The development of a time trend analysis tool for GIS and its application in the assessment of Nash Bank, South Wales

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ABSTRACT

Incorporating a temporal function (i.e. to analyse data over time) into the spatial environment of GIS has been developed and applied in the assessment of the evolution of Nash Bank, South Wales. A stringent programme of monitoring, including annual bathymetric surveys of the bank, is carried out as part of the requirements of aggregate dredging and provides suitable data to analyse changes in bank levels over time. Traditionally GIS has been used to assess the evolution of such coastal landforms by creating a digital terrain model (DTM) for each of the bathymetric datasets and then performing a simple calculation whereby one DTM is subtracted from an earlier one. However, a simple difference in levels between any two snapshots in time can be misleading when trying to evaluate long-term rates of change. The new GIS tool has been developed that calculates such rates (i.e. the time trend) by incorporating a linear regression formula. The results are then plotted out by the tool into GIS as a DTM, in which each individual data cell represents a rate of change (time trend) at that particular location, allowing a clear temporal analysis to be presented for the whole area.

Key words | bathymetry, GIS, morphological evolution, time trend

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INTRODUCTION

Coastal areas have long been recognised as a resource and, as such, have come under increasing amounts of pressure from often-conflicting requirements. One tangible outcome of the increased interest in coastal management has been the strategic planning of coastal defences against the threat of flooding and erosion. As well as the production of Shoreline Management Plans for the entire coastline of England and Wales, now entering a second phase, there has been major growth in associated monitoring. Repeated and frequent surveying of beaches and the nearshore seabed are being undertaken, with substantial amounts of data covering large areas being collected with an aim to understand temporal variations and longer-term coastal evolution. There is also a need to be able to present this information in a readily digestible fashion and use it for decision-making when considering possible intervention measures. Similar

monitoring of some areas of the seabed is also being carried out, for example in connection with aggregate dredging operations.

Rapid developments in communication and networking technology have occurred in parallel and this has led to the increased application of information technologies such as Geographic Information Systems (GIS), to environmental issues and problems. This is particularly true for the marine and coastal environment where there is an increasing need to monitor and map both offshore and nearshore areas to aid coastal managers and policy makers in decision-making. Due to the spatially varying nature of the data collected in the coastal zone and the quantity of it, assimilating these using traditional methods is often difficult and time-consuming. GIS is the ideal tool to manage, display and analyse coastal data with spatial variability. However, most

coastal landforms vary not only spatially but temporally as well and this creates difficulties for analysis of their evolution using GIS.

The short-term processes that shape the coastal landforms are difficult to analyse over time to forecast future coastal evolution within GIS, whose strengths lie in managing data with a spatial distribution. Multidimensional methods have been developed to try and assess the temporal changes of coastal landforms (Woodroffe *et al.* 2003). These methods involve the dynamic entities that contribute to the coastal landforms being frozen into a snapshot in time and comparisons being made between each of the snapshots at different times (Raper 2000). However, this technique only involves a comparison between datasets, without the rate of change being established. This type of analysis and other traditional techniques fail to provide what is often required in coastal areas, namely a reliable indication of long-term trends in levels, filtering out seasonal or short-term variations, for example caused by storm events. More advanced 'process modelling' involves representation of fluxes incorporating time as a fourth dimension. This enables temporal and spatial trends to be extracted to enable future predictions to be made. There will need to be the development of new data

models before this fully multidimensional GIS can be implemented (Kucera 1995).

This paper describes the incorporation of a temporal function (the rate of change over time) into the spatial environment of GIS (rate of change spatially) and its application in the assessment of the evolution of Nash Bank, a large sandbank in Swansea Bay, South Wales.

NASH BANK

Nash Bank is a large sandbank in the south-east of Swansea Bay, separated by a 300 m wide channel (Nash Channel) from Nash Point, South Wales (Figure 1). Nash Bank extends generally in a WNW direction from Nash Point and is around 12–15 km long with a maximum width of 1–1.5 km at the general level of the seabed in this area (BMT 1996). The Bank is highest at its eastern end, with extensive areas exposed at low water (spring tides); its crest slopes down to merge with the seabed in the west. The maximum thickness of sand in the Bank is up to 16 m above a smooth rock substrate, at 17–21 m below ODN in the east, sloping down to 23–25 m below ODN in the west.
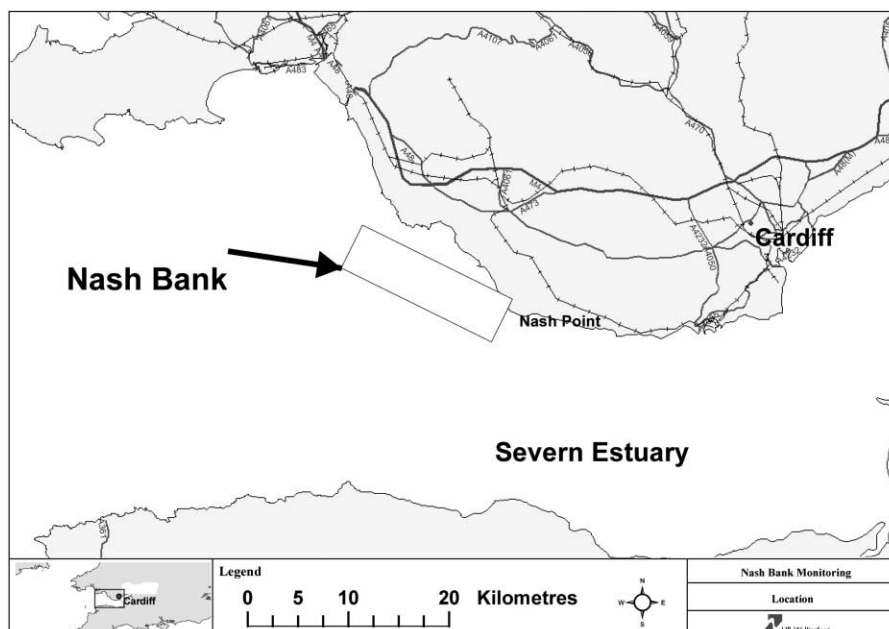

Figure 1 │ Location of Nash Bank.

The location of Nash Bank is related to the change in the coastline orientation at Nash Point. The strong ebb tidal currents in the Bristol Channel decelerate as they pass this point, and a large-scale clockwise rotating tidal eddy is created to its west. The accumulation of sand that is Nash Bank is concentrated in the centre of this eddy. The action of secondary flows tends to draw material into the flanks of the Bank which adjust until its morphology is in equilibrium with the tides and waves (Pattiaratchi & Collins 1986; BMT 1996).

Some 90% of South Wales' sand requirement is provided from the seabed of the Bristol Channel, and the western end of Nash Bank has been characterised by intense dredging of the sand for use in the construction industry for many decades. However, there is great concern over the effect this dredging could have on the adjacent coastline, the main danger arising from the reduction in the Bank's efficiency as a natural breakwater protecting the coastline in its lee. Therefore, as one of the conditions attached to its 'extraction licence', the dredging company is required to undertake a stringent programme of monitoring, including annual bathymetric surveys of the bank.

EXISTING ANALYSIS TECHNIQUES

Data reduction and storage

Bathymetric surveys of Nash Bank have been carried out annually from 1996 to 2003. The capacities of a GIS system are useful in storing and visualising large amounts of bathymetric survey data. The first step in the analysis process was to assimilate all the available bathymetric data for Nash Bank (there were 8 such surveys) into a GIS (Figure 2). A quality check was then undertaken to ensure that the data was of the required coverage and of a suitable spatial distribution and that the depths were all to Ordnance Datum Newlyn (ODN). As can be seen in Figure 2, the survey data covers the whole area of interest (Nash Bank), and beyond, with a sufficient spatial distribution of survey points. Once checked and amended, the process of creating a Digital Terrain Model (DTM) for each annual survey was initiated.

The conversion of bathymetric survey data into a DTM presents some challenges. Typically, the data is provided in the form of 'sounding lines', i.e. strings of depth values recorded by a vertical-beam echo sounder along the route taken by the survey vessel. While the spacing of these
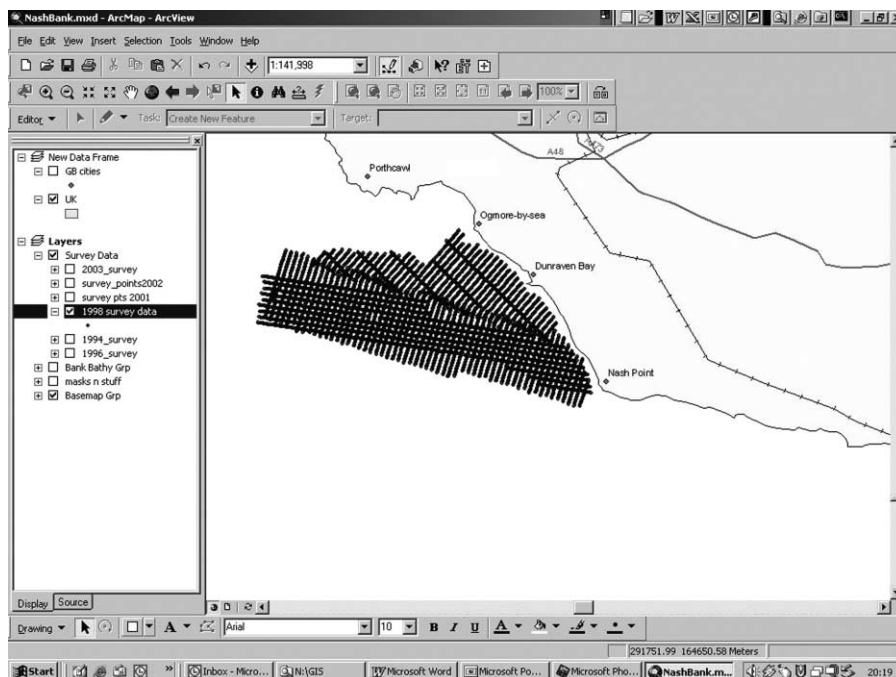

Figure 2 | Assimilation of hydrographic survey data.

individual values is only a few metres apart, the sounding lines are typically much further apart, at spacings of 50–250 m or greater, depending on the situation. These lines are typically aligned in a defined direction, with more widely spaced additional lines running roughly perpendicularly, as a check on the accuracy of the soundings. More recently, multi-beam echo sounders have been increasingly used, and these produce a 'swathe' of bed levels extending either side of the route of the survey vessel. The accuracy of the DTM produced from any bathymetric survey will therefore depend on the spacing of the survey lines run by the vessel and the type of echo sounder used. There will also be further errors arising from defining the location of the vessel and from the conversion of water depths to seabed levels, by accounting for the tidal level at the time and location where any measurement was taken. However, these errors are an inevitable element of any analysis of bathymetric surveys; they do not fundamentally affect the analysis technique presented in this paper.

Data interpolation

The surface generation functions of GIS were used to interpolate between data points. These functions predict values for areas where there are no data points, based on the values of existing data using mathematical formulae (McCoy & Johnston 2001). Using these functions a continuous surface of data representing the bathymetry of the bank for each year from 1996 to 2003 was produced (Figure 3). The surface generation functions make predictions for all locations in a raster dataset whether a measurement has been taken at the location or not. This continuous surface of data, called a Digital Terrain Model (DTM) or raster in GIS, is made up of an array of equally sized square cells of assigned specific values that correspond to the Bank level and arranged in rows and columns that produces a Cartesian matrix. The rows of the matrix are parallel to the x axis of the Cartesian plane and the columns to the y axis. Each cell has a unique row and column address and hence is referenced by its geographic x, y location. The size chosen for a cell of each DTM depends on
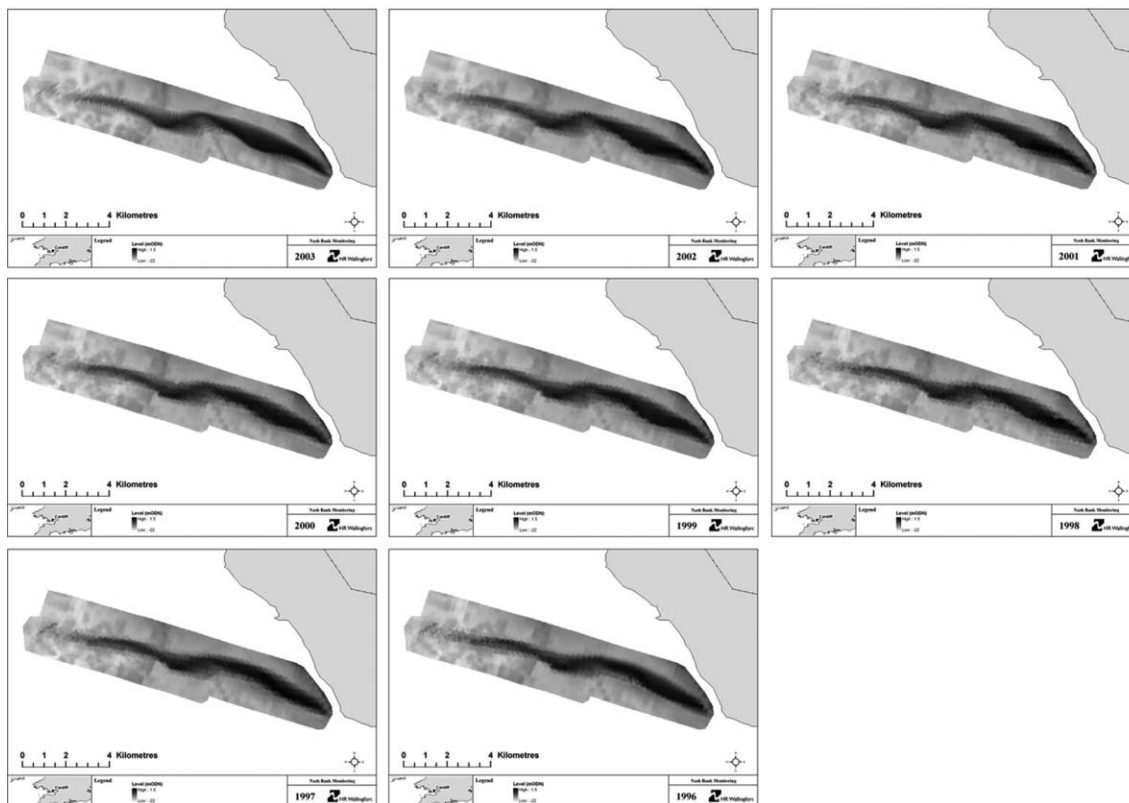

Figure 3 | DTMs of Bank levels (1996–2003).

the resolution of the input data and, since a cell size finer than the input resolution will not produce a more accurate output DTM, the cell size selected was the same as the input survey data resolution. It is not necessary to create each DTM with the same cell resolution, as GIS has the capability of analysing between datasets of differing resolutions. However, it is considered good practice to create each DTM with the same cell size and to also use a mask. A mask effectively 'block outs' all unnecessary data outside the study area of Nash Bank, so providing clearer results and improving processing efficiency.

Standard statistical analysis

Seabed levels, and similarly beach levels, are subject to rather rapid changes over time, be they long-term, seasonal or random. Often these changes over time are particularly important, for example analysing siltation within a dredged navigation channel, and this leads on to consideration of how GIS may be used to analyse and present such changes.

Various types of statistical analysis can be made on the DTMs to characterise the changes in the Bank, utilising the existing analytical functions within the GIS. It is usual to calculate these statistics in a 'Local' or per-cell manner, where an output DTM is created based on the values of each cell of the input DTMs (McCoy & Johnston 2001).

Thus maps of the mean, range and standard deviation were produced from the eight input DTMs described earlier.

The mean bathymetry (Figure 4) gives an impression of what Nash Bank would look like if all temporal variations were ignored. Although this is important, it does not provide any information concerning the magnitude or temporal pattern of movement over time. However, the range and standard deviation of the mean can be used to provide some measure of these changes. The range (i.e. the difference between the maximum and minimum) highlights the absolute changes in bank levels and so allows regions of large or small variations to be easily identified (Figure 5). However, the range tells us little about the spread of variation over time and this is an important issue, as a large range could just be associated with change between two consecutive DTMs. For example, if the last survey was undertaken just after a large storm that greatly changed the bank levels in one area, this could produce a substantial change over the whole period considered, while statistically that area can be shown to have no long-term trend. The standard deviation (Figure 6) provides a measure of the spread of variation with respect to the mean value over time but, like the range, it gives no indication of whether the values are increasing or decreasing over time (i.e. the time trend).
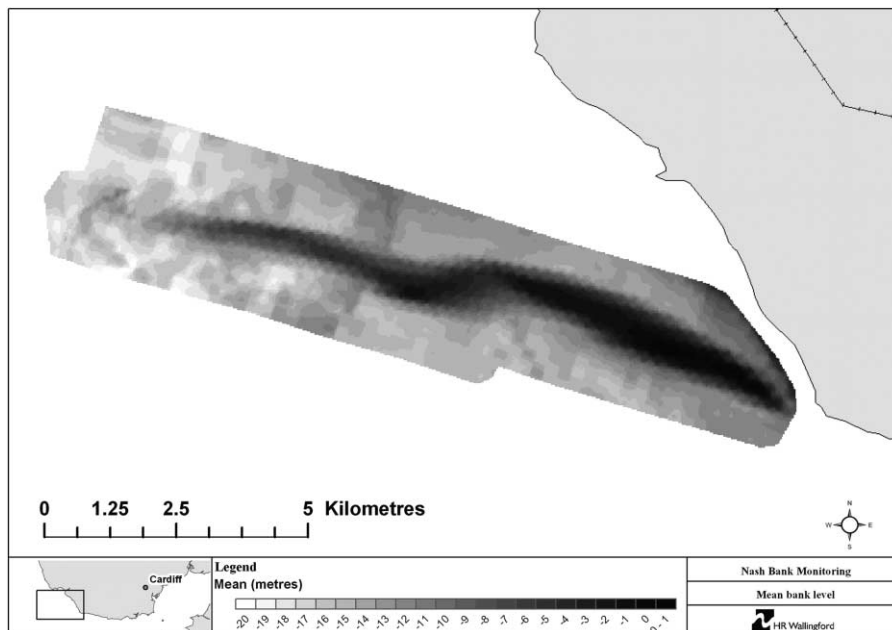

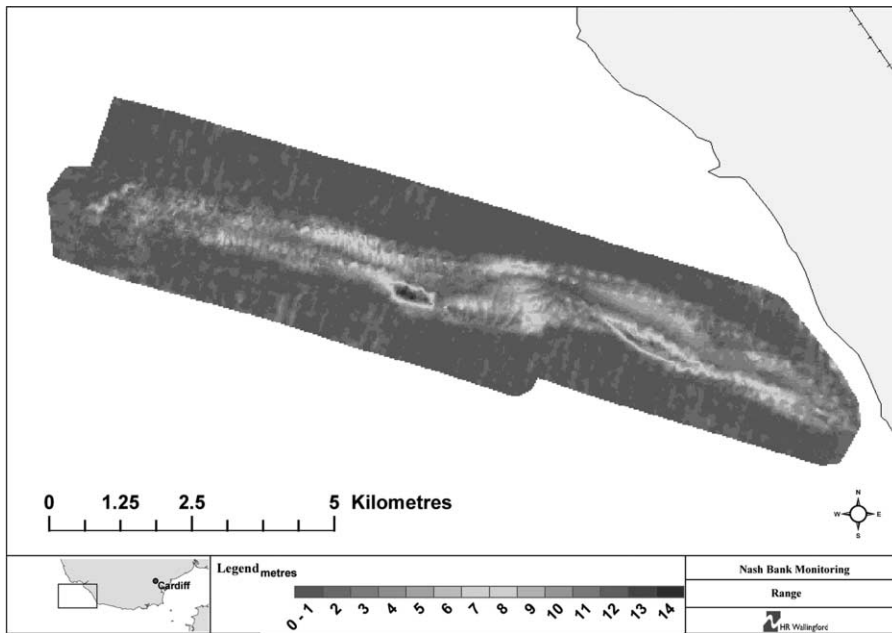**Figure 4** │ Mean bed level (1996–2003).

Figure 5 | Range in bed levels (1996–2003).

In addition to these statistical analyses, an assessment of the volume of material within Nash Bank has been undertaken. To evaluate the volumetric changes over time the volume of material above the $-15\,\mathrm{m}$ contour (ODN) has been extracted from the DTMs utilising GIS functions and plotted (Figure 7). It is noticeable that the variations in the Bank's volume from year to year are modest (typically 1 million cubic metres or about 3% of the total volume above this contour) and there is no clear pattern of change over time. The overall time trend in the volume over the period 1996–2003 has been calculated using linear regression, and is found to be downwards, but small in comparison to the
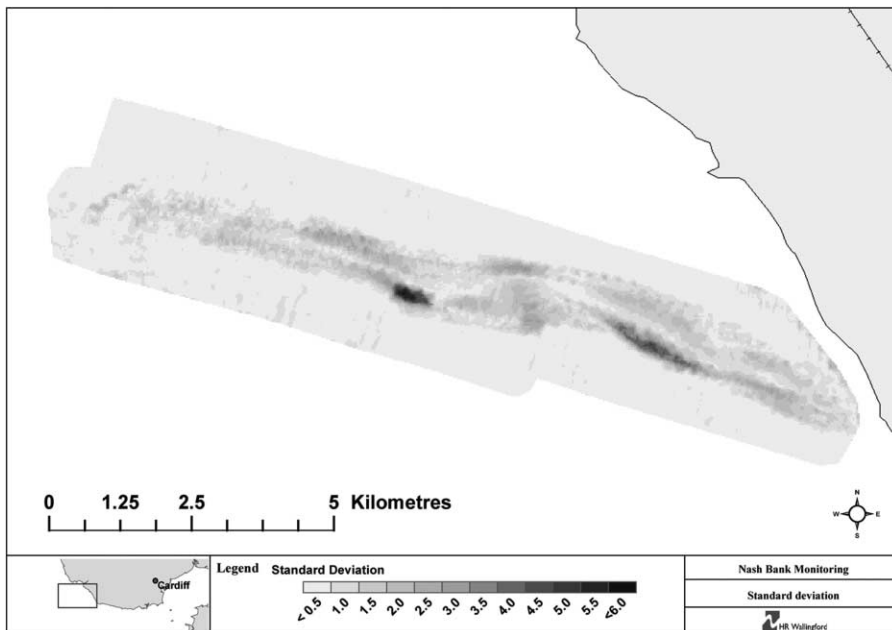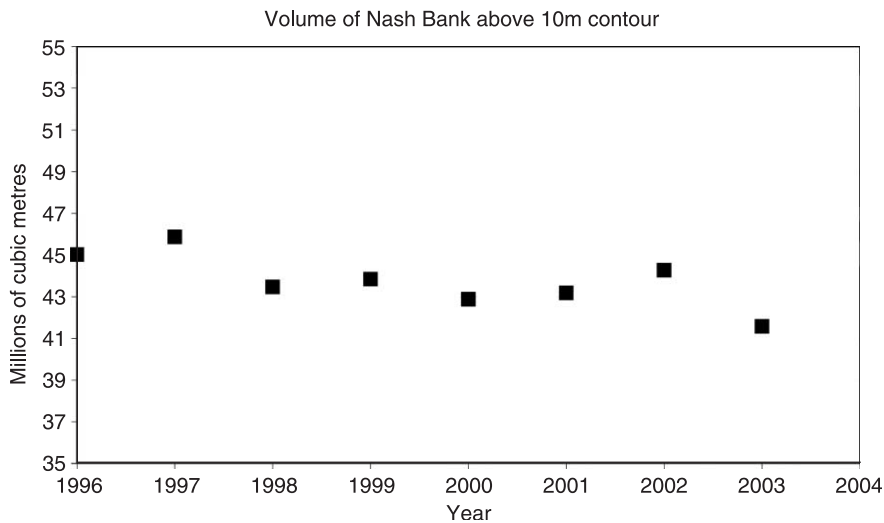

Figure 6 | Standard deviation in bed levels (1996–2003).

Figure 7 │ Analysis of volume above −15 m contour (1996–2003).

likely accuracy of the individual surveys, thus concluding that there is little time trend in the Bank's volume.

NEW TIME TREND ANALYSIS TOOL FOR GIS

The extraction of time trends is standard practice in coastal management in order to assess the evolution of coastal landforms. Traditionally GIS has not been able to calculate the change in values over time; instead, a simple but perhaps misleading technique is used whereby a DTM from a given period is subtracted from an earlier DTM. The net result of this calculation is purely the *difference* in levels between two 'snapshots' of bathymetries in time. It gives no indication of the variation of the levels between these two snapshots, and yet is often misinterpreted to illustrate the time trend of the data over time. One way to examine the time trend is to extract the bank levels for each DTM at each individual cell, plot them in a graph and perform a linear regression analysis on them, as exemplified in the volume analysis (Figure 7). However, this would be a very time-consuming process, particularly since many DTMs consist of over 10 000 data cells and this method does not provide a spatial distribution of the time trends that GIS will be able to provide. Therefore a new technique has been developed to combine the time trend analysis with the spatial distribution of GIS to show the changes of bank levels over time and space and thus providing new information regarding coastal landform evolution.

The measurements of the bank levels were treated as a statistical sample from a population assumed to have a 'Normal' or 'Gaussian' probability distribution. This seemed reasonable since changes of the bank levels are the result of many small and largely natural variations, for example in tidal currents and wave conditions with little overall change in the volume. Therefore, to calculate time trends in the data, a linear regression method was selected along with R^2, the associated square of the correlation coefficient and which can be interpreted as the proportion of the variance in the data that is accounted for by the linear regression. The closer the value is to 1, the better the linear regression predicts the time trend.

A standard linear regression formula based on the equation of a line of best fit through the data points is given by

$$y = Mx + C$$

where M = time trend and is calculated by

$$M = \frac{n.\sum xy - \sum x \sum y}{n.\sum x^2 - (\sum x)^2}$$

where n = the number of the data sets used (e.g. 8)
   x = the time (e.g. year 1, 2, 3, 4, 5, 6, 7, 8)
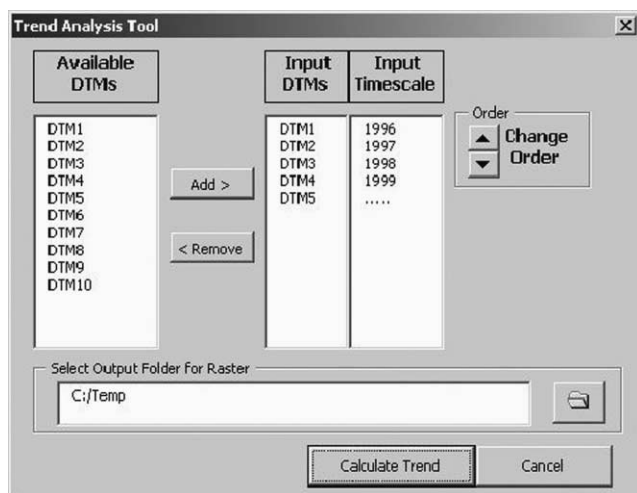 y = the data value in the DTM (e.g. bank level in metres)

Figure 8 │ Time trend analysis tool.

The correlation coefficient (R^2) between the data points is given by

$$R^2 = \frac{n.\sum xy - \sum x \sum y}{\left\{ n.\sum x^2 - (\sum x)^2 \right\} \left\{ n.\sum y^2 - (\sum y)^2 \right\}}$$

These formulae have been coded using ArcObjects VBA to create a time trend analysis tool 'Trend Tool' (Figure 8)

that can be loaded into ArcGIS as an add-on extension. Once loaded into GIS, the Trend Tool allows the user to perform a time trend analysis based on the linear regression formula above, on a cell-by-cell level for each DTM selected. The results of the analysis are output from the Trend Tool in the form of a DTM, but with each cell value not showing elevation of the seabed but the variation in elevation over time. This DTM can then be coloured in a clear way (e.g. red for erosion and green for accretion) to illustrate such areas or, equally usefully, to show areas of no change, thus giving a spatial distribution of the trend of the data values over time. This takes a large step forward from simply analysing the difference between two bathymetries and allows a coastal manager to easily identify areas of erosion or accretion and therefore act accordingly. The new Trend Tool for ArcGIS has been applied to the analysis of the evolution of Nash Bank and the resulting DTMs of time trend and R^2 analyses are mapped in Figures 9 and 10, respectively.

DISCUSSION AND CONCLUSIONS

The trend analysis tool developed for GIS has enabled a calculation of time trends for tens of thousands of individual
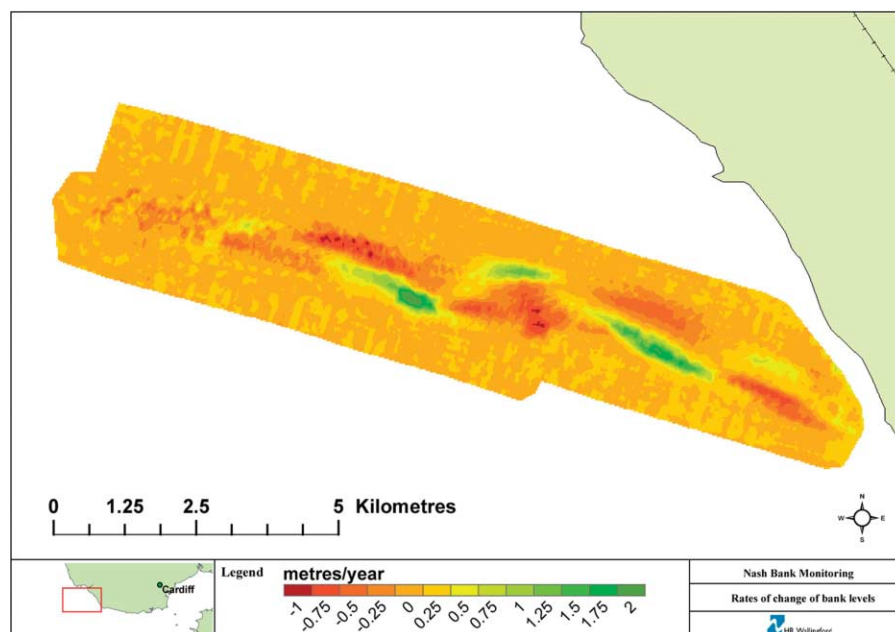

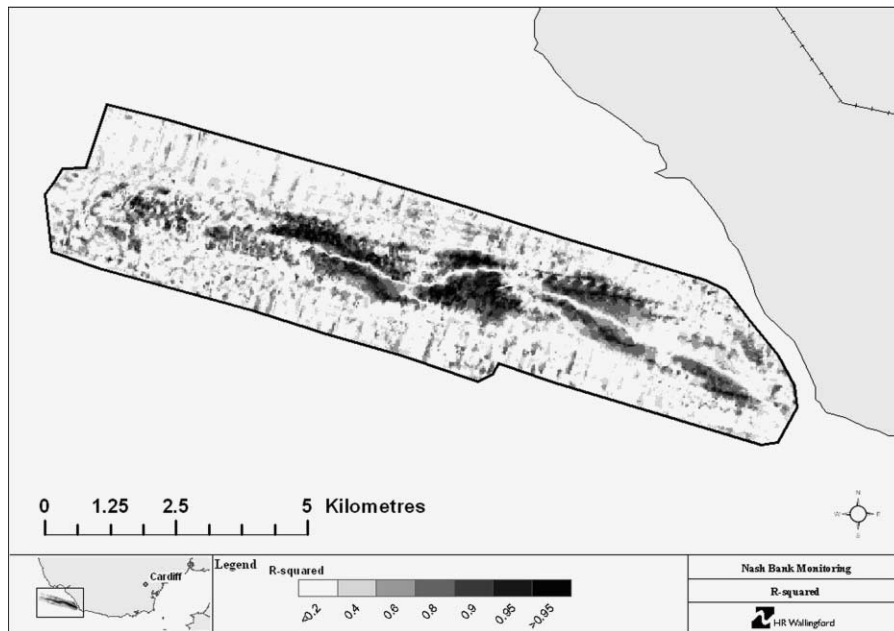**Figure 9** │ Time trend rates over Nash Bank.

Figure 10 │ R^2 values over Nash Bank.

data points covering the entire area of Nash Bank. The tool has then output the results in a DTM that has been mapped and colour-coded to allow a spatial analysis of the time trends. Whilst the range (Figure 6) indicates areas of high variability, the time trend analysis has taken this a step further and actually calculates the rate at which the bank levels are changing and whether they are increasing or decreasing. The Trend Tool has provided an interesting, new and unique analysis of the evolution of Nash Bank, with the map of the time trend DTM (Figure 9) clearly showing opposing areas of erosion and accretion along the eastern half of the Bank. It has also calculated the correlation coefficient which illustrates there is a strong correlation in the data showing time trends (Figure 10). Despite the increase in sinuosity, as shown by the time trend analysis, and despite continued dredging off its western end, the crest levels at the eastern end of the bank have remained the same. This tool could also be applied to the morphological analysis of estuaries, for example to examine change in the positions of channels, and further work is currently underway to extend the functionality of the tool to allow a time trend analysis of beach levels to be undertaken.

ACKNOWLEDGEMENTS

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