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Geomorphic change detection using historic maps and DEM differencing: The temporal dimension of geospatial analysis

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ABSTRACT

The ability to develop spatially distributed models of topographic change is presenting new capabilities in geomorphic research. High resolution maps of elevation change indicate locations, processes, and rates of geomorphic change, and provide a means of calibrating temporal simulation models. Methods of *geomorphic change detection* (GCD), based on gridded models, may be applied to a wide range of time periods by utilizing cartometric, remote sensing, or ground-based topographic survey data to measure volumetric change. Advantages and limitations of historical DEM reconstruction methods are reviewed with a focus on coupling them with subsequent DEMs to construct *DEMs of difference* (DoD), which can be created by subtracting one elevation model from another, to map erosion, deposition, and volumetric change. The period of DoD analysis can be extended to several decades if accurate historical DEMs can be generated by extracting topographic data from historical data and selecting areas where geomorphic change has been substantial. The challenge is to recognize and minimize uncertainties in data that are particularly elusive with early topographic data. This paper reviews potential sources of error in digitized topographic maps and DEMs. Although the paper is primarily a review of methods, three brief examples are presented at the end to demonstrate GCD using DoDs constructed from data extending over periods ranging from 70 to 90 years.

1. Introduction

The time domain is an important dimension of geomorphic mapping and geospatial modeling. The application of temporal analysis in GIScience has been anticipated for almost five decades and is receiving growing attention (Langran, 1992; Raper, 2000; Wikle and Cressie, 2000; Peuquet, 2003; O'Sullivan, 2005). Cartography – and by extension, much of geospatial science – is potentially four-dimensional with the planimetric dimensions, X–Y, forming the traditional basis, and the third dimension consisting of elevation or other attributes describing a statistical surface. Time may be regarded conceptually as the fourth dimension (Langran, 1992). Just as traditional cartography maps space in bounded areas, so the time dimension may have abrupt or transitional temporal boundaries. For historical reconstructions, the sequent snapshots produced by available maps or imagery define a space-time cube, but the temporal resolution tends to be coarse, so rates of change must be interpolated (Fig. 1A). Discrete temporal periods are often defined by the availability of reliable data rather than the occurrence of events. The time of each map or image brackets the period in which change occurred but does not specify the time or the agents of change (Langran, 1992). Where change occurred in space can be identified specifically, but how and precisely when and why the change happened must be inferred from other information. In *geomorphic change detection* (GCD), inferences about processes and times of events may often be made from knowledge of the record of natural events such as storms, floods, or earthquakes, and these inferences can improve estimates of rates of change (Fig. 1B).

Historic changes in geomorphic systems can be quantified with geospatial processing of empirical data from historical maps, airborne or satellite imagery, or field surveys. Where accurate historical topographic data are available, time-discrete elevation surfaces can be developed and registered to topographic data from one or more other times for quantitative comparisons. The development methods for digital elevation models (DEMs), described in this paper, generate static data layers, but differencing two or more sequential DEMs is a rudimentary form of spatially distributed dynamic geomorphological analysis. Even in the static mode, time-discrete DEMs can be used to identify locations of geomorphic stability or change, past trends, processes and rates of change, as well as to construct sediment budgets. They may also be used to calibrate dynamic models of change for greater time integration in GIScience. For example, accurate historic topographic reconstructions can be used to establish initial boundary conditions for continuous simulation models at higher temporal resolutions (Rumsby et al., 2008).

2. Volumetric geomorphic change detection (GCD) by DEM differencing

Change detection in remote sensing of environmental systems includes a wide range of techniques, including changes in spectra (surface brightness values), planimetry (2-dimensional position), or elevations

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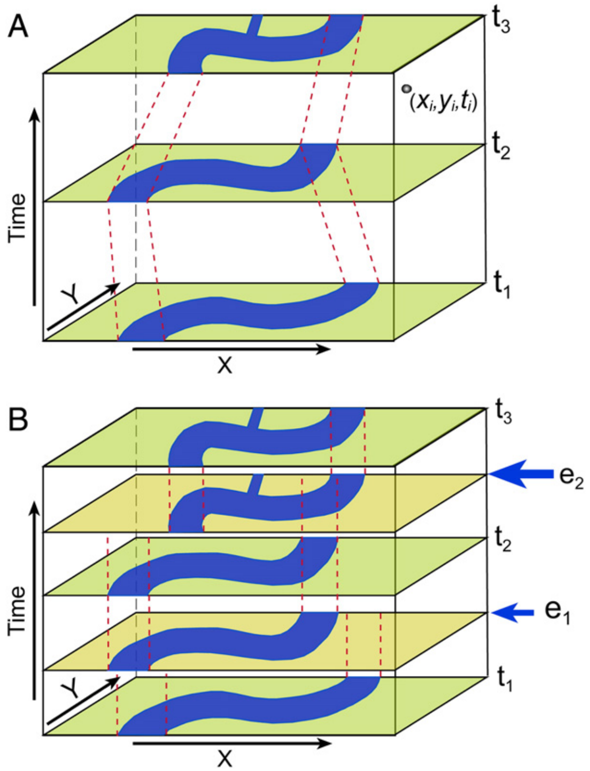

Fig. 1. Space-time cubes. (A) Geomorphic conditions at three discrete times (t1 through t3) with process rates assumed constant between each condition. With high temporal resolution reconstructions, conditions at any point, *Xi*, *Yi*, *Ti*, in the cube can theoretically be inferred. (B) Addition of known geomorphic events (e1, e2) and assumptions of stable conditions between events separated by step-functional changes during events may allow refinement of timing and identification of processes.
(Adapted from Langran, 1992).

(Jensen, 2007). Change detection may provide quantitative measures on a cell-by-cell basis, but it can also reveal spatial patterns of change or changes in pattern based on clusters of cells, which may be more diagnostic than magnitudes of change (White, 2006). Examples of recent studies that have used DEMs for change detection in order to map or monitor erosion, deposition, and volumetric changes, and construct sediment budgets include the work by Martínez-Casasnovas et al. (2004) and Wheaton et al. (2009). Although digital terrain models (DTMs) may be produced in a variety of data model forms, the following discussion assumes conventional two-dimensional arrays (cellular or finite-difference) of orthogonally gridded elevation data. The term 'DEM' refers to the square-cell data model in this paper. The differencing of sequential DEMs to create a *DEM of difference* (DoD) or change in elevation grid is particularly relevant to geomorphic studies because a DoD may provide a high resolution, spatially distributed surface model of topographic and volumetric change through time (Brasington et al., 2003; Rumsby et al., 2008). This form of GCD is a powerful tool that may be used to identify and quantify spatial patterns of geomorphic change. Once two DEMs have been developed and registered to the same grid tesselation, a DoD can be made by subtracting the earlier DEM from the later DEM:

$$\Delta E_{ij} = Z_{2ij} - Z_{1ij} \qquad (1)$$

where ΔE_{ij} is the i, j grid value of the change in elevation model, Z_{1ij} is the i, j value of the early DEM, and Z_{2ij} is the i, j value of the later DEM. The resulting DoD represents reductions in elevation as negative values and increases in elevation as positive values. Determining the cause of this change (e.g. erosion, deposition, subsidence, anthropogenic modification, precision, accuracy, or uncertainty) is more challenging.

Of particular interest to this study is the extraction of topographic data from historical contour maps to allow construction of historical DEMs for DoD analysis. Most DoD studies have been concerned with temporal scales less than decadel based on field surveys or remote sensing data (Heritage et al., 2009). Historic reconstructions of greater duration require historical imagery or the use of cartographic data. Cartographic data are especially important for reconstructions of surfaces prior to the availability of stereoscopic aerial photographs or in heavily vegetated areas where conventional remote sensing methods cannot penetrate the canopy. If a high-resolution historic topographic map is available from a ground or canopy penetrating photogrammetric survey, this map may be used to develop an early DEM for the area. Historical reconstructions based on analysis of aerial photography can extend the time dimension back several decades under favorable conditions. The challenge of using historic remotely sensed imagery or topographic maps is first dependent on the source materials and processing methods for their construction (Hodgson and Alexander, 1990). For example, contour lines on many early (i.e. pre 1940s) topographic maps were "artistically" drawn with little intervening field observations between field measurements. Modern methods of topographic map construction (e.g. remote sensing based) use a comparatively dense set of observations (e.g. every few meters planimetrically) for contour construction.

The methods of volumetric change detection described in this paper are a subset of a broader set of comparison methods for spatial data. Four traditions in map or imagery comparison can be identified (Table 1). Comparisons may be made using cell-based or feature-based statistics or with spatial patterns. This paper is primarily concerned with the first two methods — accuracy of historic spatial data and methods of change detection. It begins with the importance of extending historical geomorphic research and GCD back in time, followed by a brief sampling of past studies and examples of historical reconstructions and DoD analysis. Limitations and uncertainties associated with historical reconstructions using maps, airborne imagery, DEMs, and DoDs are described, emphasizing topographic maps that can be used to extend volumetric GCD back in time. Finally, application of DoD analysis to an extended temporal scale is demonstrated with three case studies of fluvial and hill-slope systems. DEMs are developed from early 20th century large-scale topographic maps and differenced with modern DEMs from aerial photographic stereo pairs or Light Detection and Ranging (LiDAR) data to construct DoDs. These studies demonstrate the utility and limitations of the method for volumetric analyses of decadal to centennial change.

3. Importance of historical reconstructions

Historical reconstructions, GCD, and geomorphometry are important potentials of geospatial analysis that will be of growing importance to studies of global change and broad-scale anthropogenic impacts on the environment. The geomorphic effectiveness of anthropogenic change has accelerated over historical time and interest in global change and climate change has grown accordingly in recent decades. Understanding these processes requires a greater emphasis on historical knowledge of geomorphic systems. Time and space dimensions of geomorphic processes are closely linked. As the geographic extent of landforms

Table 1
Methods of map comparison.
(Adapted from Boots and Csillag, 2006).

1. Map accuracy assessments — comparisons with a reference map.
2. Change detection — differences between maps or images collected at different times.
3. Model comparisons — comparisons of model output to observed landscapes or to other model outputs.
4. Landscape comparisons over time — similar to change detection, but focus is on global (i.e., area wide) spatial metrics calculated from map data, and may be used to compare different geographical areas. Primarily used in landscape ecology but a growing trend in geomorphometry.