Error analysis of Ordnance Survey map tidelines

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Abstract

Historical trend analysis is often used at the coastline to provide rates of coastal erosion or accretion as part of shoreline or beach management studies. The long-term data for historical trend analysis at UK sites often comes from tidelines (representing high or low water) from Ordnance Survey (or older) maps. Recent Ordnance Survey digital maps no longer retain the date of survey, which is needed for historical trend analysis. An alternative is to use datum-based tidelines from survey data, although these are different from the proxy-based tidelines on OS maps.

The plotting of tidelines on Ordnance Survey maps is reviewed and the errors involved in establishing the positions of tidelines are divided into source uncertainty, interpretation uncertainty and natural shoreline variability. Methods of calculating these errors are presented and examples provided. The methods for including uncertainties in historical trend analysis are introduced. Adoption of these methods would allow the significance of changes in tidelines to be assessed, which will assist coastal management.

Keywords

Coastal engineering; History; statistical analysis

1. Introduction

Historical trend analysis (Whitehouse *et al* 2009, Defra, 2006) has been widely used in studies of coastal geomorphology including many shoreline management plans and coastal strategy studies in the UK in order to calculate rates of coastal erosion or accretion. The most common form of historical trend analysis is by least-squares fitting of a linear trend to data showing cross-shore position against time. The data for historical trend analysis often comes from tidelines plotted on maps, although other features and types of measurement can also be used. For example, features such as cliff top position or dune limits can be plotted (Dornbusch *et al*, 2008a, Moore *et al*, 2003a) while the cross-shore position of a shoreline can be obtained from levelling, RTK GPS, LiDAR, photogrammetry, terrestrial laser scanners, video systems, aerial photography and satellite images (Moore *et al*, 2003b, Rogers *et al*, 2010, White *et al*, 2011). Many of these measurement systems have been recently introduced, while few beach profiles precede the 1960s and few suitable aerial photographs precede the late 1930s (Moore *et al*., 2003a). Maps are therefore the only widespread source of information which can be used to quantify trends in coastal evolution over periods greater than about 70 years, and are the only data source discussed here.

In the UK most topographic maps are produced by the Ordnance Survey (OS). Extensive descriptions of OS mapping have been provided by Harley (1975) and Oliver (2005), both of whom discuss tidelines. However there have only been a few studies of the positional errors of tidelines on OS maps in the UK, such as those by Oliver (1996, 2005), Ryan (1999), Taylor *et al*. (2004), Dornbusch (2005), Sutherland *et al.* (2007) and Dornbusch *et al.* (2008b).

This paper reviews the plotting of tidelines on Ordnance Survey maps from different epochs, then analyses the errors involved in their plotting. Estimates of the total uncertainty in tideline (or shoreline) position are a combination of source uncertainty, interpretation uncertainty and natural short-term variability (Ruggiero *et al*, 2003) and expressions for each term and the total error are presented. The implications for the results from a least-squares best-fit line to the historical tideline positions are then discussed.

2. OS map epochs

Ordnance Survey maps of England and Wales have shown tidelines (High Water Line and Low Water Line) since the introduction of the first series of OS 1" to the mile (1:63,360) maps in 1801 (Oliver, 2005). In theory therefore OS maps provide time series of shoreline position that can extend back up to 200 years. Older maps tend to have significantly lower accuracy and might be used to evaluate general geomorphological trends (see, for example, de Boer and Carr, 1969) but should not be included in a trend analysis unless their accuracy can be determined.

Better accuracy can be obtained by using larger scale maps and in September 1841 surveying began in Lancashire on the first map at 6" to the mile (1:10,560) scale. Rural 1:2,500 scale maps (roughly 25" to the mile) were commissioned in 1854 and in 1880 the production of these maps was accelerated to cover the whole country. These maps are known as the County Series as each county was surveyed separately and often on its own grid system. The County Series were the first maps to have been surveyed with regard to a geographical reference system that was displayed on the map itself.

The projection most commonly used by the OS at this time was the cylindrical Cassini projection (Harley, 1975) which introduces scale effects that are different to those from the Transverse Mercator projection that was adopted as the basis for the National Grid. This makes GIS analysis of original paper maps that use the different projections more difficult.

All maps were transferred to the National Grid in 1944-1945. The standard scales for detailed mapping became 1:2,500 in rural areas, 1:1,250 in urban areas and 1:10,000 in upland areas (Oliver, 2005). There is considerable overlap between the series, particularly the National Grid overhaul which began in 1945 and continued until the 1980s. A programme to digitise National Grid maps was started in 1971 and was accelerated in the 1980s when the demand for digital data increased (Ordnance Survey, 2006). These maps have been revised digitally since their capture and are marketed as the Land-Line® product. Converting the unstructured tile-based data into an object-based, seamless dataset took from April 2000 to October 2001 and resulted in the Mastermap® product.

3. Tidelines on OS maps

Surveyors in the 19th and 20th centuries were given detailed instructions on when and how to survey these lines, which were of legal importance (Johnston, 1905, Winterbotham, 1934, Oliver, 1995, 2005). Early OS maps portray tide lines from ordinary spring tides on maps of England, Scotland and Wales. Maps of Scotland have continued to show high and low water marks for ordinary spring tides, which “generally occur the third of fourth tide after new or full moon” (Johnston, 1905).

The tide lines mapped on the County Series maps of England and Wales since 1879 are Low Water Mark of Ordinary Tides (LWMOT) and High Water Mark of Ordinary Tides (HWMOT) which are “those of high and low water of ordinary tides (i.e. tides half way between neaps and springs) which define the limit of the foreshore” (Ordnance Survey, 1882). The Ordnance Survey (1882) instructed surveyors to use tide tables to ascertain the high and low tides that most closely correspond to HWMOT and LWMOT. If tide tables were not available then Ordnance Survey instructions state that, “As the next best approximation…the fourth tide before new and full moon and before first and third quarters” should be utilised. The Ordnance Survey’s 1905 instructions to field examiners (Johnston, 1905) contained similar advice: surveys of Mean High Water (MHW) and Mean Low Water (MLW) were taken from “tides half way between a spring and a neap, and should generally be taken at the fourth tide before new and full moon”.

The name changes from MHWOT to MHW and MLWOT to MLW are not significant as the definitions remained the same. Note, however, that MHW and MLW are not given in Admiralty Tide Tables, which is not a problem provided consistent calculations of MHW and MLW are performed.

Surveys were to be made during calm weather (Ordnance Survey, 1882) which limited the opportunities to survey but at least meant that changes in water level due to storm surge and wave setup were minimised. Note, however that calm weather is often associated with high pressures, which could have led to systematically low water levels (Dornbusch *et al*, 2008).

Tide lines on County Series maps usually came from measured line surveys with offsets (Ryan, 1999). A proxy tideline (a physical feature taken to represent the shoreline) was surveyed. High tide lines were captured by 1 of two methods:

1. Objects were placed on the beach at the time of high water. The positions of the objects were surveyed and the surveyed points were joined to form the MHW or MLW mark. The sketching between points is expected to have added a greater error than that at surveyed points.
2. The mark left by high tide was surveyed. Winterbotham (1934) noted that high tide “generally leaves a clear mark … there is not much difficulty in surveying this line”.

Low tide lines were captured in similar ways, with low water surveys undertaken half an hour either side of low water. Ordnance Survey instructions of 1932 and 1963 contained the same information, although the 1963 definitions were expanded to include procedures for conducting air surveys (Ryan, 1999). Since about the 1970s the Ordnance Survey has mainly provided tide line data from aerial surveys preferably using black & white infrared film as this shows the water/foreshore interface more clearly. Admiralty tide tables were examined to find high and low tides which were within ± 0.3metres of MHW and MLW. The aerial photographs were taken at the time of low tide and provided an instantaneous snapshot of the tide line position. Note, however, that MHW and MLW on the same map could have been surveyed in different years and that the older methods were still used in some cases.

Today, major coastal and non-coastal defences designed to reduce the risk of flooding are in the OS Category A, which means they will be captured as part of a continuous revision process within six months of completion. Mean high and low water when affected by changes to other features (such as coastal defences or jetties) and significant changes to tidelines (when evident from aerial photography conducted as part of the national sweep or when notified by a customer) are classified as Category B and will be captured as part of a national sweep programme, which occurs every few years.

Note, however, that no historical records are maintained about the date of survey for continuous revision so that it is becoming difficult to establish when OS tidelines were re-surveyed (as already noted by Moore *et al*, 2003a). If this policy continues, it will make modern digital mapping from the OS less and less useful in establishing trends in coastal evolution (or indeed, the evolution of any feature) at a time when digital mapping and coastal change analysis within GIS systems (Thieler *et al*, 2008) are becoming more prevalent.

If the Ordnance Survey cannot be persuaded to add the date of survey to its digital products, a move must be made to obtaining recent MHW or MLW positions from other sources. Fortunately, an increasing volume of beach level data is being regularly and systematically collected, from which the positions of contours representing MHW and MLW can be obtained. This is primarily from beach profile surveys undertaken by the coastal observatories or from LiDAR flights run by the Environment Agency. These sources can be used to produce a datum-based tideline by extracting a contour at the local MHW or MLW level, whereas the tidelines on OS maps are proxy-based as they were produced by identifying the location of a shoreline. The differences between datum based and proxy based shorelines do not appear to have been analysed in the UK, although they will be similar in principle to those found in the United States (Ruggiero *et al*, 2003, Ruggiero and List 2009).

3.1. Problems with OS tidelines

Oliver (2005) noted that some of the pre-1868 spring tide lines were simply copied onto maps produced after this date (i.e. first series County Maps) and were renamed but not resurveyed. First series County Maps may, therefore, show spring tide lines and not ordinary tide lines, which makes their use in historical trend analysis less reliable than later series maps. Admiralty Surveys use Mean Low Water Springs and these data were also sometimes used on OS maps of England and Wales and a note provided to explain this, which may not be obvious. There would be a systematic and in some cases significant difference between the positions of tidelines mapped at Mean High/Low Water Springs and Mean High/Low Water. For example, MLWS is about 0.8 m below mean low water in the southeast England (Dornbusch *et al*, 2008) so on a 1:80 beach slope MLWS and MLW would be about 60 m apart.

Johnston (1905) noted that “on long flat foreshores the lines of high and low water mark are generally surveyed and plotted” but “if the foreshore has sandbanks or difficulties which would make the survey expensive, or if it is steep and rocky with only small sandy bays the low water mark will often be supplied by the Examiner” and were presumably not actually surveyed. A judgement on whether this has been done or not has to be made on a case by case basis based on comparisons between successive county series maps.

Ordnance Survey (2003) reported problems in matching the OS MasterMap® topographic representation of MHW line and MLW line and the UKMO depth area polygon bounded by MHW and MLW and concluded that Mastermap® does not have a clean and coherent MLW line, so judgement must be used in analysing even the most recent maps.

4. Uncertainties in shoreline position

The total error in the positions of tidelines on maps is made up of a source uncertainty, an interpretation uncertainty and a variability error (Ruggiero *et al*, 2003). Source uncertainty reflects the errors involved in the measurement of any point and includes errors in triangulation, the resolution of and type of corrections applied to aerial photos and GPS errors. Interpretation uncertainty represents the error in turning the data into a shoreline. This includes the difficulty of determining the shoreline from an aerial photo and the error in determining the mean high water position from a single visit. Variability errors reflect the dynamic changes in the position of the tidelines that occur in response to changes in waves and water levels.

These errors are assumed to be independent, so may be combined by calculating the square root of the sum of the squares of the standard deviations. It follows that the root-mean-square total error, RMST, is given by Equation 1.

$$\mathrm{RMST} = \sqrt{\mathrm{RMSS}^2 + \mathrm{RMSI}^2 + \mathrm{RMSV}^2} \tag{1}$$

Where RMSS = root-mean-square source uncertainty, RMSI = root-mean-square interpretation uncertainty and RMSV = root-mean-square variability error. If the total errors are approximately normally distributed, about two thirds of the tideline positions will lie within one standard deviation of the mean tideline position and about 95% will lie within two standard deviation of the mean.

The three error types are discussed below.

4.1. Source uncertainty

The location of a point has an absolute error, which is a measure of the error in determining the position of a feature relative to the National Grid and a relative error, which is a measure of the error in determining the position of a feature relative to close-by features. Relative errors are always less than absolute errors. Absolute errors of features with respect to the National Grid can be 20 m (Dornbusch 2005) while edge mismatches between adjacent maps in historical OS 1:10,000 scale maps can be up to 200 m (Sims *et al*, 1995). Tidelines should ideally be measured relative to fixed local features. Any comparison of the position of tidelines between successive maps should also include some measurement of fixed points, to check the relative and absolute errors that can occur.

Ryan (1999) compared the positions of fixed points on 1:2,500 County Series maps and National Grid maps to the results from a detailed GPS/total station survey around Porlock, Somerset. The root-mean-square error varied between 2.62 m for the 1972 National Grid map and 3.47 m for the 1902 County Series map, as shown in Table 1, which also partitions the root-mean-square error into the root-mean-square systematic error and the root-mean-square random error. The systematic errors were generally less than random errors.

The Ordnance Survey (2004) Positional Accuracy Improvement (PAI) programme has increased the absolute accuracy of data at 1:2,500 scale relative to OS National Grid and has been applied to Land Line® and Mastermap® data (Table 2). In map tiles that are part land and part sea cover, however, the sea cover areas have not been altered by PAI, although the relativity of tidelines and landform have been maintained (Ordnance Survey, 2004). Tidelines cannot therefore claim the post-PAI accuracies quoted above, but should be treated as having pre-PAI accuracy.

Tables 1 and 2 indicate that a root-mean-square source error of 3.3 m can be taken for the County Series (1:2,500) while 2.8 m can be used for the National Grid and MasterMap® 1:2,500 tidelines.

4.2. Interpretation uncertainty

The estimation of root-mean-square interpretation error is made on the assumption that the MLW was surveyed and not added later by the Examiner. Interpretation errors come from:

- Uncertainty in the elevation of low or high water with respect to the target value;

- Uncertainty in deciding the instantaneous position of the moving shoreline which is subject to some irregular wave action.

Further sources of uncertainty in the elevation of low or high water include (i) error in tide table level, (ii) difference between measured water level and MHW/MLW, (iii) variation in water level within 0.5 hours of MHW and MLW and (iv) variation in tideline position due to wave setup and swash. Each is discussed below.

4.2.1. Tide table accuracy and residual levels

Levels in tide tables are set to the nearest 0.1 m so have a maximum error of 0.05 m, implying a root-mean-square error of about 0.025 m.

Water levels at the predicted time of high/low tide may not be at the MHW/MLW level. Surveys were to be taken when the predicted water level was close to the MHW/MLW level. The limits on accuracy of elevation are unclear, but on the switch to aerial photography a limit of ±0.3 m was set. Ryan (1999) interpreted this to be an absolute maximum and inferred a standard deviation of 0.1 m from this.

Admiralty Tide Tables have been used to identify tides at four standard ports that were predicted to fall within the MHW ± 0.3 m limit during the summer (May to September) of 1996. Tides during the summer were chosen to avoid the worst storms and provide a data set close to normal conditions. 1996 was an arbitrary choice of year.   The mean and standard deviation of the residual (measured – tide table) MHW levels are given in Table 3. These strictly apply only at the standard port and only for summer 1996. The procedure demonstrated can, however, be applied to other locations and years for site-specific studies and the similarity of the results indicates that they may be more widely applicable.

If a suitable tide was not available, surveys for OS map tidelines could be conducted at the fourth tide prior to new and full moon. The uncertainties introduced by this approach were highlighted by Dornbusch *et al.* (2008) who calculated the mean low water elevation for these tides for the tide gauge at Newhaven in 2004. The elevations varied between 0.35 m above mean low water and 0.6 m below mean low water. The average level of these tides was 0.12 m below the mean low water elevation, with a standard deviation of about 0.25 m. These tides were only used if suitable tide tables were not available, but it is not clear on which parts of which maps these tides were used. These results are similar to the results from Table 3.

4.2.2. Variations due to timing and waves

The variation in the water level within half an hour of high or low water can be estimated for primary ports from Admiralty Tide Tables mean spring and neap curves. For example, the maximum changes in elevation at a number of primary ports are given in Table 4, based on the 1991 Admiralty Tide Tables. The elevation changes near low water are larger than the elevation changes near high water. Apart from Avonmouth (which has an unusually high tidal range) the maximum changes were 0.1 m at high tide and 0.15 m at low tide. The relationship between the elevation change 0.5 hours from high or low water and the root-mean-square elevation change from a survey during this period depends on the shape of the tide curve near high or low water. The root-mean-square error has been estimated to be half the maximum. This can be calculated from the nearest primary port or, as a first approximation the following values can be used: root-mean-square error = 0.05 m for high water and 0.1 m for low water.

Tidelines were to be surveyed during calm conditions, when there will be a limited swash zone, so a vertical root-mean-square error of 0.05 m is proposed for surveying the instantaneous position of the tideline with a plane table and a staff.

4.2.3. Combining errors

The four errors are assumed to be independent, so are combined by calculating the square root of the sum of the squares of the standard deviations (as for Equation 1). This gives typical values of root-mean-square error in level of 0.23 m for high tide and 0.29 m for low tide. This combination of errors ignores the measured mean errors (Table 3) which will bias the results. The method is therefore only valid if the mean errors are essentially invariant with time. This has not been investigated, although the method is likely to be valid in cases where the mean error is low.

The horizontal error then depends upon the beach gradient, which is likely to be greater for MHW than for MLW. Gradients should be determined for each site from local beach profiles.

4.3. Natural variability

The root-mean-square variability error (RMSV) is a measure of the horizontal variability in the cross-shore position of a given contour, due to natural changes in the waves, currents and water levels. Values for this figure should be obtained for each site by analysing beach profiles. Each profile should be interpolated to give the cross-shore position of MHW and MLW for each survey. Analysing a number of surveys will provide a time series of each. This time series should be de-trended (a straight line fit should be sufficient) and the root-mean-square value obtained. This is the RMSV.

An example of this is provided by beach profile data collected in Lincolnshire between 1959 and 1991 (Sutherland *et al*, 2007). MHW was estimated to be the average of mean high water for spring tides (MHWS) and mean high water for neap tides (MHWN) at Skegness, while MLW was estimated as the average of mean low water for spring tides (MLWS) and mean low water for neap tides (MLWN) at Skegness (from the 1991 Admiralty Tide Tables). An example of de-trended cross-shore position of MHW from the cross-shore profiles at Mablethorpe Convalescent Home (at national grid coordinates 551,278 mE, 384,400 mN) is shown in Figure 1. The resulting root-mean-square variability errors at a number of cross-shore profiles are given in Table 5, which includes values for MHW, mean water level (MWL) and MLW. In some cases there were insufficient surveys at MLW to provide a reasonable estimate. These cells have been left blank. The number of years of data used in the analysis is given in column 2. In cases where 10 years' data was used, the time span was 1981 to 1991.

The root-mean-square variability error increases on going down the beach profile, as the beach profile flattens, as shown in Table 5. The root-mean-square variability error is zero at MHW at Trusthorpe Outfall as the beach level was so low, only the position of the sea wall was recorded. The range of other root-mean-square variability errors at MHW was from 2.0 m to 14.5 m. The root-mean-square variability error at MLW was not obtained for half the profiles where there were insufficient results at that level. The range of measured errors at MLW was from 10.8 m to 22.2 m.

4.4. Summary and Examples

It has been easier to estimate the root-mean-square vertical variations in some cases. These can easily be translated into typical horizontal distances if the local beach slope is known. The natural variation in the position of MHW and MLW can be derived from beach profiles and this should be done on a case-by-case basis. The sources of error are summarised below:

1. The root-mean-square source error (RMSS) for 1:2,500 scale mapping decreases from 3.3 m for County Series maps to 2.8 m for National grid maps. Mastermap mapping is taken to have the same error as National Grid mapping.

2. The root-mean-square interpretation error (RMSI) is given approximately by 0.23/tan(α) m for MHW and 0.29/tan(α) m for MLW where α is the beach slope. Similar values apply for County Series, National Grid and Mastermap. Regional differences are possibly larger than differences between map series.
3. The root-mean-square variability error (RMSV) can be determined from beach profiles. As an example, in Lincolnshire between 1959 and 1991, the RMSV at MHW varied between 0 m and 8 m, while that at MLW varied between 10 m and 23 m. Beach profiles were relatively steep, being around 1:30 at MLW. Larger errors may be anticipated on flatter beaches.

These values are not necessarily applicable outside the areas they were derived for and local values should be estimated whenever practicable. In the absence of supporting evidence, the figures provided may be used as a first estimate of the errors.

A number of examples from Lincolnshire are set out below:

- MHW on a National Grid map with a 1:25 slope would have a root-mean-square total error of 6 m to 10 m.
- MLW on a National Grid map with a 1:30 slope would have a root-mean-square total error of 14 m to 24 m.
- MLW on a National Grid map with a 1:100 slope would have a root-mean-square total error of 31 m to 37 m.

So, for example, two surveys of MLW (if on a 1:100 slope) could be up to 150 m apart (approximately four standard deviations) with the differences being caused by the survey methods used and the natural variations in the beach morphology. No net erosion or accretion need have taken place. The above examples are not necessarily the worst-case scenarios as there are obvious problems in determining MLW in cases where there are sandbanks (if the inshore channel level is about MLW) and ridge and runnel beaches. In the former case the channel bed may be above MLW and MLW will run at the seaward side of the sandbank or it may be below MLW and the MLW will run along the beach side of the channel. In the latter case the position of low water will depend on the configuration of ridges and runnels. However, in most cases of interest the beach slope is steeper and the error is much less.

5. Including uncertainty in trend analysis

Trend analysis typically starts with the digitisation of tidelines in a GIS. Two methods of detecting changes in shoreline position are commonly deployed:

1. Cross-shore transects with their origins on the landward side are drawn at set positions along the study frontage. The distance of each tideline from the origin is calculated and recorded with the year of survey.
2. The study frontage is divided into sections and the digitised tidelines are bounded onto polygons extending from a baseline on the landward side. The average distance of the tideline from the baseline is estimated as the area of the polygon divided by the sector length. This is recorded with the year of survey.

Long-term shoreline change rates can be determined using linear regression on cross-shore position versus time data. Normally no account is taken of the uncertainties in tideline position, as quantified in this paper. Genz *et al.* (2007) reviewed linear regression methods, including end point rates, the average of rates, ordinary least squares (including variations such as jackknifing, re-weighted least squares, weighted least squares and weighted re-weighted least squares) and least absolute deviation (with and without weighting functions). Genz *et al.* (2007) recommended that weighted methods should be used if uncertainties are understood, but not otherwise. The ordinary least squares, re-weighted least squares, jackknifing and least absolute deviation methods were preferred (with weighting, if appropriate). If the uncertainties are unknown or not quantified then the least absolute deviation method was recommended. Thieler *et al.* (2008) implemented several of the favoured analysis methods in a GIS while uncertainties in position and time can be input into many least-squares regression routines, including in spreadsheets.

Confidence limits can be calculated to provide a measure of the reliability of the erosion or accretion rate. They provide a range for the calculated erosion or accretion rate and depend on the variance of the data, the number of samples and the desired level of confidence. They strictly apply only to the time period the data was collected in. The extrapolation of trends and confidence limits into predictions assumes that the future hydrodynamic climate will be statistically similar to the climate during the period the measurements are made. Limits on the predictive skill of an extrapolated trend line have been discussed by Sutherland *et al.* (2007).

6. Conclusions

Ordnance Survey maps provide long, irregularly spaced, time series of tideline positions that have been used in the assessment of long-term coastal evolution. The Ordnance Survey has consistently used the same definitions of mean high water and mean low water from 1879 onwards (with some early exceptions) as far as changes in technology would reasonably allow, which allows useful information to be obtained from successive releases of the same map. However, the Ordnance Survey no longer retains records of the date of survey of tidelines, which makes recent OS digital maps increasingly difficult to use in analysing coastal change. This may precipitate a move to plotting recent tidelines as contours from digital elevation models, as obtained from LiDAR or other survey methods. However, these datum-based tidelines are not the same as the traditional proxy-based tidelines, which are obtained by surveying a feature on the beach, and the differences between the two do not appear to have been analysed in the UK. Further work will be needed to enable datum-based and proxy-based tidelines to be used together with confidence.

The tidelines on the first series county maps should be treated with caution as some tidelines were copied from earlier maps which used different water levels, so analysis of tidelines would ideally start with the second series maps. The errors in plotting proxy-based tidelines have been separated into source uncertainty, interpretation uncertainty and natural shoreline variability. Methods of calculating these errors have been presented and examples provided. The methods for including uncertainties in historical trend analysis have been introduced. Adoption of these methods would allow the significance of plotted changes in tideline position to be assessed, which will assist coastal managers in appraising coastal management options.

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7. Tables

Table 1: RMS Source Errors from County Series and National Grid maps

Statistic	1888 County Series	1902 County Series	1928 County Series	Average County Series	1972 National Grid
Root-mean-square error	2.96	3.47	3.37	3.27	2.62
Root-mean-square systematic error	1.59	1.88	2.38	1.95	1.24
Root-mean-square random error	2.50	2.90	2.37	2.59	2.31

Source: Ryan, 1999

Table 2: Accuracy of OS 1:2500 National Grid Overhaul Mapping and post-PAI Mastermap

Map Series	Type of error	RMSE at 63.2% confidence limit [m]	RMSE at 95% confidence limit [m]
National Grid 1:2500	Absolute	< ± 2.8m	< ± 5.8m
National Grid 1:2500	Relative	< ± 1.8m	< ± 4.7m
Mastermap 1:1250	Absolute	< ± 0.3m	< ± 1.0m
Mastermap 1:2500	Absolute	< ± 1.1m	< ± 2.4m

Source: Ordnance Survey 2004

Table 3: Mean and standard deviation of residual water level (measured – MHW)

Port	mean residual (m)	standard deviation in residual (m)
Liverpool	-0.16	0.21
Devonport	0.10	0.21
Dover	-0.01	0.22
River Tyne	-0.01	0.18

Table 4: Maximum elevation change within 0.5 hours of high and low water from Admiralty mean spring and neap curves

Port	Elevation change 0.5 hours from MHW (m)	Elevation change 0.5 hours from MLW (m)
Liverpool	0.1	0.15
Swansea	0.05	0.1
Avonmouth	0.2	0.5
Devonport	0.05	0.15

Port	Elevation change 0.5 hours from MHW (m)	Elevation change 0.5 hours from MLW (m)
Southampton	0.05	0.15
Dover	0.1	0.15
Lowestoft	0.05	0.1
Immingham	0.1	0.2
River Tyne	0.05	0.15

Table 5: Root-mean-square variability errors for Lincolnshire profiles

Location	No. years	MHW	MWL	MLW
Mablethorpe Convalescent Home	32	7.45	10	
Mablethorpe Convalescent Home	10	6.07	10.36	
Trusthorpe Outfall	10	0	9.33	10.82
Sutton Pullover	10	2.01	14.34	22.25
Boygrift Outfall	10	6.31	13.65	15.57
Jacksons Corner	32	14.5	14.52	

8. Figure

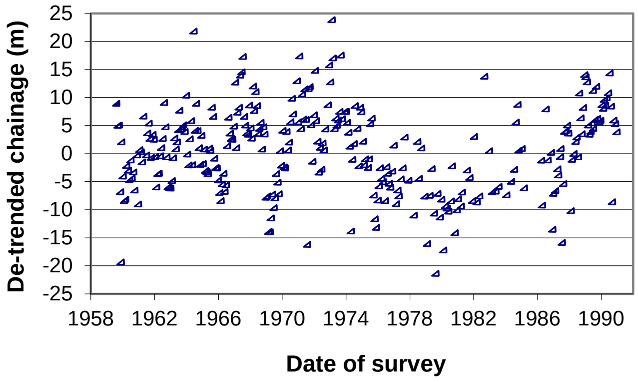

Figure 1: De-trended cross-shore position of MHW level at Mablethorpe Convalescent Home

Notation

α	beach slope
OS	Ordnance Survey
HWMOT	High water mark of ordinary tides
LWMOT	Low water mark of ordinary tides
MHW	Mean high water
MHWN	Mean high water of neap tides
MHWS	Mean high water of spring tides
MLW	Mean low water
MLWN	Mean low water of neap tides
MLWS	Mean low water of spring tides
RMST	Root-mean-square total error
RMSI	Root-mean-square interpretation uncertainty
RMSS	Root-mean-square source error
RMSV	Root-mean-square variability error