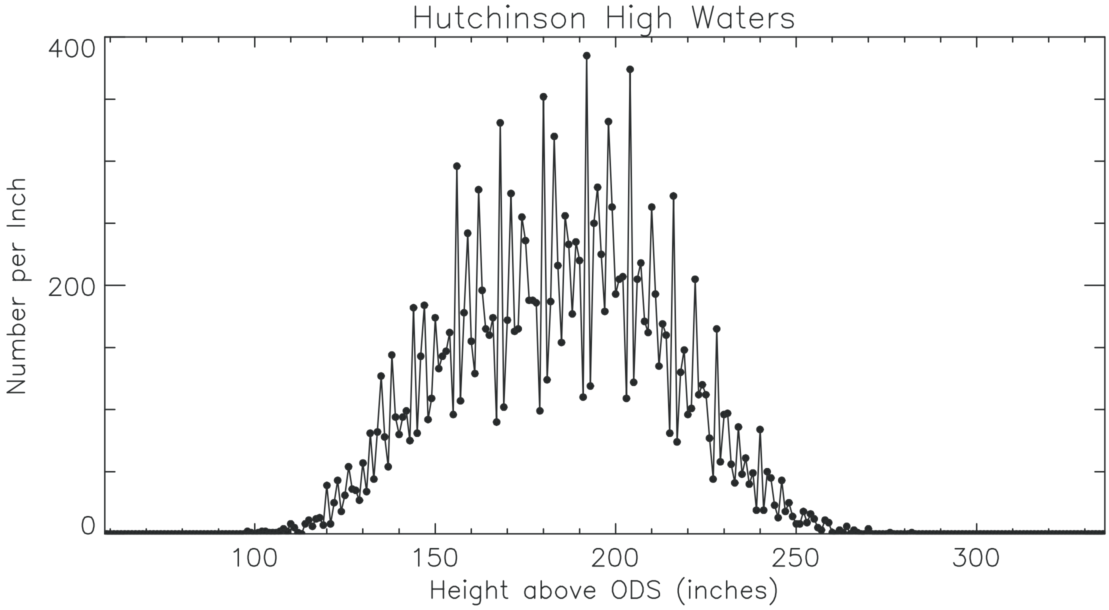

QUEENS DOCK
QUEENS BRANCH DOCK No 1
QUEENS BRANCH DOCK No 2
KINGS DOCK No 1
KINGS DOCK No 2
WAPPING DOCK
WAPPING BASIN
WAPPING
SALTHOUSE DOCK
ALBERT DOCK
CANNING DOCK
CANNING HALF TIDE DOCK
CANNING PLACE
CUSTOM HO.
STRAND ST.
PRINCE'S DOCK
PRINCES PARADE
PRINCES LANDING STAGE
GEORGES LANDING STAGE
RIVERSIDE STATION
PRINCE'S HALF TIDE DOCK
ST NICHOLAS PLACE
FLOATING BRIDGE
MERSEY TUNNEL
SCALE OF HALF A MILE

Figure 5

(a)


Hutchinson High Waters
Number per Inch
Height above ODS (inches)
400
200
0
100
150
200
250
300

(b)

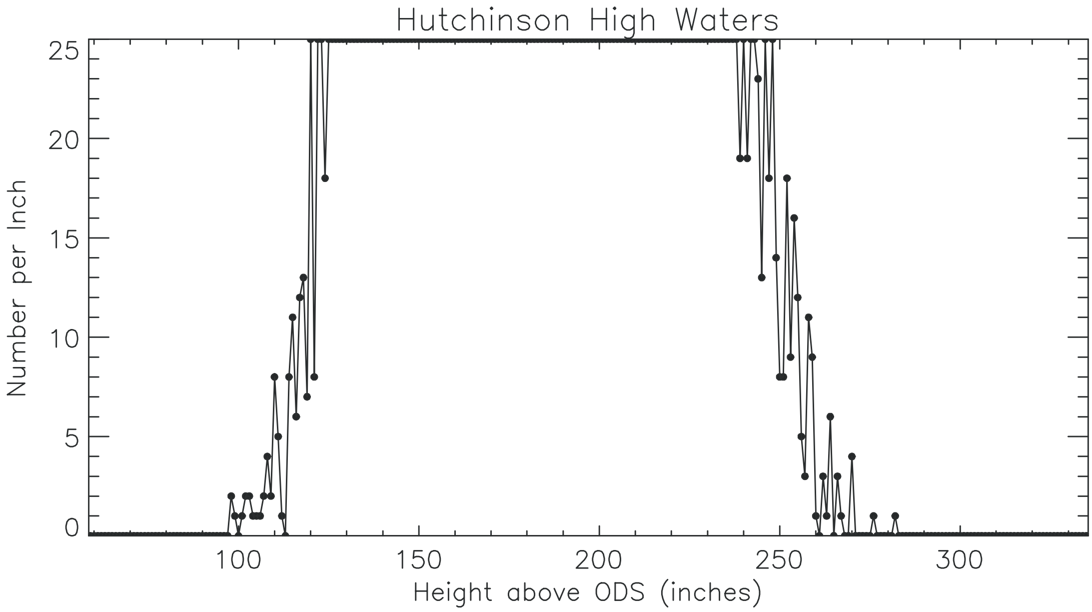
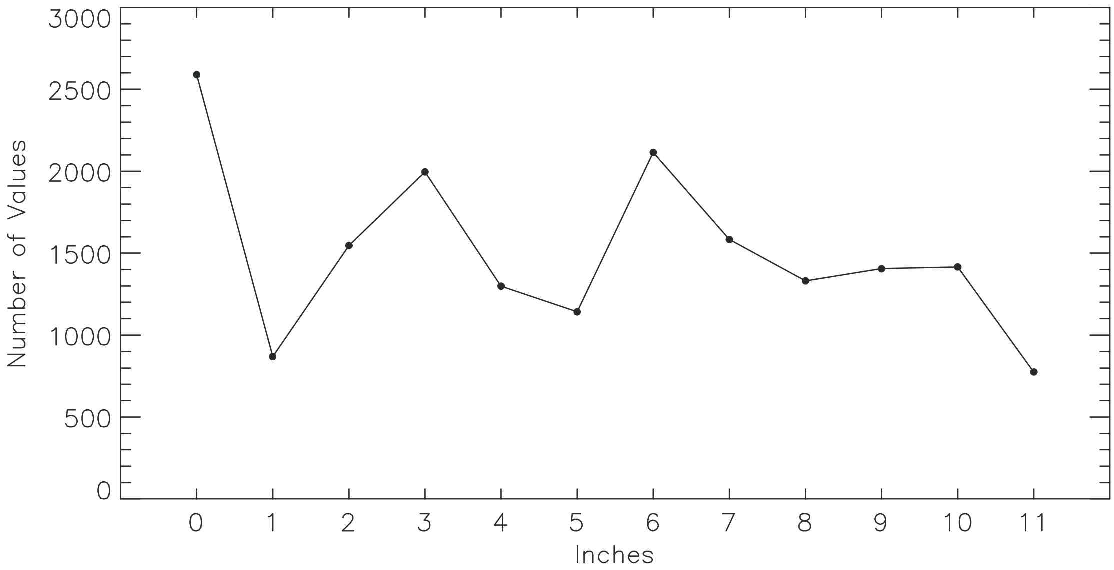

Hutchinson High Waters
Number per Inch
Height above ODS (inches)
25
20
15
10
5
0
100
150
200
250
300

Figure 6



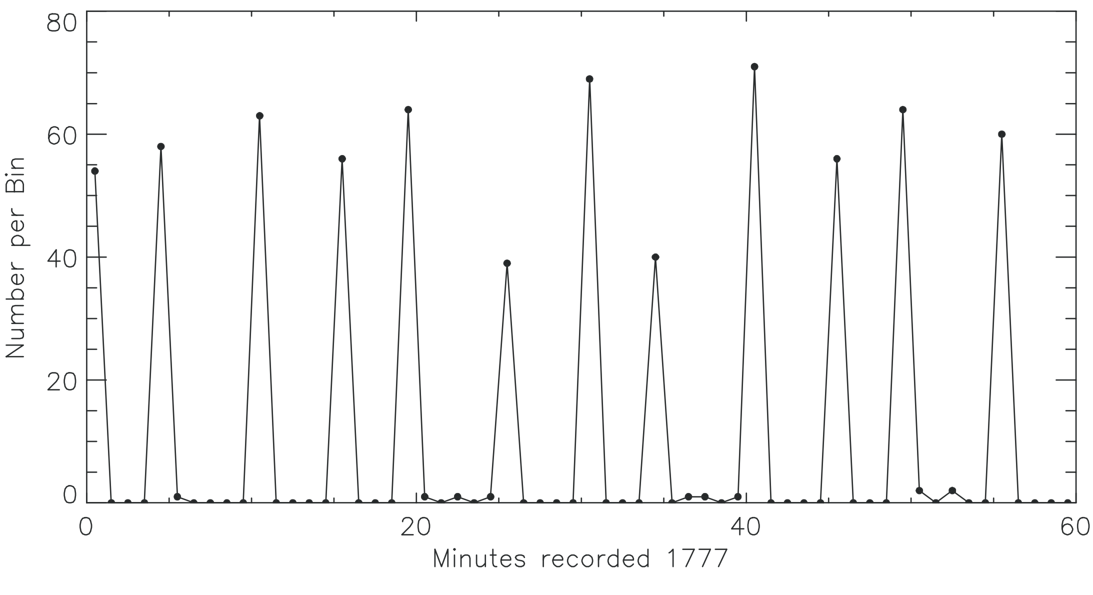
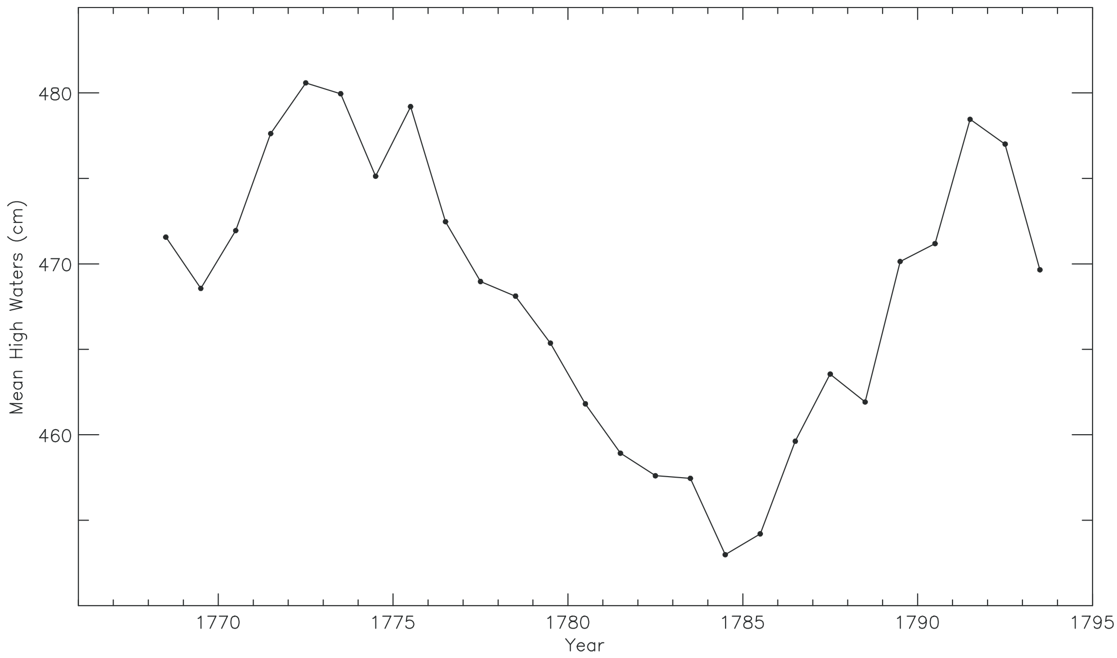


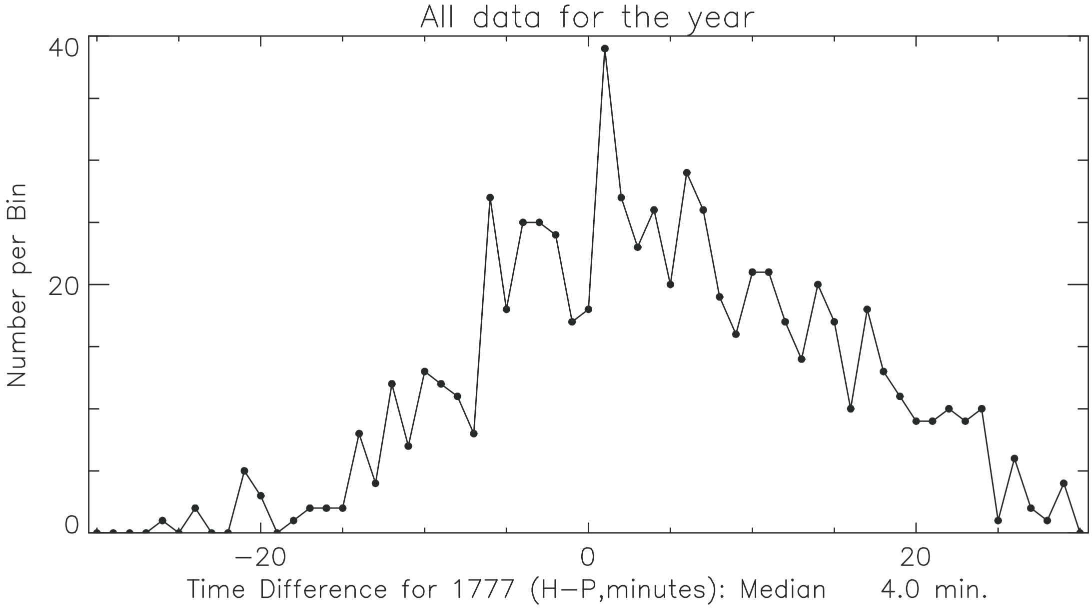
Figure 7 (top) and Figure 8 (bottom)



480
470
460
Mean High Waters (cm)
1770
1775
1780
1785
1790
1795
Year

Figure 9

(a)


All data for the year
Number per Bin
40
20
0
−20
0
20
Time Difference for 1777 (H−P,minutes): Median 4.0 min.

(b)

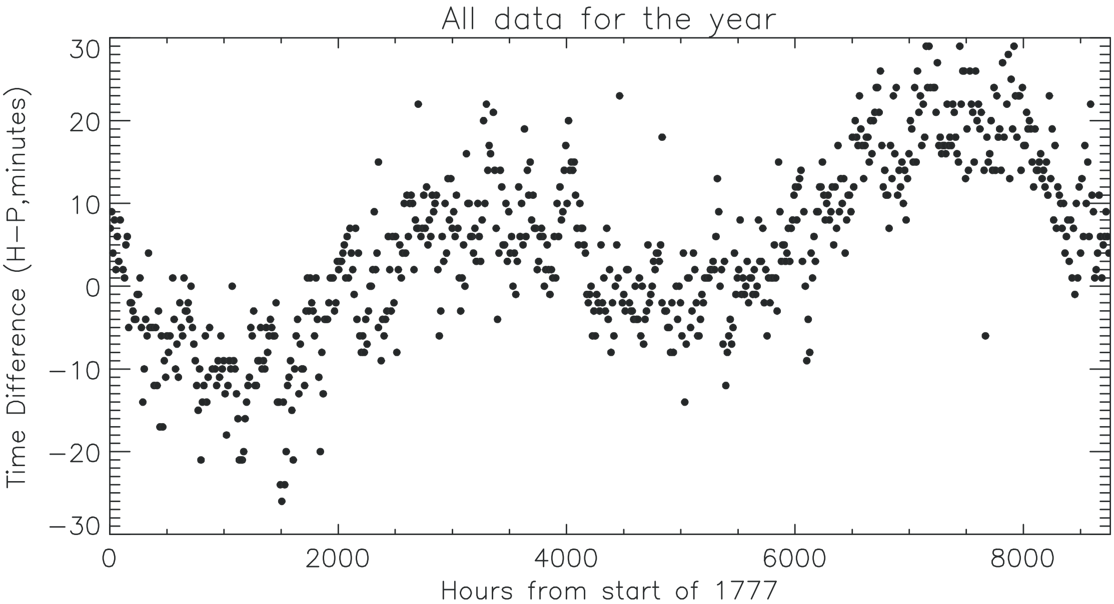

All data for the year
Time Difference (H−P,minutes)
30
20
10
0
−10
−20
−30
0
2000
4000
6000
8000
Hours from start of 1777

Figure 10

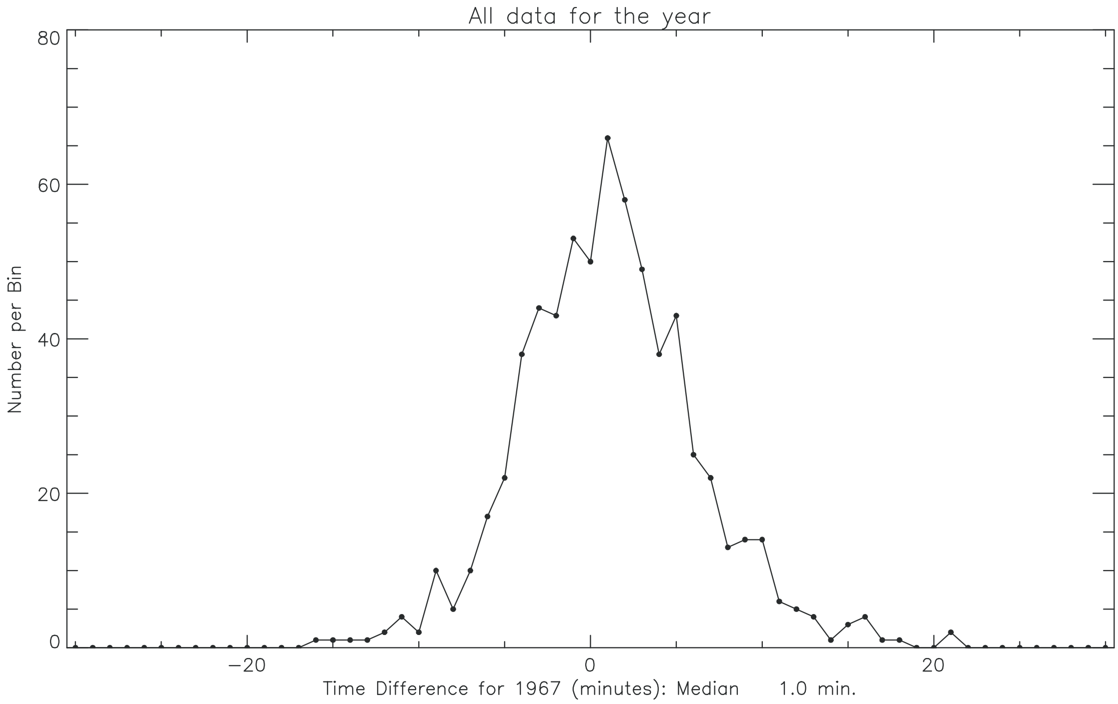
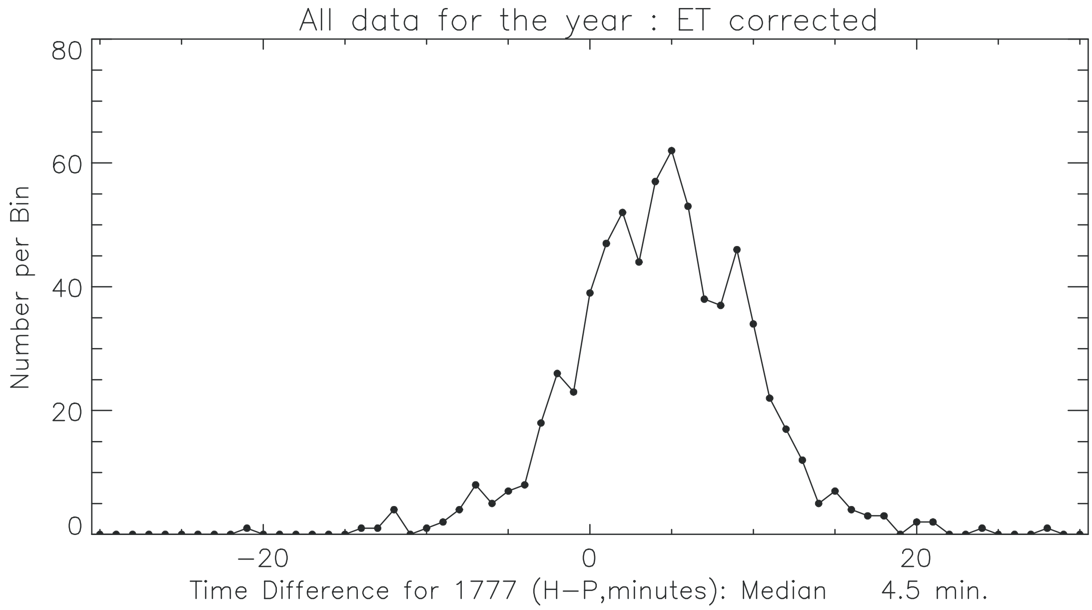

All data for the year
80
60
40
20
0
Number per Bin
−20
0
20
Time Difference for 1967 (minutes): Median 1.0 min.

Figure 11

(a)


All data for the year : ET corrected
Number per Bin
80
60
40
20
0
−20
0
20
Time Difference for 1777 (H−P,minutes): Median 4.5 min.

(b)

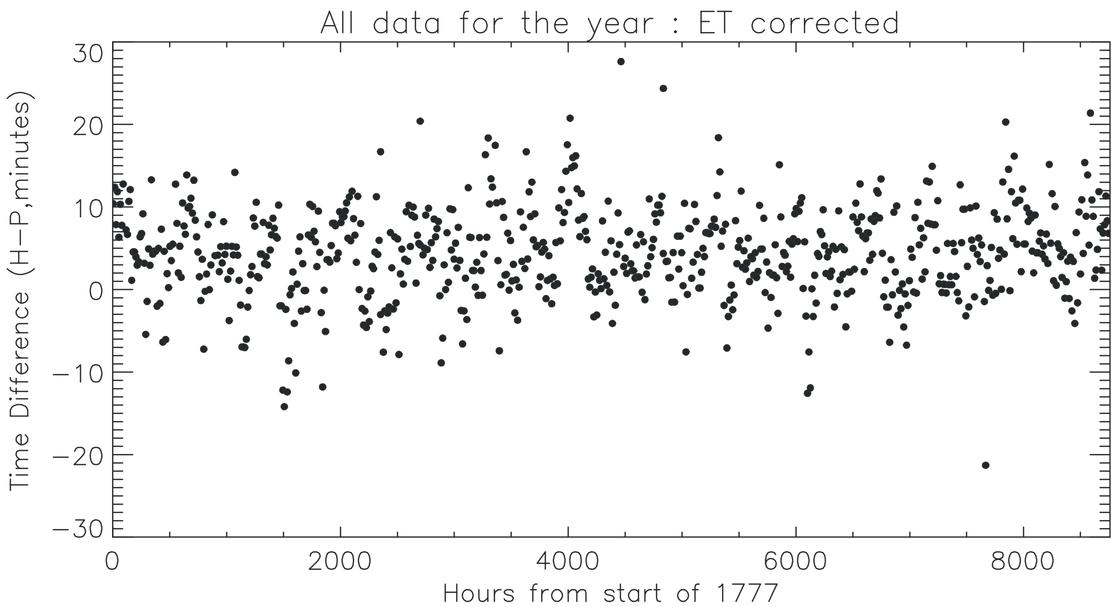

All data for the year : ET corrected
Time Difference (H−P,minutes)
30
20
10
0
−10
−20
−30
0
2000
4000
6000
8000
Hours from start of 1777

Figure 12

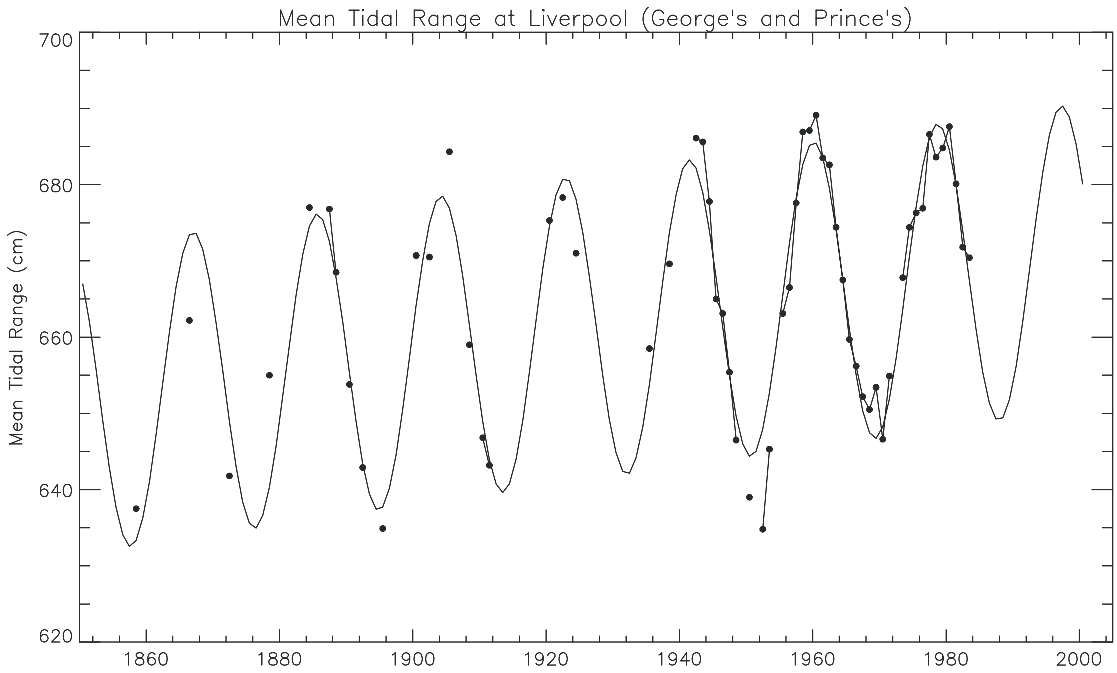


Figure 13

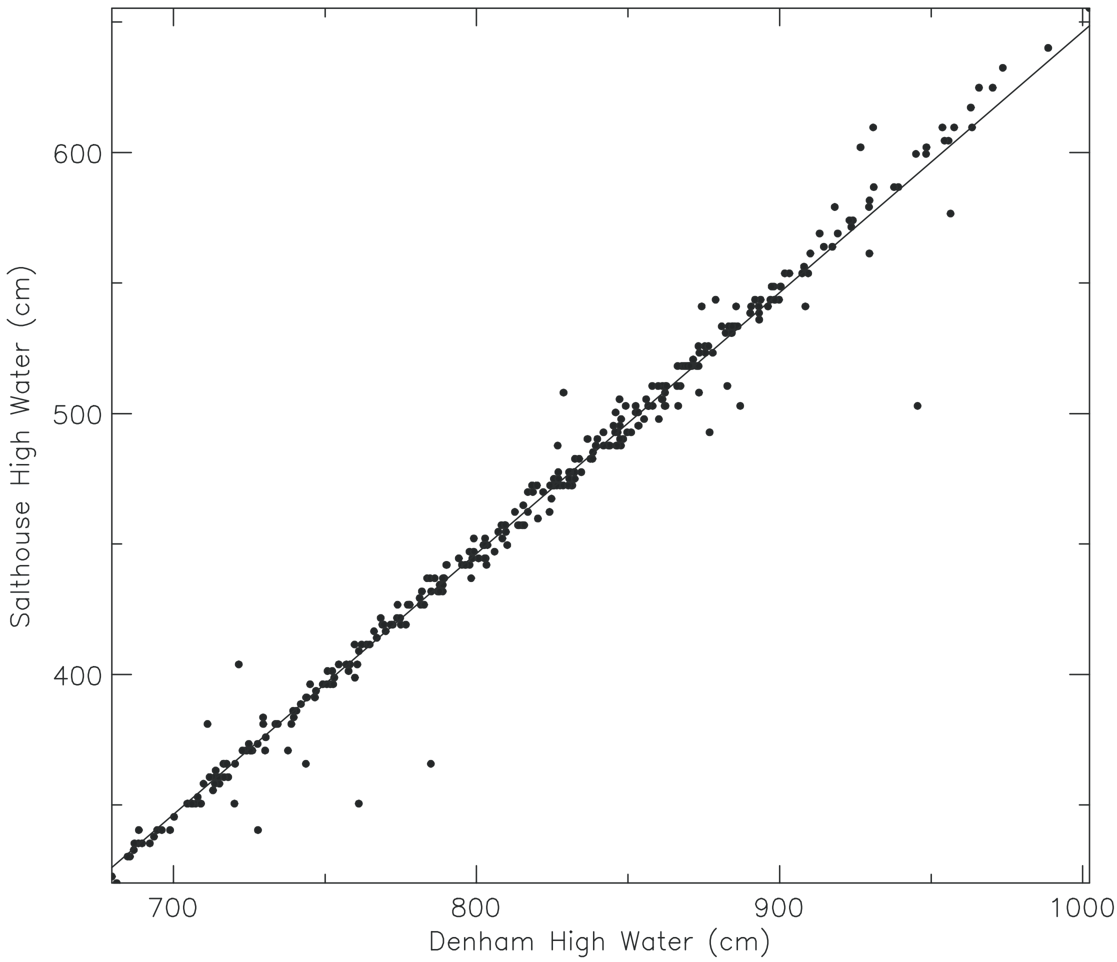


Figure 14

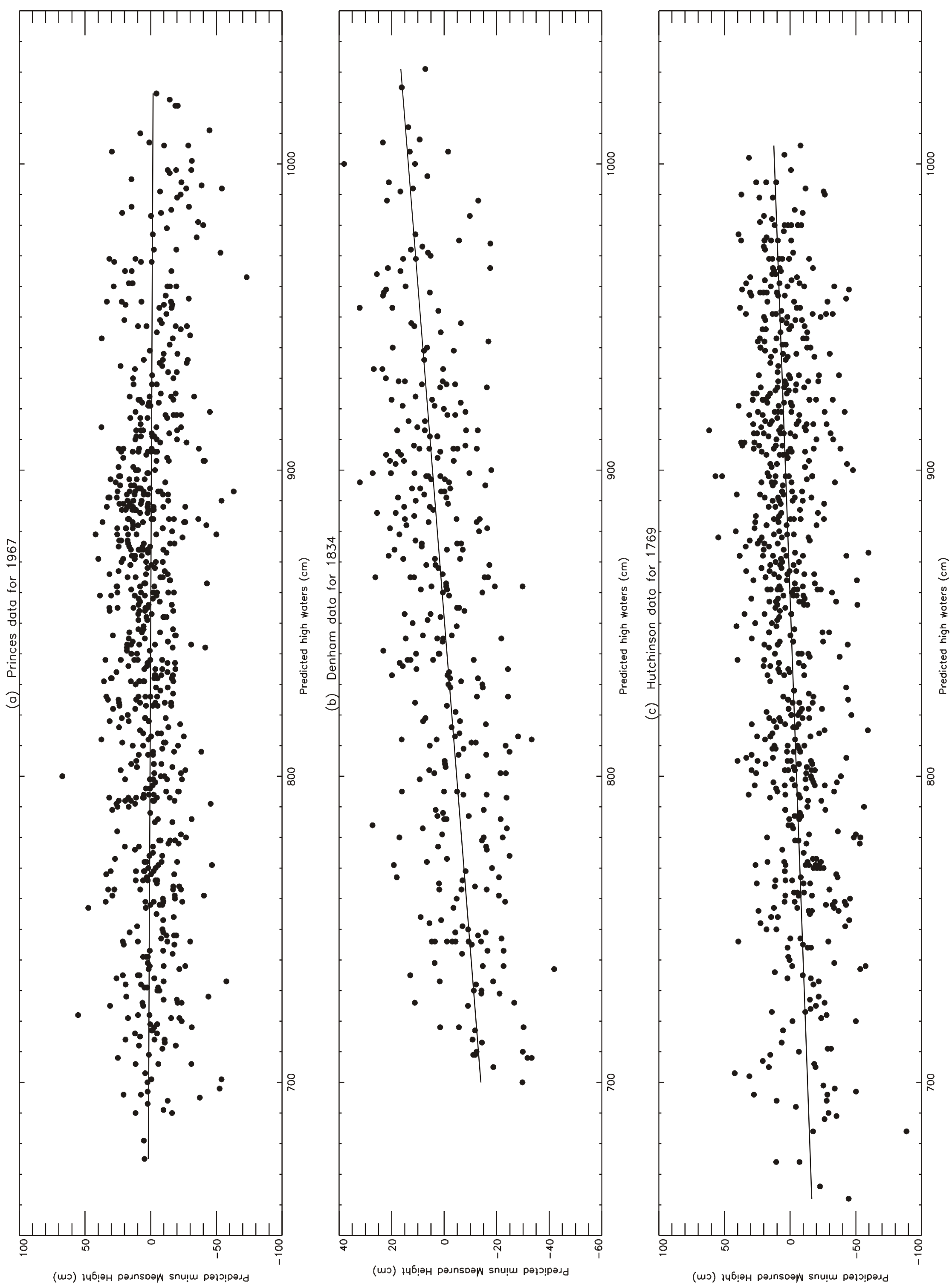

(a) Princes data for 1967
(b) Denham data for 1834
(c) Hutchinson data for 1769
Predicted high waters (cm)
Predicted minus Measured Height (cm)

Figure 15

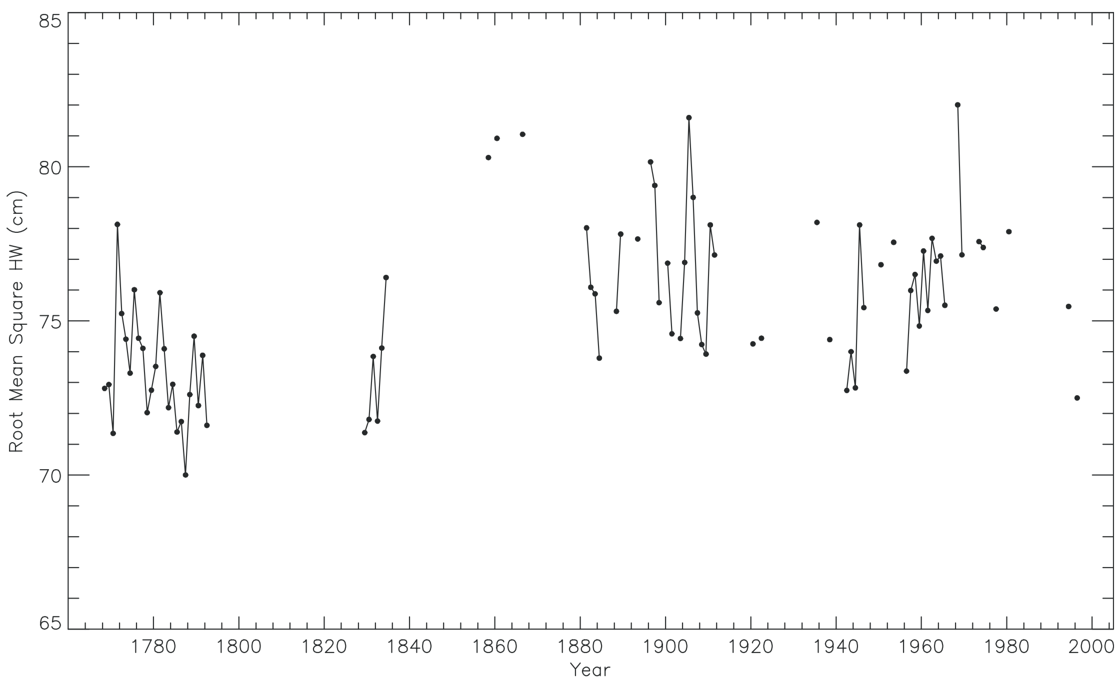
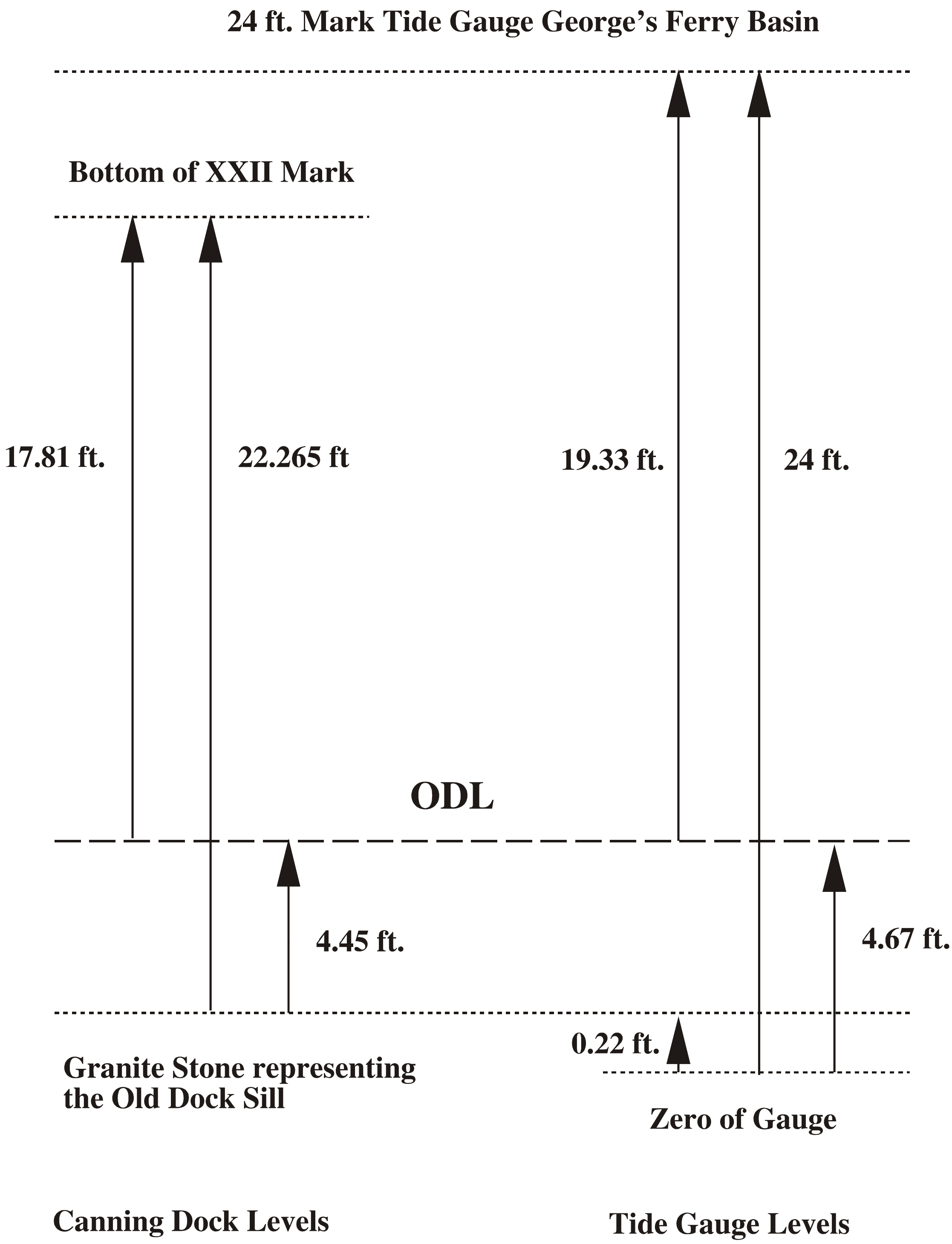

85
80
75
70
65
Root Mean Square HW (cm)
1780
1800
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
Year

Figure 16

Figure 17



Copy of Diagram drawn by Col. Clarke in May 1877.

Figure 18

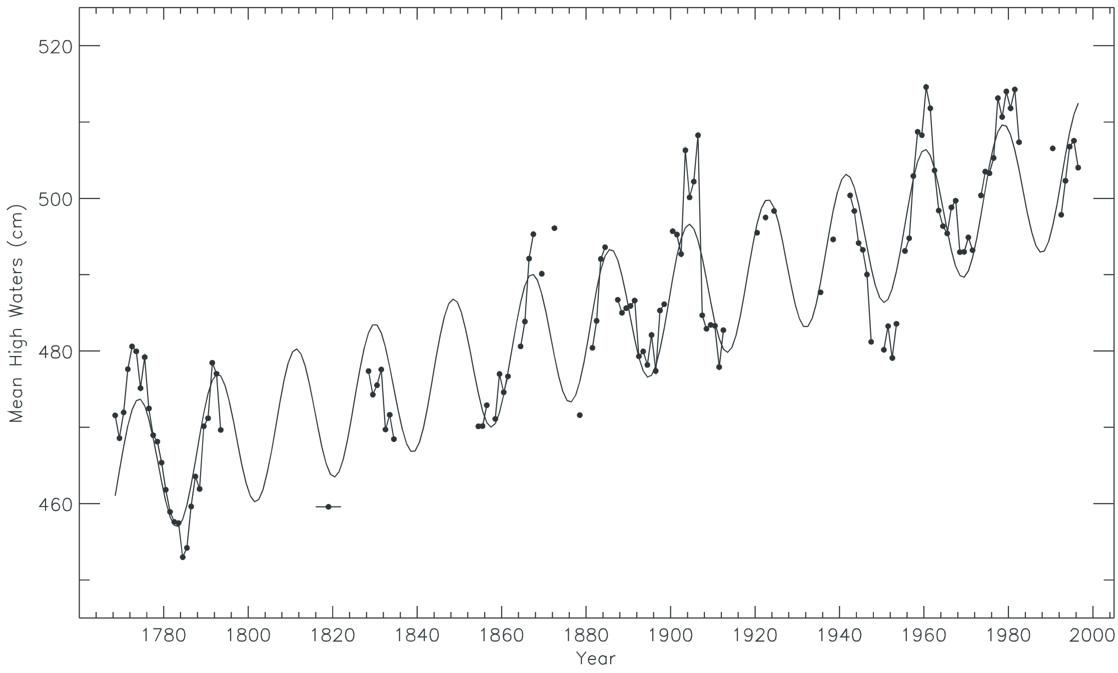


Figure19

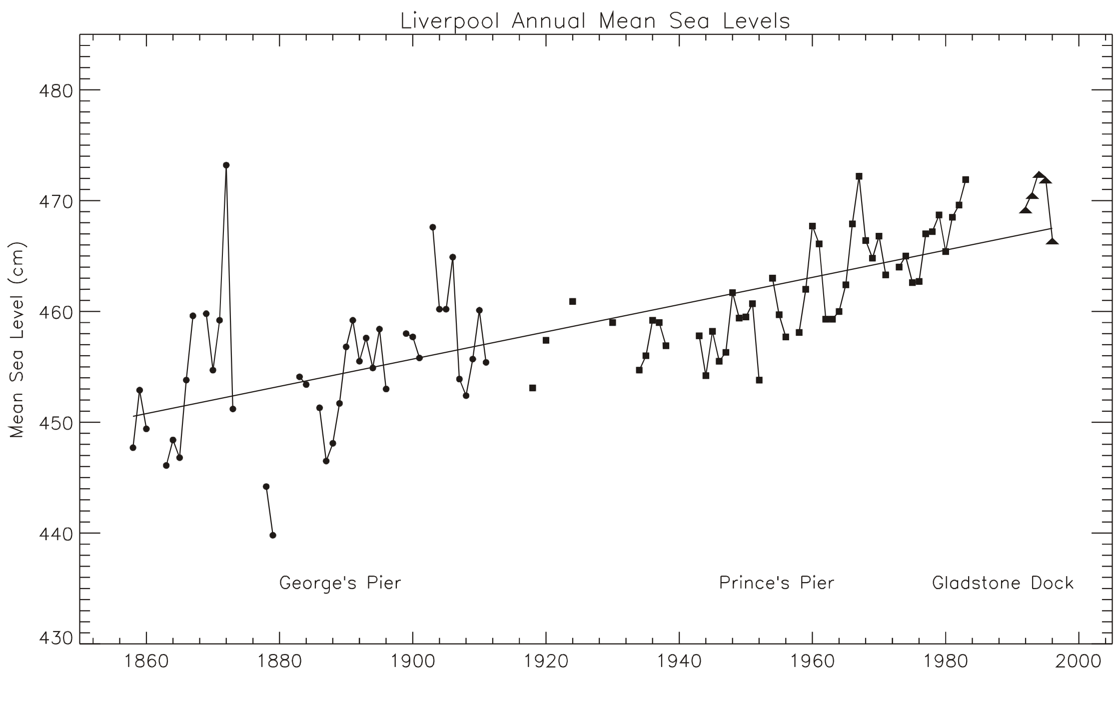


Figure 20

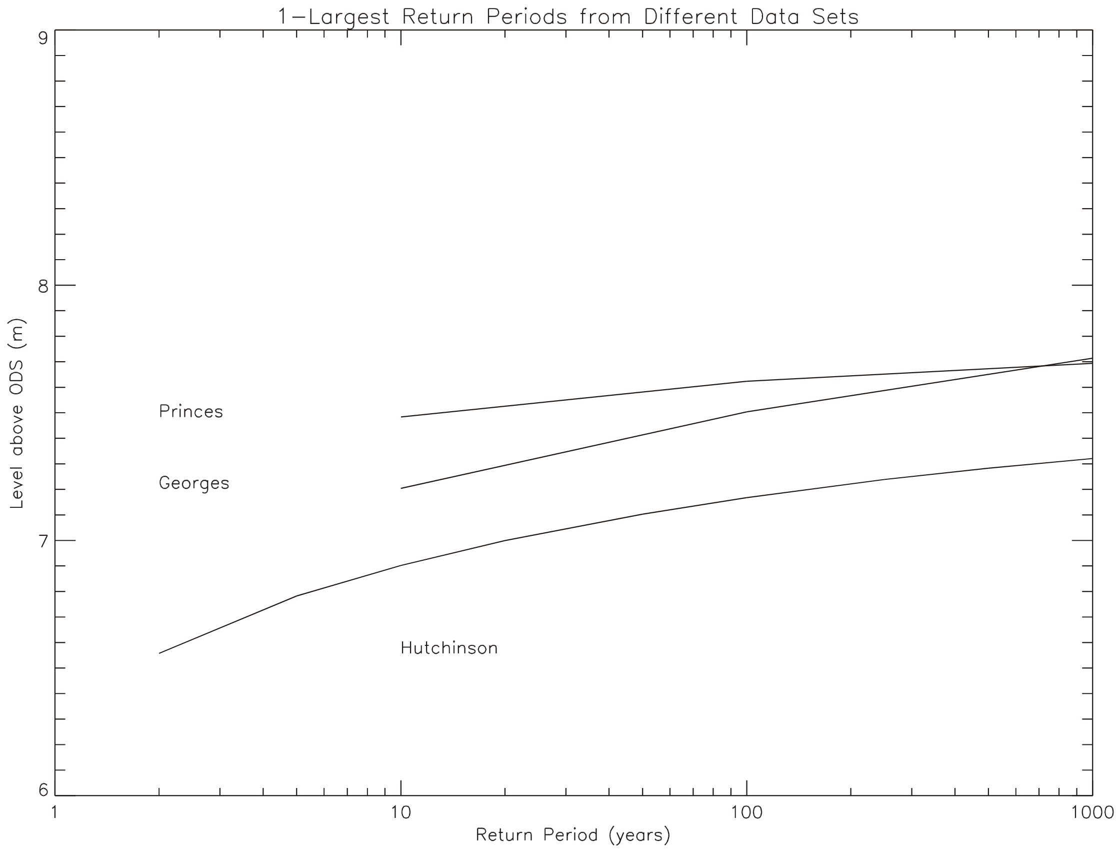


Figure 21

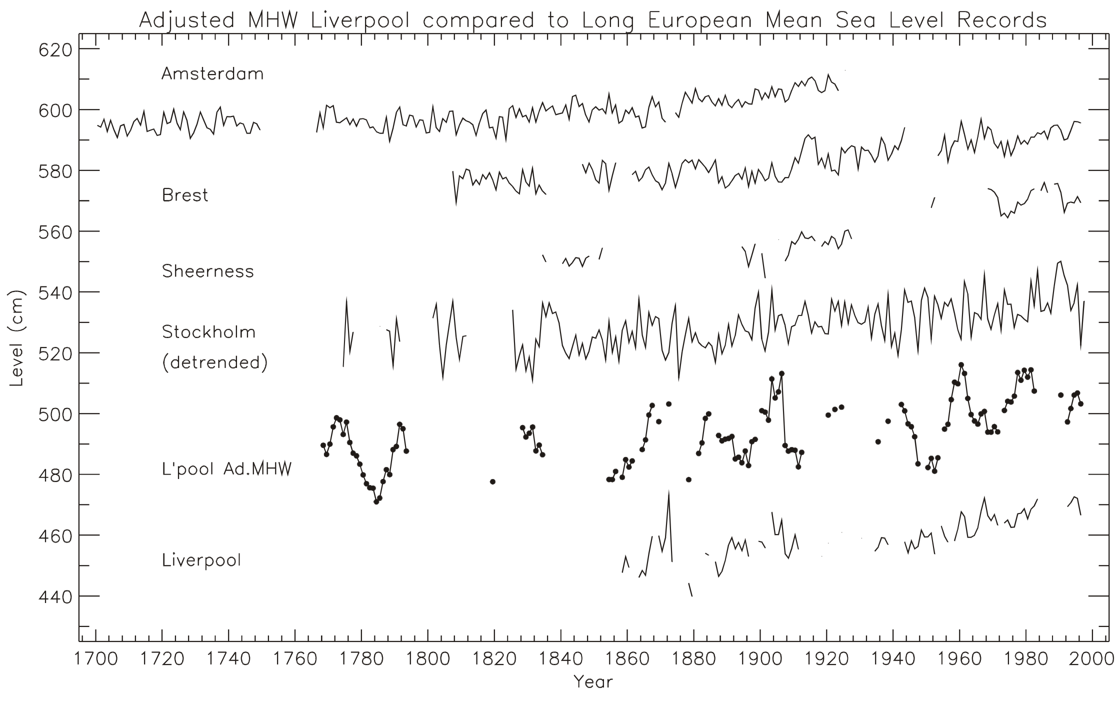


Figure 22