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# A methodology for quantifying river channel planform change using GIS

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**Abstract** Historical map and air photograph sources provide information on the planform of river channels at specific times in the past. This paper describes a method for quantifying river channel planform change through the capture, integration and analysis of the boundaries of river channels at different dates within a Geographic Information System. The application of GIS-based techniques to handling historical planform data allows flexibility in data analysis and a more precise estimation of the accuracy of the results. The potential and limitations of this approach are illustrated using information for sections of the Rivers Towy and Dee.

## INTRODUCTION

Studies of river planform change from historical map and air photograph information promote an appreciation of the historical stability of rivers and of the sensitivity of river channels to human induced change (e.g. Brizga & Finlayson, 1990; Graf, 1983, 1984; Hooke, 1977; Hooke & Redmond, 1989a; Petts, 1989). The historical period that can be investigated is limited by the degree to which the historical sources represent river channel changes to within tolerable levels of accuracy. Although a variety of earlier map sources are available, most academic studies of river channel planform change in England and Wales which have attempted to identify the extent of change with some precision have been limited to about 100 years before present; the period for which large scale (1:10 560 and 1:10 000) maps have been produced by the Ordnance Survey. The requirement for confident identification of true planform change has also meant that the majority of studies have concentrated upon dynamic rivers where there is sufficient stream power to initiate changes that may be readily detected from the historical information (Brookes, 1983). As rivers decrease in activity or size, the changes in planform between historical sources become increasingly subtle, and so it is important to establish the degree to which measured changes are likely to exceed the errors that are inherent in the source materials and that are introduced during the analysis of channel planform change.

Quantitative estimates of planform change have typically relied on the manual overlaying of sources onto a medium on which the channel banks may be represented at a common scale. Under these circumstances it is difficult to quantify the errors involved in manipulating the data and thus the degree to which observed planform changes are likely to be genuine. This paper outlines a computer-based approach for handling, integrating and analysing information derived from historical sources within a Geographic Information System (GIS). Such an approach has two groups of advantages over manual approaches; the first group relates to the ability to quantify many of the error components which impact upon the precision of the analytical results; and the second group relates to the flexibility with which a variety of indices of channel planform change may be derived.

This paper first considers the advantages of a GIS-based approach to the analysis of historical information on channel planform change. The potential magnitude of locational errors associated with such an approach are then assessed and quantified using information from manipulation of recent (1979: 1:10 000 scale) and older (1876: 1:10 560 scale) Ordnance Survey map coverage of a section of the River Dee. An analytical methodology for characterizing river planform change is then described and some results of its application to sections of the Rivers Towy (in South Wales) and Dee (on the Welsh-English border) are presented. Whereas the Towy is a dynamic river where planform change could be readily identified using manual methods, the more subtle planform changes on the Dee provide an illustration of the great potential of the computer-based methodology for analysing changes in lower-energy environments.

## THE ADVANTAGES OF ADOPTING A GIS-BASED APPROACH

Visual/manual approaches to the identification of river channel change from cartographic and aerial photographic sources are quick and inexpensive, but they are limited in their ability to superimpose effectively the character of the channel at a large number of dates and in their ability to support the derivation of accurate area summary statistics (Hooke & Redmond, 1989b). A GIS-based approach produces a solution to these problems and has a number of advantages over traditional manual methods of comparison:

(a) Digitized boundaries derived directly from the source documents provide geometrically stable representations which are readily stored, retrieved and manipulated.
(b) Digital warping methods (Burrough, 1986) aid the correction of planimetric errors in the source documents and the registration of the corrected information to a common scale and map projection.
(c) Quantitative analysis of linear and areal displacements can be achieved by the comparison of individual records or sequences of records within the GIS.
(d) A variety of map products can be produced and refined until they represent the patterns of interest in the most effective way.
(e) Digital statistical outputs may be exported directly from the GIS into other analytical software packages for further analysis.

A major advantage of a GIS-based approach is the great flexibility with which the data can be manipulated. However, before such manipulation can be undertaken, it is necessary to transfer information on channel bank positions at different dates from the historical sources into the GIS. In the present case data handling was undertaken using the Tydac Technologies product SPANS and the following data-handling and analytical approaches were adopted.

## DATA PREPARATION AND ENTRY

Historical sources were assembled to describe the changing planform of the river sections of interest. Ordnance Survey 1:10 000 (previously 1:10 560) scale maps were selected for the present British studies because they represent a compromise between a sufficiently-detailed spatial scale to identify channel planform change, and a sufficiently frequent resurvey to provide a sequence of river planform information for different dates. Ordnance Survey 1:10 000 and 1:10 560 scale maps adopt a consistent definition of river bank position as "normal winter water level" (Harley, 1975), which ensures comparability between maps of different date. The map record can then be augmented by air photograph survey information. In order to avoid the introduction of spatial-scale-dependent errors, it is preferable to use photographs that are relatively close to the 1:10 000 scale of the maps. However, there is an additional problem associated with air photograph interpretation in that the identification of the bank location is not as clear-cut as when using maps.

Information on river bank positions and any other features of interest was then digitized from the historical sources. Changing the scale of the historical sources is unnecessary because data are captured at the scale of the original source and then all scale adjustments are undertaken within the GIS. In order to achieve this conversion the precise location, in latitude-longitude or grid units (e.g. the Ordnance Survey National Grid), of a number of fixed control points across the digitized map must be used. A relatively large sample of control points is desirable because a more accurate adjustment can be achieved and rogue points can be identified and discarded or replaced. When data are extracted from maps which have the mapping grid clearly marked, then grid intersections can be used as control points. In the present case, the Ordnance Survey National Grid was used so that all maps could be registered to that standard map projection. If such a grid is not printed on older maps then control points need to be based upon features which can be precisely identified and be confidently expected to remain at a fixed location (e.g. the corners of buildings).

Digitizing produces files in an arc-node vector format which, for the purposes of the planform analysis described in this study, requires transformation to a raster format, where the basic unit of the raster is the grid cell. For each individual map file, grid cells are assigned a class to depict the attribute they represent. In the present case the attributes were class "1" representing channel occupancy and class "0" representing non-occupancy, for each individual file.

## ASSESSMENT OF ERRORS IN THE GIS-BASED APPROACH

The process by which information is transferred from the real world at the time of observation to its destination (the user) is called data transcription (Fig. 1). Errors occur at all stages of data transcription and are propagated through the data handling and analysis processes to a total error estimate. By adopting a GIS-based technique, the results obtained may not be more accurate than those from manual methods, but there will be an increase in the speed and efficiency of data processing, and a basis from which a number of the components of the total error can be quantified. A full discussion of the sources of error represented in Fig. 1 is provided in Downward (submitted). The following discussion focuses on three particular elements of error which relate to the

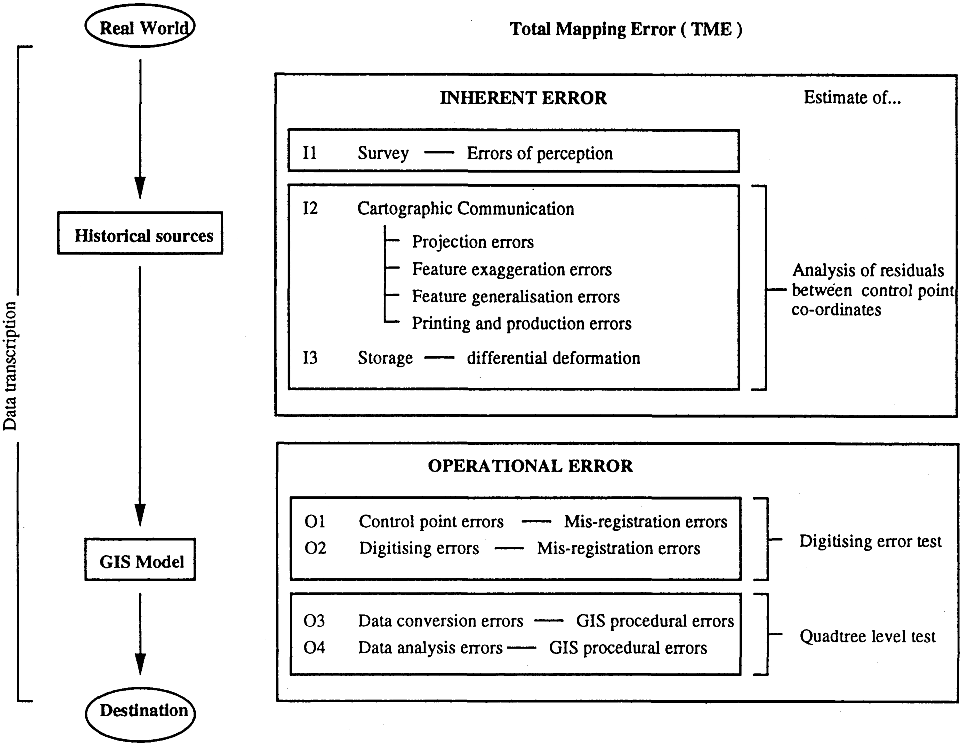

**Fig. 1** Propagation of errors to a total mapping error in a GIS-based analysis of historical map sources.

computer-based data handling techniques: errors associated with the registration of different historical sources to a common geographical base; errors associated with digitizing channel planform; and errors associated with transformation of the arc-node vector representation to a raster representation.

One of the advantages of adopting a GIS-based approach is that the historical sources are registered to a common scale and map projection using a network of control points defined across the map or air photo surface. A linear or nonlinear least squares transformation is estimated for each data set using the map coordinates of the control points on the common base and on the historical source. The transformation is never perfect and so the residual values for the eastings and northings of each of the control points provide a basis for estimating the potential error resulting from the registration process when information from historical sources is combined. Recent original maps with a clearly marked coordinate grid are likely to be associated with the smallest residual errors, whereas old maps, particularly if they are photocopies, are likely to be associated with larger residuals. A linear transformation of the information is preferable, since nonlinear warping is more susceptible to being adversely affected by one or more rogue control points. However, when old photocopied sources are transformed, it could be argued that differential shrinkage of the source document or differential distortion during photocopying could warrant the use of a nonlinear transformation.

The likely magnitude of transformation errors can be illustrated by the residuals for control points associated with a 1:10 000 1979 Ordnance Survey map sheet and a

1:10 560, second generation photocopy, 1876 Ordnance Survey map sheet for the River Dee, as a result of registering the sheets, using a linear transformation, to the Ordnance Survey National Grid. In addition to the difference in the age of the sheets and the fact that the older sheet had also been photocopied, the 1876 sheet was not overprinted with the National Grid so that other features had to be used as controls, introducing a further element of uncertainty in relation to the stability of the features and the degree to which they were accurately surveyed and plotted. Thus the analysis of these two sheets provides an indication of the likely range of errors associated with the use of maps of a similar spatial scale but very different age.

Thirty-nine and 38 control points were used for the 1979 and 1876 map sheets, respectively. The deviation of each control point from its correct position with respect to the National Grid was estimated by taking the square root of the sum of the squares of the residual easting and northing values. This produced mean and standard deviation values of 1.36 m and 0.59 m for the 1979 sheet and 4.48 m and 1.34 m for the 1876 sheet. The normality of each frequency distribution was established using a $\chi^2$ test and the sample data were used to estimate the probability of exceedance of specific magnitude deviations of locations on the transformed map from their true position with respect to the National Grid. Deviations in excess of 1.83, 2.13, 2.36 and 2.72 m were estimated to be associated with exceedance probabilities of approximately 0.22, 0.1, 0.05 and 0.01 for the 1979 map whereas the same probabilities were associated with deviations of 5.57, 6.22, 6.76 and 7.57 m for the 1876 map.

In addition to the registration errors, there are errors associated with digitizing channel boundaries from the map sources. By analysing the variability in the digital representation of a river channel boundary as a result of repeat digitizing, it is possible to observe the distribution of digitizing errors. The test procedure involved re-digitizing the same channel boundary position between two fixed nodes, and then overlaying these boundaries within the GIS. The outcome of each overlay was a "sliver" or area between the nodes which represented the displacement between the two digitized lines. The two slightly differing line lengths between the nodes were queried to obtain the mean channel boundary length. The area displacement was then divided by the mean channel boundary length to estimate the average positional error of the line as a lateral displacement in mm. The process was repeated 50 times to produce a frequency distribution of positional errors. Based on the particular hardware employed and test data from the River Towy, a normal distribution of positional errors was estimated with standard deviation of 0.101 mm. This translates to an error margin of approximately ±2.02 and 2.12 m (exceedance probability of 0.05) for digital maps produced from source material at scales of 1:10 000 and 1:10 560, respectively. The errors resulting from map registration and line digitizing can be accumulated to give a total error from these two sources, and the joint probability of particular magnitudes of error can be estimated. For example, if we assume an equal error exceedance probability from the two error sources of 0.22, this produces a joint error of 6.84 and 3.04 m from the 1876 and 1979 map sources, respectively, with an exceedance probability of 0.05.

In the area analyses for the GIS-based methodology used in this study, vector representations of the channel boundary are converted to grid cells and individual cells are classified as channel or non-channel. Where the vector data imply a mix within a cell, the cell is classified according to whether the larger proportion of it is channel or non-channel. The chosen grid cell size determines the spatial resolution to which the data are generalized. It might seem reasonable to undertake the vector to raster conversion at the finest spatial resolution possible, but, in practice, the spatial accuracy has already been delimited as the result of the inherent source errors and the GIS vector representation. Therefore, as long as the spatial resolution falls within the boundary of positional accuracy, overall information loss should be minimized and, indeed, the raster representation should help to smooth the data to the known level of spatial error incorporated within it. Thus, in the case of the River Towy, 2.5 m cells were chosen, which are within the probable errors indicated by the registration and digitizing tests described above. A finer spatial resolution would have had minimal benefits for overall analytical accuracy and would substantially increase the number of cells to be stored and processed.

## ANALYSIS OF CHANNEL PLANFORM CHANGE WITHIN THE GIS

Once the data have been prepared and imported into the GIS using the above procedures, three types of analysis are undertaken:

(a) Vector overlay within a GIS may be thought of as a similar procedure to a manual overlay. Any number of overlays may be undertaken and information on bank position may be displayed in different colour or line styles to differentiate between the dates that the vectors represent. The magnitude of planform migration at any location can be directly measured so that a variety of analyses can be supported.

(b) Area Map Overlay combines any two raster maps for the same location but at different dates by employing a classification matrix. Each grid cell has a unique spatial location, so the same landscape element may be compared between different map dates and represented as a reclassified map showing the locations of net erosion, deposition and no change between the two chosen dates. The distribution of change may be quantified by crosstabulating the attributes of the class type (erosion/deposition/no change channel) within specified spatial units or polygons defining channel reaches. The river channel planform changes that are observed indicate the net change over the period and, therefore, provide the minimum estimate of the rate of change. By dividing the area of change statistics by the period between the chosen dates it is possible to estimate the mean percentage channel change per year associated with each land unit.

(c) Historical Stability Overlay employs the classification matrix function outlined above but utilizes all of the sources in the historical record. Historical channel stability is defined as the total period of channel occupancy for any given cell over the period of the historical record. The individual quadtree maps are weighted according to the number of years separating their survey date from the previous map in the record. For example, if the separation of two maps in the record is 30 years then the grid cells are assigned class attribute values of "30", to indicate presence, and "0", to indicate absence. Matrix overlay is then used to combine the first two maps in the historical series to produce a new reclassified map. This map is then overlain with the next in the series, which has been weighted in the same manner. The process is repeated until all of the maps in the sequence are included. The precision of the temporal element is limited by the number of sources analysed and their respective survey dates. To aid cartographic representation, the output map can be reclassified into even blocks of years. Figure 2 illustrates such an analysis for a

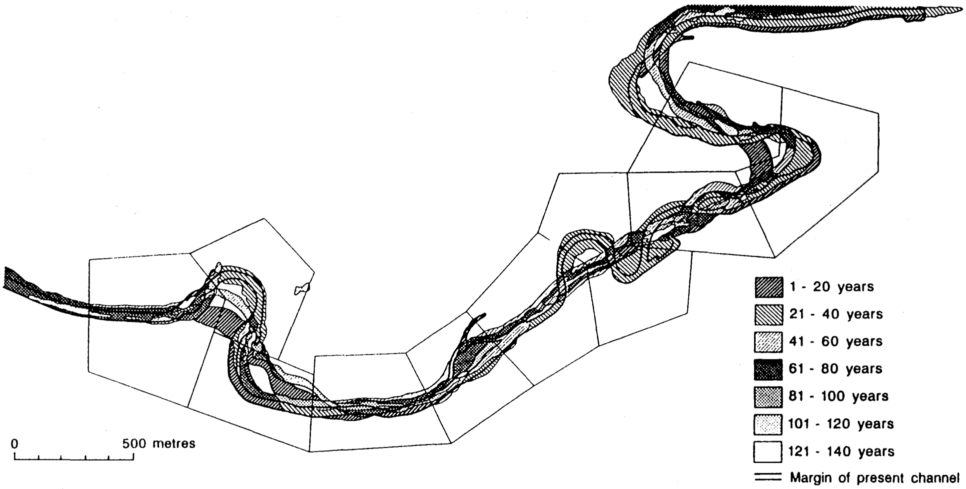

**Fig. 2** Historical stability overlay for a section of the River Towy, South Wales.

section of the River Towy. As with the area map overlay, the distribution of change can be quantified for particular sections of river by cross tabulating the attributes of the class type with specified polygons. Figure 3 illustrates a clear downstream trend in channel stability of a section of the River Dee, by quantifying the percentage of the 115 year period of the historical record within which differing proportions of 1 km stretches of the river flood plain were occupied by active river channel. A possible further stage in the analysis involves using the channel boundaries from the last date in the sequence as a template to cut away all of the map information beyond the boundary of the last channel position. The result is a map of the contemporary channel and its historical planform stability.

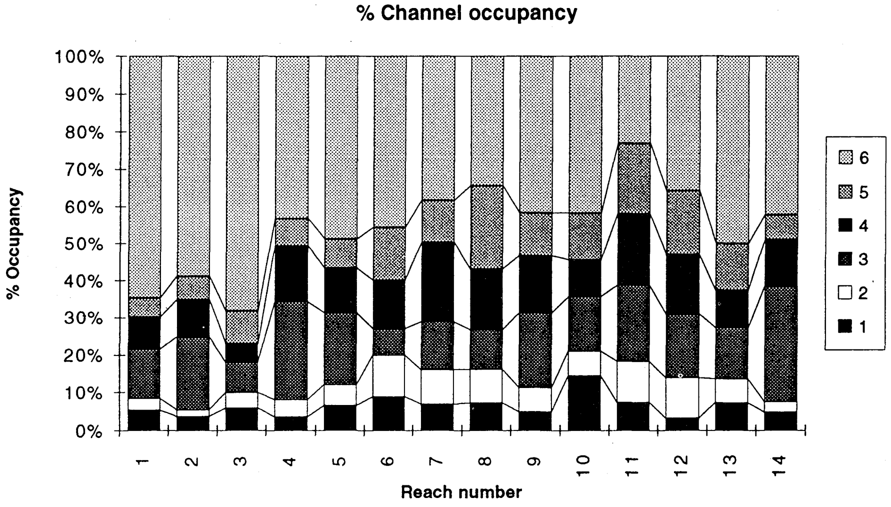

**Fig. 3** Period of occupancy (in 20 year units) of the entire flood plain area of the River Dee occupied at some stage in the 115 year record by active channel. Reaches represent 1 km sections of flood plain plotted from downstream (left of graph) to upstream (right of graph) and with class 1 representing less than 20 years occupancy and class 6 representing occupancy for the entire 115 year period.

## CONCLUSIONS

This paper has presented a GIS-based methodology for deriving estimates of river planform change from historical documentary sources. The GIS-based approach has many advantages over traditional methods in its flexibility for supporting data storage, retrieval and manipulation, and for the generation of a variety of indices and cartographic representations of channel planform change. Error quantification is essential if estimates of channel planform change are to be sensibly interpreted so that genuine changes can be identified. The information presented from the use of maps at 1:10 000 and 1:10 560 scale for a section of the River Dee suggests that for the particular hardware and data-handling methodology used, spatial displacements in excess of approximately 5 m are required before a component of genuine channel movement can be confidently inferred. This threshold varies to some extent with the age and nature of the historical sources.

A GIS-based methodology has been successfully applied to the high-energy environment of the River Towy to illustrate and quantify channel movements over the last 100 years (e.g. Fig. 2). More impressive, however, has been the ability of the approach to identify subtle downstream trends in channel movement within a relatively low-energy section of the River Dee (e.g. Fig. 3).

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