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Analysis of the behavior of three digital elevation model correction methods on critical natural scenarios

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ABSTRACT

Study region: The methods explored in this study were tested in two study areas: Italy and Cuba.
Study focus: Virtually all Digital Elevation Models (DEM) contain flat areas or depression pixels that may be artifacts or actual landscape representations. These features must be removed before any further hydrological application can proceed. Diverse algorithms have been developed for the purpose of correcting these aspects, differing in how they handle the nature of the depressions, as well as the adopted mathematical procedures. In the present work, the behavior of a standard (*Fill*) and two advanced (*TOPAZ and PEM4PIT*) DEM correction methods on three critical natural scenarios is analyzed. Extensive flat areas, abrupt slope changes and large depressions – expressed in terms of: (1) geomorphological changes (elevation, affected area and slope); (2) flow velocity; (3) river network and width functions (WF) – are affected.
New hydrological insights for the region: Results confirm improved performance of the advanced methods over the standard method for each case study in Italy and Cuba. The analyzed parameters also show that correction processes are strongly influenced by the relief, the size of the predominating depressions and the neighbouring depressions. There is no one method among those compared which works optimally for every type of correction, and given that the majority of basins have diverse topographical conditions, a different approach to the corrections process and its computational procedures is likely needed.

1. Introduction

Natural sciences, from geomorphology to vegetation sciences, show increasing interest in applications based on the accurate representation of topography, as provided by the most recent digital elevation models (DEMs) (Muñoz and Kravchenko, 2012; Elshehaby et al., 2013; Petroselli et al., 2013, 2014; Fan et al., 2014; Nourani and Zanardo, 2014). Hydrology is one discipline that has directly benefited from available terrain models. Virtually all watershed representations, however, contain flat areas or depression pixels that may be artifacts or actual landscape representations (Fisher and Tate, 2006; Pan et al., 2012). These features cause interruptions while calculating downstream flow through a DEM (Grimaldi et al., 2007; Arnold,

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2010; Petroselli and Alvarez, 2012), which is the basis for every posterior hydrological modeling step. It has been found that even applications of more recent hydrological models can provide incorrect results when performed with the most detailed DEMs if depressions and flat areas are not properly addressed (Petroselli, 2012).

Depressions can be corrected by applying diverse algorithms. Known by the acronym of *Fill* or *Filling* (hereafter Fill) (Jenson and Domingue, 1988), this method considers all depressions in DEMs to be errors caused by the underestimation of elevation at a certain point. The correction fills the sinks to permit overflow continuity. The procedure has been implemented in widely used commercial geographic information system (GIS) software packages such as ArcGIS, and the open source, Unix-based GRASS. As a result of its large diffusion and availability, Fill has become a reference for comparison with newly developed approaches and a standard for scientific and practical applications.

The Topographic Parametrization (TOPAZ) (Martz and Garbrecht, 1999) method also assumes all depressions as artifacts, however it considers the possibility of both underestimation and overestimation of the elevation of some cells. Based on these two possibilities of the sources of depressions, the procedure consists of breaching a potential wall and/or filling depressions. In addition, the flat areas generated by flooding are corrected, recalculating the elevation, iteratively adding an infinitesimal number to the pixel elevation, and in doing so, forcing the flow algorithms toward lower terrain (Garbrecht and Martz, 1997).

In an attempt at modeling natural processes, the physically based erosion model for pit and flat areas removal (PEM4PIT) was developed. This method, regardless of the nature of the depressions, performs the correction by applying a simplified physically based landscape evolution equation (Grimaldi et al., 2007). Moreover, the correction process is addressed based on local surface interpolation (e.g. Pan et al., 2012). Another potential solution is the combination of several of the previously mentioned processes (Kenny et al., 2008) – with the condition of starting from a particular kind of DEM – interpolated with the ANUDEM method (Australian National University DEM), using the river network as a boundary condition.

A different proposition consists of redirecting the flow within depressions until continuity is obtained and the basin outlet is reached (e.g. Wang et al., 2009). This method has the ability to achieve flow continuity, but does so at the cost of misinterpreting the river network. Other methods of achieving the desired results may be used (e.g. Planchon and Darboux, 2001; Temme et al., 2006; Wang and Liu, 2007; Zhu et al., 2013; Barnes et al., 2014; Jojene and Meriam, 2014), but the majority of existing methods dealing with pit filling and flat-areas are based on geometric, morphological and stochastic approaches, introducing uncertainty and/or not considering physical topographic phenomena (Petroselli, 2012).

According to different considerations regarding the nature of depressions and the adopted mathematical procedures, each method may impose particular landscapes after correction and flat area treatment. In the first instance, it is the consideration of all depressions as errors. Here the correction is addressed by one of two methodologies: flooding the depression, adopted by the standard Fill method, or by the combination of flooding the depression and/or breaching the depression edges with the imposition of an artificial gradient through the flooded region, by applying mathematical procedures (i.e. interpolation, looping addition of arbitrary infinitesimal values to the cells elevation, etc.). Alternatively, there is the physically based method, which carries the implicit consideration of all depressions as real features, and the correction consists of the simulation of natural processes over the terrain.

It is important to note that hydrological modeling, following DEM preprocessing, is influenced by the propagation of inputs and errors. Since the correction constitutes the first step in hydrological modeling, a better understanding of this process can contribute to improved accuracy. Besides the large availability of correction methods, it is common in the literature to find new methods being proposed, rather than additional detailed descriptions of the potential and limitations of those methods already developed. The majority of methodological comparisons in the literature involve assessing the application of a newly developed method and the standard Fill method to particular basins or artificial DEMs. There is a lack of comparisons between some of the more advanced methods and their efficacy in correcting critical natural scenarios that can be found in real watersheds.

The aim of the present work is to analyze the behavior of the standard (*Fill*) and two advanced (*TOPAZ and PEM4PIT*) DEM correction methods on three critical natural scenarios affected by extensive flat areas, abrupt slope changes and large depressions, expressed in terms of: (1) geomorphological changes (affected area, elevation changes and slope changes); (2) flow velocity; and (3) width function (WF).

The standard Fill method adopts the simplest solution to the correction issue. Here all depressions are considered artifacts and are flooded to permit flow continuity. However, the treatment of flat areas is not included. The TOPAZ correction, on the other hand, performs a more complex function, although still geometric, also considering all depressions as false, as well as rendering the depression edge breached; in this case, the remaining sink is flooded and the generated flat area is treated by the looped addition of infinitesimal values. The selection of this method is based on the tendency to reduce the area of the depressions with the breaching technique, and it results in a DEM without flat areas after correction (Garbrecht and Martz, 1997). The PEM4PIT was selected for this study because it is the only method that adopts a physically based method to address the correction. The three methodologies are compared simultaneously for the first time.

Three basins were selected as representative of critical geomorphological conditions; one Cuban and two Italian. The Cuban basin is characterized by irregular relief, including: peculiar isolated hills having rounded and tower-like forms, known as Mogotes; large natural depressions; and an extensive interior valley. The two Italian basins have more regular landscapes; one hilly zone of around 20% slope along the basin extension, including a large natural depression; and an almost flat plain (majority of slope values less than 6%, with a predominance of 1% slope). The selected parameters, the affected area, as well as the changes in elevation and slope are expressions of the influences of each method over the terrain; the flow