New Methods for Incorporating and Analysing Drainage Structure in Digital Elevation Models

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Abstract—**Digital elevation models (DEMs) play a key role in supporting fine scale representations of surface drainage structure. In fact, representing surface drainage structure has become a primary application of DEMs. It has directly driven the development of DEM interpolation techniques, such as the ANUDEM locally adaptive elevation gridding procedure (Hutchinson 1989; Hutchinson et al. 2009). High resolution remotely sensed elevation data sources, such as LIDAR and the Shuttle Radar Topography Mission (SRTM) DEM, have brought new challenges to DEM interpolation and applications. The inherent noise in remotely sensed elevation data needs to be appropriately smoothed to help remove drainage artifacts, especially in low relief landscapes. This smoothing also needs to be applied in conjunction with the enforcement of drainage structure using streamline data. The multi-grid structure of the ANUDEM algorithm is well suited to this task and has been upgraded to prevent corruption of stream heights by noisy elevation values. It has also been upgraded to accommodate the spatial complexity associated with high resolution streamline data. When incorporated onto a regular grid, these data can generate many spurious stream junctions and disjunctions that can significantly distort subsequent analysis of catchment structure. New procedures have been developed to make small shifts in the locations of gridded streamlines and streamline junctions to reduce the number of spurious coincident gridded streamline junctions while simultaneously maximizing the fidelity of the shifted gridded streamlines to the original data streamline network. New analytical methods for calculating specific catchment area from drainage enforced DEMs, an important DEM derivative for many hydro-ecological applications, have also been obtained (Gallant and Hutchinson 2011). Such methods are best understood by recognizing the vector field interpretation of specific catchment area.**

INTRODUCTION

Digital elevation models (DEMs), normally in the form of regular grids, play a central role in environmental modeling across a range of spatial scales [6]. A distinguishing feature for many of these applications, particularly those that operate at finer scale, is a primary requirement for information about terrain shape and drainage structure, rather than elevation. DEMs with connected drainage structure can be used to calculate hydrologically relevant topographic indices such as specific catchment area [2] and to support a wide range of hydro-ecological analyses [9,10]. The need for accurate representation drainage structure has led to the development of the ANUDEM elevation gridding procedure [4,7] where grid-based interpolation has been coupled with an automatic drainage enforcement algorithm to remove spurious depressions from the interpolated grid, together with a procedure to apply drainage structure in accordance with streamline data.

New remotely sensed elevation data sources, and the need for the systematic application of the catchments associated with streamline data to natural resource assessment, have led to two major upgrades to the ANUDEM procedure. These separately address the impacts of significant noise in dense remotely sensed elevation data and the impacts of spurious intersections in streamline data when incorporated into regular grids. Each of these upgrades is briefly described below.

The paper concludes with consideration of the calculation of specific catchment area from DEMs, a key terrain parameter for a wide range of hydro-ecological applications. It is shown that specific catchment area can be naturally interpreted as a two-dimensional vector field. This can simplify the theoretical derivation of the method recently obtained by Gallant and Hutchinson [2] and may offer further progress in the calculation and assessment of this terrain parameter.

NOISY REMOTELY SENSED ELEVATION DATA

Remotely sensed digital topographic data, from both airborne and spaceborne sensors, are an increasingly common source of fine scale digital elevation data. A major impetus for their use has been the goal of generating high resolution DEMs with global coverage. This has been achieved with the completion of the 3 second (90 m) DEM for the globe obtained from the Shuttle Radar Topography Mission [11]. These data have two generic limitations. The sensor normally cannot measure ground elevations underneath dense vegetation cover or underwater or under man-made structures, leading to significant errors, particularly in heavily vegetated areas. Secondly, all remotely sensed elevation data have significant random errors that depend on the inherent limitations of the observing instrument, as well as surface slope and roughness [3,11]. The product specification for the SRTM data was that 90% of the elevations had error within ±16m. These errors require appropriate filtering, without degrading shape and drainage structure, to maximize the utility of the data in environmental applications, particularly in areas with low relief or with significant surface cover. An additional feature of the errors associated with the SRTM data is that they are locally spatially correlated. This is due to the partially overlapping nature of the sensor footprint associated with each grid cell. The various impacts of these issues have been addressed, as described below.

Elevation data smoothing

The underlying interpolation algorithm of the ANUDEM program is described in [4,5,6]. It essentially fits a discretized thin plate smoothing spline to the data using a simple multigrid strategy to maximize computational efficiency. Elevation data are initially allocated to their corresponding grid points and the program then minimizes the sum of a user-specified roughness penalty and a weighted sum of squares of the residuals from the elevation data. The weighting of the residuals incorporates the natural discretization error associated with allocating data points to a regular grid and a user supplied estimate of the vertical standard error of the elevation data. The algorithm simultaneously respects local grid cell conditions associated with automated drainage enforcement, data streamlines, cliffs and lakes. The simultaneous application of data smoothing and these local grid cell conditions is a key factor in the quality of the resulting interpolated DEM.

For traditional elevation contour data sets, the vertical standard error of the data can be set to zero and then only the discretization error needs to be taken into account in the weighting of the data residuals. For remotely sensed elevation data, estimates of standard elevation are often available, although with mixed reliability. The latter can be calibrated within ANUDEM by experimenting with different levels of user supplied vertical standard error. This has indicated, for example, that the ±16m error specified for the SRTM data is an overestimate, as shown in [11], with experiments indicating that the standard error of the 1" data over Australia, after large errors due to vegetation cover are removed, is no more than around 2m.

An additional consideration for 1second resolution SRTM data is local correlation in the data errors for neighbouring grid cells. The multigrid algorithm within ANUDEM has played a role in detecting this local correlation, and in providing a simple method for taking it into account. Initial experiments assuming independent data errors yielded stable performance in the multigrid algorithm until the last and finest resolution was met. It can be shown that when elevation data values are averaged over larger grid cells, the cell to cell correlation in data error steadily diminishes until it becomes insignificant at the largest starting grid resolution for the multigrid interpolation procedure. It was found that by assuming a nearest cell to cell correlation of around 0.6, and by taking due account of this correlation in the data weighting applied at each grid resolution, stable behavior in the gridding process could be obtained. Effectively, the data smoothing applied at the last and finest grid resolution, relative to the amount of data smoothing applied at the second to last resolution, was larger than that appropriate for locally independent errors. The strong cell to cell correlation in these data also suggests that the 1 second resolution is somewhat finer than the true information content of the 1 second SRTM data.

Incorporating streamline data

In earlier versions of ANUDEM, where data errors were assumed to be zero, elevations on streamlines were initialized at each grid resolution by linearly interpolating along streamlines between grid points to which elevation data points had been allocated. Data points on streamlines that were higher than upstream data points were normally removed. This process becomes problematic when the elevation data have significant errors, giving rise to occasional upstream data points that are too low. These can remove accurate downstream elevation points and give rise to streamlines that are systematically too low with respect to the neighbouring landscape along extended sections of streamlines. This has been illustrated in [8].

The streamline initialization procedure has been revised to take initial streamline heights from the preceding coarser grid in the multi-grid interpolation process, rather than from the error prone actual data point heights that lie on the streamlines. The program then ensures that all initial heights on the streamlines linearly descend down each stream segment between successive stream junctions and disjunctions. The revised initialization gives rise to stable elevations on streamlines when applied to neighbouring tiles, as demonstrated in [8]. This is critical in building a continent-wide high resolution DEM with consistent overall drainage structure from a series of overlapping map tiles.

SIMPLIFYING DATA STREAMLINES

The ANUDEM gridding process normally allocates each data streamline point to the centre of the closest grid cell. This process naturally perturbs the location of the points making up each streamline. This can generate many additional spurious stream junctions and disjunctions when close, but different, streams occupy the same grid cell. This is illustrated in Fig. 1 where data streamlines are plotted with their initial gridded representations. This shows several spurious junctions and two spurious disjunctions in the gridded streamline network. Complex networks, such as those arising in braided stream networks, can also lead to distinct data streamline junctions being allocated to the same grid cell. Finer grid spacings can reduce the number of spurious junctions but the problem is a generic one that can apply at any scale. On occasion the spurious junctions can be many grid cells removed from the real stream junctions. This can make determination of gridded representations of watersheds associated with data streamlines problematic. It can also make it difficult to automatically associate gauging stations with their respective catchments.

This problem was initially recognised in the production of the Australian national 9 second DEM and its associated flow direction grid [1]. This led to the development of the first version of a stream pre-processing procedure that could move a point in the gridded streamline segment to a neighbouring grid cell if this removed the spurious junction and did not give rise to a spurious junction in the neighbouring grid cell. The move was also subject to the condition that the new location of the gridded streamline point was less than a user prescribed tolerance from the original data streamline point. An important aspect of this algorithm was to maintain simultaneous access to both the original data streamline segments and their gridded representations. This helped maximize the fidelity of the gridded streamlines to the original data streamline network. This stream pre-processing procedure substantially alleviated the problems associated with the gridded streamlines but its performance was sub-optimal, in part because the procedure attempted to simultaneously attend to both the generalization of the gridded stream segments, by removing unrealistic sharp corners, and the removal of spurious junctions and disjunctions. The procedure also did not consider making small shifts in the grid cell locations of data streamline junctions to reduce both the number of spurious junctions and disjunctions and the number of spurious coincident stream junctions.

This stream pre-processing feature has been revised to comprehensively address these issues. The process of stream generalization to remove sharp corners has been further optimized and made separate from the process of removing spurious gridded stream junctions and disjunctions. The latter process has also been revised to optimize the choice of grid points to be moved and to remove the need for a user supplied distance tolerance. The revised procedure also explicitly minimizes the distance of the gridded streamline network from the data streamline network.

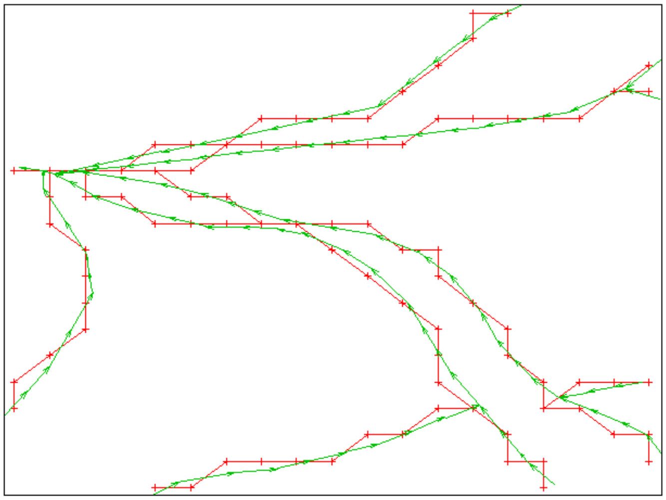

Figure 1. Streamline data in green and initial gridded streamlines at 1 second resolution in red.

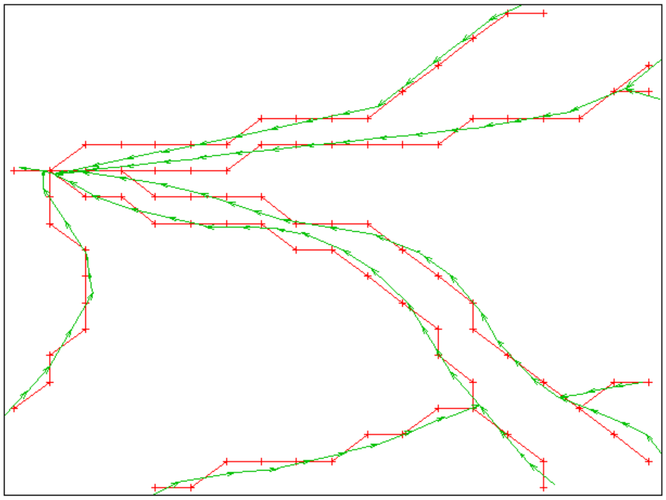

Figure 2. Streamline data in green and adjusted gridded streamlines at 1 second resolution in red.

Moreover, new procedures have been added to make small shifts in the locations of gridded streamline junctions to reduce the number of spurious coincident gridded streamline junctions.

Maximization of fidelity of the shifted gridded streamlines to the original data streamline network has been maintained as an important aspect of the new stream pre-processing procedures.

The result of applying the revised stream pre-processing procedure is illustrated in Fig. 2 where the spurious mid-stream junctions and disjunctions have been removed. The sharp junction in the southeast of Fig.1 has also been removed by shifting the stream junction one cell upstream to the east. The sum total of these small changes to the gridded streamline network can be quite large. For a 1second resolution DEM tile extending 150-151°E and 30-31°S in a low relief area of southeast Australia, containing a portion of the Namoi River, a total of 3600 spurious stream junctions and disjunctions were removed from a total of over 75,000 gridded stream segments. Of these spurious junctions and disjunctions, 1500 were removed by simple generalization of the gridded stream segments, and a further 2100 were removed by the stream shifting process described above.

SPECIFIC CATCHMENT AREA

Specific catchment area is a hydrological terrain parameter that is used widely in hydrological and ecological modeling, being directly associated with streamline patterns, areas of erosion and vegetation patterns. An important pre-requisite for its accurate calculation from a DEM is that the DEM respect the surface drainage structure of the landscape. This is a central motivation for the procedures described above. Gallant and Hutchinson [2] have recently obtained a differential equation for this quantity that can be solved using numerical methods. This has permitted assessment of various methods for calculating gridded representations of specific catchment area. All were found to overestimate specific catchment area on ridges and hilltops. The high spatial variability of specific catchment area makes its representation in gridded form problematic, on ridges and on streamlines.

One way to address this variability is to regard it as a two-dimensional vector field. It is natural to identify the downslope direction of the land surface as the direction of the vector form of specific catchment area. When so interpreted it can be readily shown that, away from depressions, the two-dimensional vector of specific catchment satisfies the fundamental identity

$$div\ \boldsymbol{\rho} = 1$$

where $\boldsymbol{\rho}$ denotes the vector of specific catchment area and *div* denotes the divergence operator. This clarifies specific catchment area's precise role as a density of area. Moreover, by appealing to the standard formula for divergence with respect to orthogonal curvilinear coordinates it can be seen that equation (34) of [2] follows. This simplifies the derivation of the main result presented in [2].

The identity given above also suggests an alternative way to represent specific catchment area in grid form. This would be to replace current somewhat ill-defined gridded specific catchment values by appropriate line integrals of the vector field along the sides of each grid cell. This would overcome the near singularity of specific catchment area on streamlines and, away from depressions, could take advantage of the natural relationship between these integrals and the area of each grid cell. Further investigation is underway to determine an efficient method for calculating such integrals.

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