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An algorithm to extract more accurate stream longitudinal profiles from unfilled DEMs

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ABSTRACT

Morphometric features observed from a stream longitudinal profile (SLP) reflect channel responses to lithological variation and changes in uplift or climate; therefore, they constitute essential indicators in the studies for the dynamics between tectonics, climate, and surface processes. The widespread availability of digital elevation models (DEMs) and their processing enable semi-automatic extraction of SLPs as well as additional stream profile parameters, thus reducing the time spent for extracting them and simultaneously allowing regional-scale studies of SLPs. However, careful consideration is required to extract SLPs directly from a DEM, because the DEM must be altered by depression filling process to ensure the continuity of flows across it. Such alteration inevitably introduces distortions to the SLP, such as stair steps, bias of elevation values, and inaccurate stream paths. This paper proposes a new algorithm, called maximum depth tracing algorithm (MDTA), to extract more accurate SLPs using depression-unfilled DEMs. The MDTA supposes that depressions in DEMs are not necessarily artifacts to be removed, and that elevation values within them are useful to represent more accurately the real landscape. To ensure the continuity of flows even across the unfilled DEM, the MDTA first determines the outlet of each depression and then reverses flow directions of the cells on the line of maximum depth within each depression, beginning from the outlet and toward the sink. It also calculates flow accumulation without disruption across the unfilled DEM. Comparative analysis with the profiles extracted by the hydrologic functions implemented in the ArcGIS™ was performed to illustrate the benefits from the MDTA. It shows that the MDTA provides more accurate stream paths on depression areas, and consequently reduces distortions of the SLPs derived from the paths, such as exaggerated elevation values and negatively biased slopes that are commonly observed in the SLPs built using the ArcGIS™. The algorithm proposed here, therefore, could aid all the studies requiring more reliable stream paths and SLPs from DEMs.

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1. Introduction

A stream longitudinal profile is a graph representing the relationship between altitude and distance along the course of a river (Goudie, 2004, p. 630). Most such profiles tend to have a smoothly concave-up curved form, although some have locally steep points known as knickpoints or knickzones. The observed concavity is considered as the result of adjustments between hydraulic factors in the course of a river in equilibrium (or 'graded river') (Gilbert, 1877; Mackin, 1948; Flint, 1974), and has been quantitatively described in much of the literature (e.g., Hack, 1973; Whipple and Tucker, 1999). In contrast, an abrupt change in a stream longitudinal profile can not only indicate equilibrium response to lithological variation, but also result from disequilibrium due to local deformation, knickpoint propagation in response to surface uplift or sea-level change, and channel migration (Goldrick and Bishop, 2007). These features observed from stream longitudinal profiles, therefore, have long been used to explore the dynamics between tectonic, climate and surface processes, and to estimate the control of lithology on landscape evolution (e.g. Kirby and Whipple, 2001; Hayakawa and Oguchi, 2009; Font et al., 2010).

While the studies using parameters derived from stream longitudinal profiles have a long history, the methodology generating the profiles has greatly evolved over recent decades. It was once a very time-consuming job to extract stream profiles from topographic contour maps, but most stream profiles are now extracted semi-automatically from digital elevation models (DEMs). Such a change in the methodology reduces the time spent on creating stream profiles and also allows regional-scale studies requiring the analysis on a lot of profiles (e.g., Kirby et al., 2003). Moreover the additional stream profile parameters that are easily extracted from DEMs, such as upstream contributing area, permit new analysis of, for example, area–slope relationship used to evaluate the steady state topography as well as to separate landscape into regions dominated by different surface processes (e.g., Willgoose, 1994; Montgomery, 2001; Wobus et al., 2006).

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Despite the advantages of using DEMs, there are several problems related to the accuracy of stream profiles extracted from DEMs. For example, the river profiles generated from DEMs actually represent points partway up valley walls, especially along narrow bedrock valleys lacking substantial flood plains (Montgomery and López-Blanco, 2003). Moreover they frequently show unrealistic step-like characters with long segments of zero slope separated by abrupt steps with steep slopes (Peckham, 2009). In particular, such stair steps in the profiles are mostly associated with the pre-processing procedure for the continuity of flows across the DEM (Wobus et al., 2006). A stream longitudinal profile is typically generated by the following procedures: 1) deriving a channel network using a series of hydrologic functions (filling sinks, assigning flow direction, and calculating flow accumulation) implemented in Geographic Information System (GIS) software such as ArcGIS™, 2) recording the values needed for generating profiles along the channel network (i.e. elevation, location of stream path), and 3) creating realistic-looking stream profile through a smoothing technique. The first step, however, must accompany the alteration of DEMs. Especially the filling of sinks, which is necessary to obtain hydrologically consistent flows across the DEM, inevitably distorts the stream profile by introducing features such as stair steps, biased elevation values, and even inaccuracies in the stream path.

Here we propose an algorithm to extract more accurate stream longitudinal profiles from the depression-unfilled DEMs (henceforth we will call them the unfilled DEMs). This algorithm is built on the groundwork laid by a few exceptional studies assuming that the depressions in DEMs are not necessarily artifacts, but can provide detailed information useful for determining hydrologic flows (Chou et al., 2004; Arnold, 2010). Specifically, the new algorithm traces the line of maximum depth of each depression in the unfilled DEMs, and then extracts the more optimized parameter values needed for defining the profile along that line. The algorithm proposed here is expected to provide less distorted stream paths and profiles, and ultimately to increase the reliability of research using stream longitudinal profiles. This paper first reviews the problems arising from using the filled DEMs to extract stream profiles, then introduces the outline and procedures for the new algorithm using the unfilled DEMs, and finally shows the results from comparative analysis with the previous method to illustrate the usefulness of the new algorithm.

2. Methodological background

2.1. Problems in the use of the filled DEMs to extract stream longitudinal profiles

Raster DEMs have many topographic depressions, which obstruct the continuity of flows across them (Fig. 1A, B). Such depressions are mostly considered as artifacts that do not exist in the real landscape, because they often occur due to the errors in collecting or interpolating from elevation source data for DEMs, and also result from limited vertical resolution or inadequate grid spacing (or grid placement) of DEMs to resolve real flow paths (Lindsay and Creed, 2005a,b). Actual depressions in the natural landscape are, on the contrary, so small that it is inadequate to represent them with the scale of DEMs. Moreover they would simply fill with water and then overflow, and thus preserving the continuity of flows is more important than accurately dealing with the processes within depressions at a catchment scale (Lindsay and Creed, 2006; Arnold, 2010). Therefore the removal of the depressions from DEMs has been generally justified.

Various methods to remove depressions in DEMs have been developed, and can be classified into two broad groups: depression filling and depression breaching (Lindsay and Creed, 2005b). The depression filling method involves identifying each depression due to a sink (or pit), finding the lowest pour point (or outlet) along a rim of the

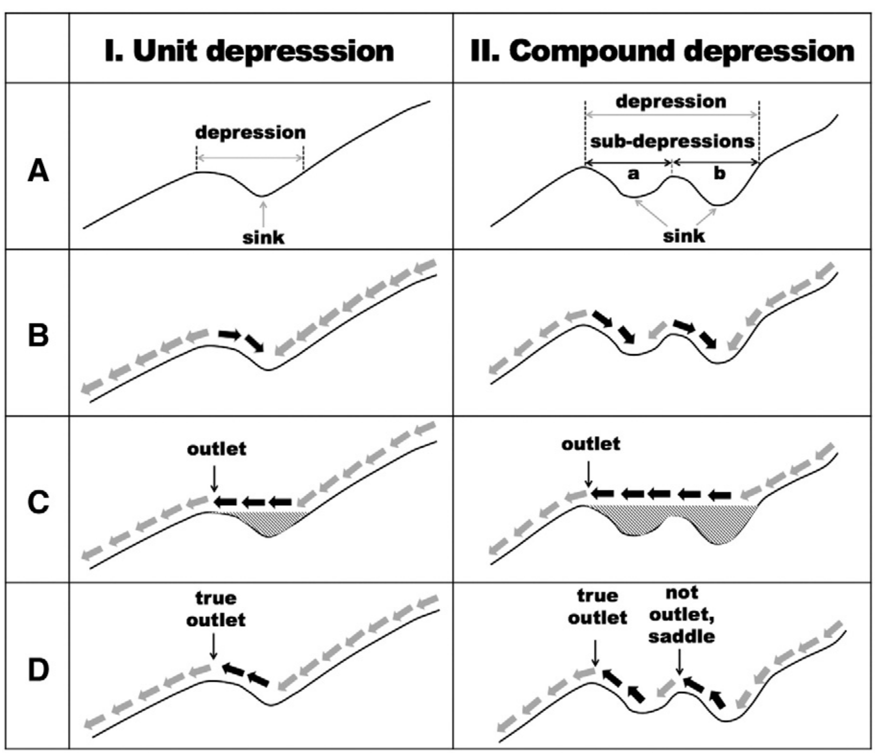

Fig. 1. Conceptual diagram for two types of depressions with flow directions determined by the method of Jenson and Domingue (1988) and the algorithm proposed here. A. Two types of depressions: unit depression and compound depression. The extent of a depression is defined as the areas flowing toward its sink. Where at least two adjacent depressions are combined, each depression becomes a sub-depression of a large, compound depression (A-II). B. Disrupted flows due to a depression. C. Modified flow directions over a filled depression by the method of Jenson and Domingue (1988). D. Modified flow directions over an unfilled depression by the algorithm proposed here. The lowest elevation cell on the rim of the sub-depression 'b' is not a 'true outlet' (we call it as 'saddle' here), through which flows continue downstream outside the sub-depression 'b' into 'a'. The saddle will be used as a starting point when reversing the 'initial' flow directions of the sub-depression 'b'.

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