

Abstract

TopoToolbox is a MATLAB software for the analysis of digital elevation models (DEMs). With the release of version 2, the software adopts an Object-Oriented Programming (OOP) approach to work with gridded DEMs, and derived data such as flow directions and stream networks. The introduction of a novel technique to store flow directions as topologically ordered vectors of indices allows for easy coding, increased processing speed and reduction in memory overhead. Graphical user interfaces enable visual exploration and interaction with DEMs and derivatives and provide access to tools targeted at fluvial and tectonic geomorphologists. With this new release, TopoToolbox has become a more memory efficient, faster and more user-friendly tool for digital terrain analysis that can be used as a framework for building hydrological and geomorphological models in MATLAB.

1 Introduction

An increasing number of research studies use digital elevation models (DEMs) for automated spatial analysis and advanced process-based modeling. Although Geographical Information System (GIS) software packages such as ArcGIS include various interfaces for implementing user-specific codes and models, many users prefer programming environments such as MATLAB that already include large libraries for different computational tasks. Since its release in 2010, the TopoToolbox, a code library for MATLAB, has been used in various studies of the Earth's surface and surficial water and material fluxes. Applications include topics such as supraglacial meltwater dynamics (Clason et al., 2012), contaminant transport in streams and groundwater (Messier et al., 2012), tectonic geomorphology (Shahzad and Gloaguen, 2011), soil nutrient dynamics (Schwanghart and Jarmer, 2011), karst hydrology (Borghini et al., 2011) or flood modeling (de Moel et al., 2012), among others.

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Despite broad attention and positive feedback, the lack of a user-friendly graphical user interface (GUI) may also have discouraged interested users who favor a visual approach towards DEM processing and analysis. Moreover, processing very large DEMs, or, within a modeling framework, processing certain computations a large number of times, are common challenges in modern geomorphological studies and require efficient computational techniques. While very large DEMs are easiest handled with software that implements efficient input/output (I/O) communication between internal and external memory, a strategy pursued by ESRI's ArcGIS or more specialized DEM processing software such as terraflo (Arge et al., 2003), the memory constraint exerted by MATLAB's primary use of the main memory is an obstacle even for medium sized DEMs. Although spread of 64-bit computers has allayed the memory problem somewhat, MATLAB's heavy use of double precision data imposes too rigid limits for larger analyses and modeling tasks.

Here we introduce several important modifications and various extensions that come with the release of version 2 of the TopoToolbox. Specifically, we report the development of an object-oriented design towards grid, flow routing and stream network representation and give account of a suite of GUIs that provide easy access to a variety of new and existing methods frequently used in topographic studies. Our strategy to reduce memory constraints, which have been particularly pertinent to flow-related algorithms, enables much faster and memory efficient work flow and thus processing much larger DEMs than with previous versions of TopoToolbox. We think that these advances will encourage users to apply our algorithms in tool development and for advanced modeling purposes.

2 Object-oriented design

Gridded DEMs and terrain attributes incorporate a variety of information other than a gridded set of points. A DEM has physical units and is georeferenced, that is, it is associated with physical space by a set of geographical or map coordinates. In addition,

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DEM derivatives (or terrain attributes) are tightly linked to algorithms and models and lend themselves for specific types of analysis. These task- and object-specific properties provide the basis for an object-oriented approach to DEMs. In object-oriented programming (OOP) data, attributes and procedures are coupled into objects that encapsulate the model of what each object represents (Register, 2007). Typical objects in DEM analysis are surface flow paths and the resulting stream networks. In TopoToolbox the aim of using OOP is to organize data and functions into classes with specific object-related attributes that organize and encapsulate information on spatial referencing, flow topology, and geometry, and thereby facilitate data handling and analysis.

TopoToolbox 2 includes three main object classes: GRIDObj is a class to store and analyze gridded data (grid objects). FLOWObj is a class for flow-path networks (flow objects) that is derived from an instance of GRIDObj. STREAMObj represents the channelized fraction (stream objects) of the flow-path network from which it is derived. Additional object classes, such as SWATHObj, which contains swath profiles that are derived along directed linear features, e.g., an instance of STREAMObj, are more tool-specific and not as tightly coupled within TopoToolbox as the three main object classes. These classes are templates for the creation of specific instances of each class. Whereas an instance of GRIDObj simply contains the data grid as well as georeferencing data, instances of FLOWObj and STREAMObj implement a novel storage approach that represents the directed network of flow paths and stream networks, respectively.

3 A graph-theoretical representation of flow directions

Topography governs the transport mode and the magnitude of lateral material and water fluxes on the Earth's surface and in the near-surface underground. Among topographic variables, the flow direction is the most important because it forms the basis for many other flow-related topographic variables. Algorithms to derive flow directions are classified into single-neighbor and multiple-neighbor flow algorithms (Gruber and Peckham, 2009). Single-neighbor algorithms pass the flow from each cell to its lowest

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neighboring cell (usually referred to as SFD or D8 algorithm, O’Callaghan and Mark, 1984). Multiple-neighbor algorithms, such as MFD (Quinn et al., 1991), D_{∞} (Tarboton, 1997), DEMON (Costa-Cabral and Burges, 1994), of the Mass-Flux Method (Gruber and Peckham, 2009), encompass a number of different approaches to model disper-
sive flow, which is particularly important to simulate water distribution on hillslopes.

TopoToolbox supports the SFD and MFD algorithms. In contrast to other GIS soft-
ware, in the first version of TopoToolbox flow directions were stored in a sparse,
weighted adjacency matrix to represent the flow network. While this strategy allows
calculating flow accumulation and other flow related terrain attributes using MATLAB’s
builtin sparse matrix routines (Schwanghart and Kuhn, 2010), it also requires large
memory space. The MFD and SFD matrix require approximately 6- and 2-times the
memory space of the DEM, respectively, if all variables are stored in in the same data
formats.

In the newly introduced flow direction class (FLOWobj), the storage of flow directions
takes advantage of the fact that flow networks can be modelled as directed acyclic
graphs (DAGs). Our approach is similar to MATLAB’s sparse matrix storage organiza-
tion but uses the “tuple” format, which is a collection of row, column, and value 3-tuples
of the nonzero elements of the flow direction matrix (Kepner, 2011). The important dif-
ference is that row and column indices are stored in topologically descending order
(Fig. 1), an approach which was recently adopted in a numerical landscape evolution
model (LEM) (Braun and Willett, 2013) and a dynamic overland flow routing model
(Huang and Lee, 2013). Topological sorting is only possible for DAGs and refers to
the permutation of nodes that brings the flow direction matrix to a lower triangular
form (Chen and Jacquemin, 1988). The storage of flow directions in topological order
in a FLOWobj allows for easy coding and speeds up the computation of flow-related
topographic attributes by about 500 %. Furthermore, the FLOWobj requires 89 % of
the memory of the associated multiple flow direction matrix and 33 % of the single
flow direction matrix (see benchmarks in Table 1). Because the nodes can be divided
into independent subsets according to drainage basin affiliation (Fig. 1), they can be

4 Further changes and enhancements

The main goal of TopoToolbox is to provide access to DEM analysis in form of functions that can be used as library in custom scripts or functions for advanced analyses or modeling purposes. Most functions available with TopoToolbox 1 are now methods associated with the new classes GRIDObj and FLOWObj (Table 2). Changes to calling syntaxes are few and were mainly made since the new classes encapsulate information such as cell size and spatial referencing in their properties, which previously had to be supplied to functions as additional input arguments. Thus, function syntaxes have become simpler and more intuitive. A new suite of functions was developed around the class STREAMObj and allows for creating, modifying and analyzing stream networks. Emphasis is placed on tools that facilitate the study of drainage networks and their relation to the tectonic setting, e.g., the analysis of longitudinal river profiles using slope-area plots (Wobus et al., 2006) or χ -plots (Harkins et al., 2007; Perron and Royden, 2013).

Performance increases were achieved with some of the flow related algorithms written in C-MEX code (Table 1). Computation speed is particularly significant when functions for calculating flow networks and accumulation are called repeatedly such as in numerical LEMs (e.g., Willgoose, 2005; Pelletier, 2008; Tucker and Hancock, 2010). While rivers act as major pathways of sediment and upstream migrating knickpoints in mountain environments, they encompass only a small portion of the entire landscape. Accordingly, in LEMs the heterogeneous distribution of upslope areas leads to numerical solutions that require very small time steps to be numerically stable. Though implicit methods exist that relax the time step constraints (Fagherazzi et al., 2002; Braun and Willet, 2013), they fail to include the planform changes of river and flow network development, thus making frequent updating of the flow directions necessary. With its new implementation, TopoToolbox 2 can serve as a function library for the development of LEMs in MATLAB by providing fast executing codes in a programming language that already supports a large library of numerical tools.

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In most studies detailed topographic analyses are preceded by an initial visual exploration to familiarize with and assess the quality of a DEM, or to explore the results of model routines during coding. Furthermore, certain tasks are often easier and more rapidly accomplished through direct interaction with DEMs and their derivatives, as compared to writing and running scripts. Thus, TopoToolbox 2 now comes with several applications that allow usage and exploration of various toolbox functions with a graphical user interface (GUI).

The *topoapp* is an explorative tool for visual DEM analysis that provides rapid access to many basic and several advanced functions of the TopoToolbox 2. Importantly, *topoapp* is defined as an own object class that, when working on an instance of *topoapp* with the GUI, remains in the workspace and is constantly updated with every action of the user. Additionally, it was written in a way that allows users to add their own functions or modules to it and therefore provides an expandable platform for displaying the graphical outcomes of DEM analysis with the TopoToolbox and other MATLAB tools. With the currently embedded functions, users can quickly and easily extract and plot simple profiles, entire drainage networks or subsets of it, watershed boundaries, and individual channel reaches. The created features can be used to build swath profiles, subset the DEM, or compute simple catchment statistics, amongst other options. Depending on the availability of MATLAB's Mapping Toolbox or other existing, freely available MATLAB functions, all created objects can be exported as shapefiles or kml-files.

Manual editing of DEMs with spurious sinks is often required to produce hydrologically correct DEMs. Although automated ways to distinguish between actual and spurious sinks exist (Lindsay and Creed, 2006), choosing which sinks should be filled, carved or retained may be preferred and requires visual interpretation of the data and results. The new *preprocessapp* enables a combination of automatic and manual hydrological correction of a DEM by providing interactive tools to fill topographic depressions or carve along least-cost paths to breach features that obstruct digital flow paths. The *flowpathapp* is a tool to map individual streams or a stream network by interactively

setting channelhead locations and the *slopeareatool* provides an interactive tool to study slope-area relationship for individual streams or stream networks.

5 Conclusions

With the release of version 2, the TopoToolbox for MATLAB has become a more memory efficient, faster and more user-friendly tool for digital terrain analysis. The main difference to the previous version is the adoption of an object-oriented representation of grids, flow direction and stream networks. Topological ordering reduces the memory bottleneck of the previous, sparse matrix approach to flow direction while increasing computation speed and allowing parallel computing. Software quality and particularly reusability are improved so that TopoToolbox can be used as a framework for implementing dynamic, hydrological and geomorphological models. Finally, newly introduced, interactive tools will not only be valuable for researchers to perform rapid analysis but also for conveying and exploring the richness of Earth surface processes in classrooms or labs.

Supplementary material related to this article is available online at <http://www.earth-surf-dynam-discuss.net/1/261/2013/esurfd-1-261-2013-supplement.zip>.

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Table 2. Selection of object-specific methods and functions.

Function	Input	Description
Class: GRIDobj		
GRIDobj	DEM (Geotiff, ASCII)	Generates a new instance of GRIDobj from a geotiff image or ESRI ascii file
ASPECT	GRIDobj	Creates a GRIDobj with surface aspects
CROP	GRIDobj	Trims a GRIDobj based on extent indicators
CASTSHADOW	GRIDobj	Topographic cast shadow based on sun azimuth and elevation
CURVATURE	GRIDobj	Second derivatives of a DEM
FILLSINKS	GRIDobj	Flood filling of a DEM
GRADIENT8	GRIDobj	Steepest downward gradient
HYPSCURVE	GRIDobj	Hypsometric curve
INPAINTNANS	GRIDobj	Interpolate missing values
LOCALTOPOGRAPHY	GRIDobj	Elevation range within a moving window
RESAMPLE	GRIDobj	Resizing of a DEM
ROUGHNESS	GRIDobj	Surface roughness parameters incl. topographic positioning index, ruggedness etc.
...		
Class: FLOWobj		
FLOWobj	GRIDobj	Flow direction object derived from a DEM
DEPENDENCEMAP	FLOWobj	Upstream area for specific locations in a DEM
DRAINAGEBASINS	FLOWobj	Drainage basin delineation
FLOWACC	FLOWobj, GRIDobj	Flow accumulation (upslope area, contributing area), weighted and incl. decay
FLOWDISTANCE	FLOWobj	Upstream and downstream flow distance
FLOWobj2GRIDobj	FLOWobj	Convert instance of FLOWobj to ESRI ArcGIS flow direction grid
IMPOSEMIN	FLOWobj, GRIDobj	Downstream minima imposition for DEM carving
INFLUENCEMAP	FLOWobj	Downstream area for specific locations in a DEM
STREAMORDER	FLOWobj, GRIDobj	Strahler stream order
UPSLOPESTATS	FLOWobj, GRIDobj	Upslope statistics (e.g., sum, mean, variance, standard deviation, minimum, maximum)
VERTDISTANCE2STREAM	FLOWobj, STREAMobj	Vertical distance to stream network
...		
Class: STREAMobj		
STREAMobj	FLOWobj, GRIDobj	Stream object derived from flow direction and stream grid
EXTRACTCONNCOMPS	STREAMobj	Interactive stream network selection
GRADIENT	STREAMobj, GRIDobj	Stream gradient
KLARGESTCONNCOMPS	STREAMobj	Retain <i>k</i> largest connected components in a stream network
MODIFY	STREAMobj	Trim stream network to meet user-defined criteria
PLOT	STREAMobj	Overloaded plot command
PLOTDZ	STREAMobj, GRIDobj	Plot distance from outlet vs. elevation
SNAP2STREAM	STREAMobj, coordinates	Snap gauges to be congruent with the stream network
STREAMORDER	STREAMobj	Strahler stream order
TRUNK	STREAMobj	Extract trunk stream of a network
...		
Tools		
SWATHobj	GRIDobj	Swath profile mapping along profiles or stream networks
CHIPLOT	STREAMobj, GRIDobj	Chi plot of a stream network
SLOPEAREA	STREAMobj, GRIDobj	Slope area plot of a stream network incl. power law fitting
Graphical User interfaces		
TOPOAPP	GRIDobj	Opens GUI window for processing and analyzing DEMs
FLOWPATHAPP	FLOWobj, GRIDobj	Interactively map streams based on flow direction
SLOPEAREATOOL	FLOWobj, GRIDobj	Interactively analyze slope-area relation

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