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The application of geospatial interpolation methods in the reconstruction of Quaternary landform records

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ABSTRACT

Erosional landform features and their associated sedimentary assemblages (river terraces) often provide important records of long-term landscape evolution. However, the methods available for spatial representations of such records are typically limited to the generation of two-dimensional transects (valley long profiles and cross sections). Such transects limit the full quantification of system responses in a three-dimensional landscape (e.g., the identification of spatial changes in net sediment flux within a hydrological basin). The purpose of this paper is to explore the use of geospatial interpolation methods in the reconstruction of Quaternary landform records. This approach enables more precise quantifications of terrace landform records at a range of spatial scales (from a single river reach to geological basin scales). Here we use a case study from the Tabernas basin in SE Spain to test the applicability of multiple methods of geospatial interpolation in the reconstruction of Quaternary landforms (river terrace and alluvial fan remnants). We take steps in (1) refining the terrace data sets and the methods of technique application in order to reduce modelling errors, and (2) in highlighting the requirements for an assessment of interpolation method suitability when modelling highly fragmented landform records. The results from our study show that the performance of interpolation methods varies considerably and is dependent upon the data modelled. Method performance is primarily controlled by the inherent geomorphological characteristics (surface morphology and elevation) of the data; however, the attributes of data structure are significant. We further identify the importance of predefined model parameters (e.g., search radius) upon technique performance, increasing the appreciation of these commonly neglected variables in such studies. Ultimately, the overall applicability of the interpolation process is evidenced by the close correlation of surface volume data generated by all interpolation methods. These data would suggest that the interpolation technique can be applied in many forms as a useful tool in the reconstruction of Quaternary landform features.

1. Introduction

In tectonically active regions patterns of long-term landscape development are primarily driven by base-level lowering (e.g., Stokes et al., 2002; Bridgland and Westaway, 2008; Gibbard and Lewin, 2009). The record of such change is often well demonstrated in the landscape by the formation of extensive erosional surfaces that are sometimes capped by sediments (e.g., river terraces) (e.g., Lewin and Gibbard, 2010). These erosional surfaces can be reconstructed as geomorphic markers that help us to understand and quantify spatial and temporal patterns of base-level change as driven by tectonics, climate, or internal geomorphic system dynamics (Maddy and Bridgland, 2000; Mather, 2000; Bridgland and Westaway, 2008; Gibbard and Lewin, 2009; Westaway et al., 2009; Lewin and Gibbard, 2010; Antón et al., 2012; Viveen et al., 2013).

In river terrace studies, methods in the spatial reconstruction of terrace surfaces have classically focused on the generation of idealised transects in both the downstream and across-valley aspects (e.g., Bridgland et al., 2004, 2012). Such transects have been fundamental in developing process–form relationships that explain fluvial landscape development (e.g., evidencing the significance of post 'mid-Pleistocene revolution' climatic forcing on global river terrace formation; Bridgland and Westaway, 2008). However, the two-dimensional form of transects is often a limiting factor when attempting to fully quantify patterns of landscape change in a three-dimensional or even four-dimensional perspective (e.g., representing spatial changes in net sediment flux, or localised variations in incision between fluvial systems throughout time within a sedimentary basin (Stokes et al., 2002)). In this study, we focus on the requirement for further quantitative methods of spatial reconstruction, proposing the application of geospatial interpolation as a way of generating paleolandscape data from fragmented Quaternary terrace records.

Abbreviations: IDW fix, inverse distance weighting — fixed; IDW var, inverse distance weighting — variable; ME, mean error; MAE, mean absolute error; RMSE, root mean squared error multiquadratic; MRBF, radial basis function; OK, ordinary kriging; RST, regularized spline with tension; UK, universal kriging.

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1.1. Geospatial interpolation in geomorphology

The many forms of geospatial interpolation work by estimating the value of an environmental parameter(s) at a given point with no direct observations using data from known point observations (Li and Heap, 2011). These data point estimations are then used to create continuous data sets or data surfaces (Burrough and McDonnell, 1998; Chaplot et al., 2006; Haberlandt, 2007; Li and Heap, 2011). In geomorphological research, interpolation techniques have been extensively applied in the creation of digital elevation models (DEMs) (Wilson and Gallant, 2000; Chaplot et al., 2006; Heritage et al., 2009; Bell, 2012) with recent studies demonstrating the applicability of the approach in the (i) reconstruction of geomorphologic units in landslide susceptibility mapping (Gorum et al., 2008); (ii) the development of soil moisture profiles at a range of catchment scales (Yao et al., 2013); and (iii) in the generation of paleolandsurfaces via the reconstruction of spatially fragmented Quaternary landform records (Della Seta et al., 2005, 2008; Alexander et al., 2008; Calderoni et al., 2010; Troiani and Della Seta, 2011). The latter forms the focus of this paper.

1.2. Current and potential applications: reconstruction of Quaternary landform records

To date, the most developed method in the reconstruction of fragmentary Quaternary landforms is that of Troiani and Della Seta (2011), refined from earlier studies (Della Seta et al., 2005, 2008; Calderoni et al., 2010). In their approach, Quaternary terrace surfaces that form parts of a coastal fan system are used as known observation points in the digital infilling (interpolation) of erosional landscape features across the major northern Marche rivers in the Umbria-Marche Apennines of Italy (see Fig. 3 of Troiani and Della Seta, 2011). The interpolated data sets generated are taken to represent paleolandform surfaces that occurred prior to the onset of incision. These surfaces are subsequently quantified by means of topographic analysis and further investigated by various geomorphic indices such as stream-length gradient and steepness indices (see Troiani and Della Seta, 2011, for application methods). Throughout their research, Troiani and Della Seta (2011) and others (Della Seta et al., 2005, 2008; Calderoni et al., 2010) have demonstrated the value of the interpolation process in the identification of (i) localised variations or irregularities in erosional/depositional surfaces as a result of climatic and tectonic factors; (ii) differences in averaged incision rates, as evidenced by variations in the height–age relationships of depositional units; and (iii) the existence of multiple depositional events within geomorphic features, as identified by more precise surface geometries and boundaries.

Adopting the approaches of Troiani and Della Seta (2011) and earlier works (Della Seta et al., 2005, 2008; Calderoni et al., 2010), the interpolation process can feasibly be adopted in wider fields of geomorphological research. Although dependent upon the nature of the data sets being modelled, the approach allows for the reconstruction of landscape features over a range of spatial (from single thread channels to basinwide fluvial systems) and temporal scales (1 year to 100 Ka). The reconstruction of such landform features forms a vital base in many computational modelling packages such as FLUVER2 (Viveen et al., 2014) and CAESER (Coulthard and Van de Wiel, 2013) where a detailed primary DEM (prior to onset of incision) forms the basis for all further modelling exercises. In addition, the development of precise spatial patterns of landscape change can be further supplemented by absolute age data (e.g., luminescence dating or Cosmogenic exposure techniques) in order to determine the significance of intrinsic and extrinsic processes of landscape change (e.g., tectonics, climate, river captures, or anthropogenic) within Quaternary environments.

1.3. Limitations: reconstruction of Quaternary landform records

Although the benefits of interpolating Quaternary landforms are clear, many factors affect the accuracy and precision of the interpolation technique(s) applied and the data sets they generate (Li and Heap, 2011; Bell, 2012). Such factors can be related to (i) the inherent geomorphological characteristics of the data being modelled (e.g., topographic setting or surface form) (Aguilar et al., 2005; Chaplot et al., 2006); and/or (ii) further attributes of data structure, such as sample point spacing, sample point density, or degree of variance within the data (see Li and Heap, 2011, for full review). Surprisingly, in current reconstructions of Quaternary landform features, these diverse variables have been commonly neglected or poorly accounted for. For example, in their early studies Della Seta et al. (2005, 2008), and Calderoni et al. (2010) did not assess the accuracy of the interpolation technique applied (ordinary kriging) and assumed applicability from other research alone. More recently, Troiani and Della Seta (2011) did attempt to identify the most suitable method of interpolation by means of cross validation (e.g., difference between estimated and actual data points); however, the efforts taken in proving method suitability were severely out-weighed by the interpretation of the data generated. This contrasts with the approaches developed within similar fields of application, including other aspects of geomorphology (e.g., the creation of DEMs or soil moisture profiles), where an assessment of interpolation method applicability is a fundamental requirement in evaluating the overall success of the estimation process (e.g., via measurable errors) (Robeson, 1997; Zimmerman et al., 1999; Chaplot et al., 2006; Chen and Yue, 2010; Li and Heap, 2011; Bell, 2012).

The aim of this paper is to develop the application of geospatial interpolation methods in the reconstruction of Quaternary landforms (notably river terraces) by incorporating stages of technique performance assessment (estimation accuracy and precision) and data refinement in the interpolation process. Initially, we address practical ways of improving terrace data sets in order to reduce overall errors in the modelling process. We then focus on the applicability of different interpolation methods when modelling terrace data sets, assessing the overall accuracy and precision (performance) of six widely used interpolation methods. Finally, we assess the reliability of interpolation techniques in generating surface volumes (quantified data) from the interpolated surfaces.

Throughout our study, we use the Quaternary terrace record of the Tabernas basin in southeast Spain (Fig. 1) to test these application measures. The Tabernas basin is a Neogene sedimentary basin located within the Betic Cordillera of SE Spain (Sanz de Galdeano and Vera, 1992). It was chosen as it possesses a well-preserved inset terrace record of fluvial and alluvial fan remnants whose coupled planar nature and extensive spatial occurrence fulfil the multiple prerequisites of the interpolation process (further detailed in Section 2.1).

2. Study data sets

2.1. Data set prerequisites

It's well established that a comprehensive data set is the foundation of any geophysical modelling exercise (Bonham-Carter, 1994). This particularly holds true in the reconstruction of Quaternary terrace records where the following criteria must be met prior to the modelling stage: (i) the terrace record must be factually well understood with significant input from field observations. Such field observations should include elements of terrace sedimentology, morphology, and topographical occurrence (e.g., the altitudinal relationships of terrace base and or surface above current drainage level) (Stokes et al., 2012). (ii) The spatial occurrence of terrace groupings must be complete enough to enable accurate estimations at the defined spatial and temporal sampling frequencies of the study (such aspects should be tested by means of a pilot study adhering to the approaches of this paper prior to detailed