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Studying Stream Morphology With Airborne Laser Elevation Data

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Much progress has been made linking the fields of geomorphology, hydrology, ecology, and tectonics over the past approximately 20 years using digital elevation models (DEMs) to study stream processes. DEMs forming the basis of such research were created by interpolating between contour lines digitized from topographic maps, which were generated from aerial photographs. With pixel sizes of 10–90 meters on each edge, these grids allowed investigators to make measurements of parameters such as stream gradient and contributing drainage area over entire channel networks; these parameters also found use as inputs for basin-scale models of stream erosion and sediment transport [e.g., *Wobus et al.*, 2006].

However, the accuracy of these "traditional" DEMs varies spatially because map contour interval (typically 3–20 meters) and density (set by landscape gradient) dictate the resolution of information available to interpolate an elevation value for each pixel on the grid. Thus, traditional DEMs miss many fine-scaled features, particularly those in low-relief terrain. DEMs generated from space shuttle or satellite radar surveys have similar pixel resolution (10–90 meters) but do not measure land surface elevations in forested regions, limiting their applicability for studies of channels.

Now, DEMs generated from airborne laser elevation (light detection and ranging, or lidar) surveys open up new opportunities for research on stream processes because they improve resolution by an order of magnitude compared with traditional DEMs. With pixel sizes of 0.5–5 meters on each edge and the ability to measure height down to 5–20 centimeters (compared with the contour interval of traditional DEMs), lidar DEMs enable researchers to identify channel features, such as the water surface, bank edges, and floodplains, as well as measure the slopes of channels over short stream reaches. Furthermore, they provide new types of data about watershed land cover, such as the height and density of the tree canopy, because the laser instrument receives returns from both treetops and the land (or water) surface.

These new DEMs will revolutionize the scientific community's ability to visualize and quantify landscape processes and changes, although they also pose new technical challenges, such as how to automate extraction of channel networks and features. This article summarizes and illustrates some of these opportunities and challenges, beginning with a short tutorial on methods of extracting

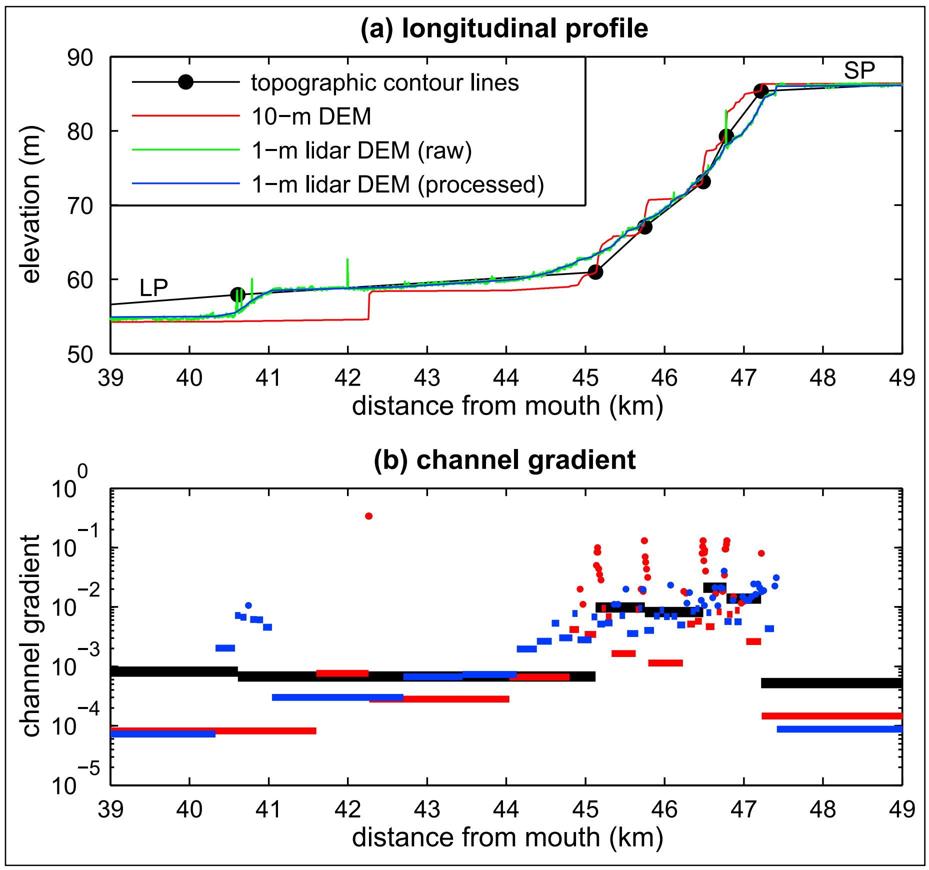

Fig. 1. Comparison of (a) longitudinal profiles and (b) channel gradient measured from topographic maps, a 10-meter digital elevation model (DEM), and a 1-meter light detection and ranging (lidar) DEM from a 10-kilometer section of the Sheepscot River, Maine, between Sheepscot Pond (SP) and Long Pond (LP). All profiles were extracted along the same channel path to facilitate comparisons. For the DEMs, channel gradient was calculated from the processed profiles over 0.5-meter vertical intervals; where this corresponds to less than 50 meters of horizontal distance, the data are plotted as points, not lines. The 10-meter DEM profile (red) connects minima in the downstream direction and is nearly identical to the profile obtained using a standard flow-routing algorithm. Note the distinct "stair step" pattern in the red curve of the longitudinal profile, which results in spurious steep slope values because the channel gradient was calculated over a vertical change less than the contour interval (6.1 meters) of the topographic map used to create the 10-meter DEM. The 1-meter lidar profile (green curve) was processed using a moving average filter, and then by connecting minima, which removed peaks from bridges and other nonchannel features from the resulting longitudinal profile (blue curve). Note that the blue curve is plotted on top of the green curve.

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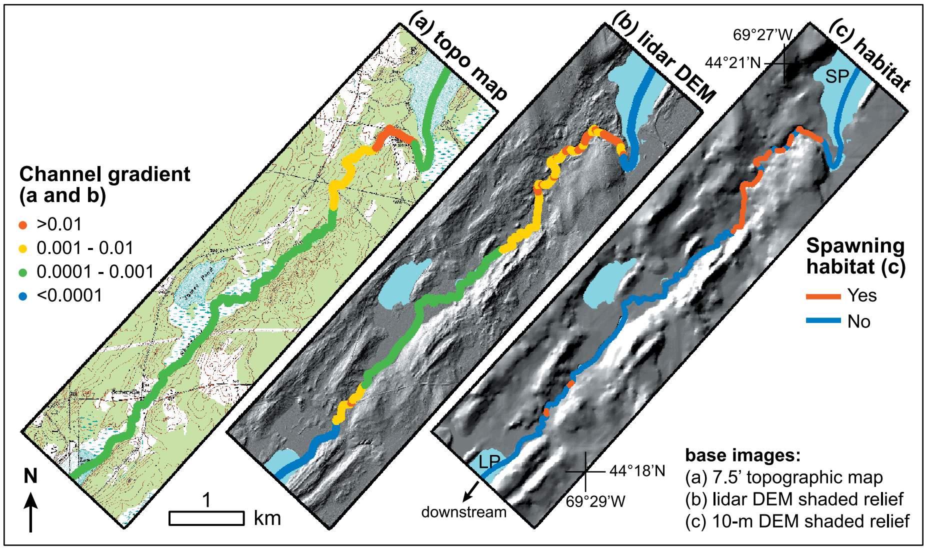

Fig. 2. Maps of channel gradient measured from (a) topographic contour maps and (b) a lidar DEM and (c) Atlantic salmon spawning habitat, for the same segment of the Sheepscot River shown in Figure 1. For comparison, the maps show three different base images. The habitat mapping (Figure 2c) is based on field surveys by the U.S. Fish and Wildlife Service (available from http://megis.maine.gov/). Note the greater resolution provided by the lidar DEM image and profile (Figure 2b), and the correspondence of higher slope (Figure 2b) with spawning habitat (Figure 2c).

channel morphologic data from DEMs in general.

Extracting Data From DEMs

To obtain stream morphologic information, researchers process DEMs using a series of algorithms, some of which are parts of geographic information system (GIS) software packages.

The first step is to identify the channel in two-dimensional map view, commonly done using algorithms that estimate flow paths by identifying the steepest downhill neighbor of every pixel on a DEM that has been processed to be hydrologically continuous (i.e., if necessary, small depressions introduced by the grid interpolation process are filled). Channels are identified by tracking the number of upstream pixels, resulting in a measurement of contributing drainage area for every pixel. These algorithms yield an excellent match with channels mapped from other sources (e.g., topographic maps, aerial photographs) in mountainous landscapes where the pixel size is of the order of channel width and changes in elevation are large [*Wobus et al.*, 2006]. In low-gradient landscapes or large rivers, this method often cannot resolve sinuous channel paths. A simple alternative method is to use channel paths generated from aerial photographs or topographic maps, as was done to measure the example profiles in Figure 1a.

In the second step, elevation values are extracted from the original (unfilled) DEM along the channel path, which yields a profile of elevation in terms of distance along the length of the channel. The profile may need to be processed to remove peaks that are either artifacts of the DEM gridding process or points sampling adjacent floodplain or hillslope topography. Various methods are used to accomplish this; in Figure 1a, profiles from DEMs were processed by interpolating between minima, ensuring the best representation of the water surface (i.e., the lowest part of the landscape). Finally, the channel's gradient is calculated, typically over a fixed vertical or horizontal interval.

Comparing Traditional DEMs With Airborne Lidar DEMs

Work with DEMs generated from topographic maps has led to breakthroughs in understanding processes related to hillslope-channel coupling [e.g., *Dietrich et al.*, 1993] and the response of rivers to changes in climate and tectonics [e.g., *Wobus et al.*, 2006]. The gridding algorithm used to make the highest-quality DEMs takes into account mapped water bodies, which improves automated measurement of flow paths and drainage area. However, changes in channel gradient can be resolved only over the original contour interval.

Figure 1 illustrates the limitation using data from a low-gradient river in Maine. Calculations of gradient from the 10-meter traditional DEM at a resolution finer than the contour interval of the topographic map source (6.1 meters, or 20 feet) yield spurious extreme values related to the stair steps on the profile. This is problematic in low-relief landscapes, where 6 meters of elevation change may occur over 6 kilometers of channel distance. This stream length may include wide variations in morphologic characteristics that are missed by topographic maps and associated 10-meter DEMs (Figures 1 and 2).

Lidar DEMs free researchers from many limitations of traditional DEMs. In the example shown in Figures 1 and 2, gradient is calculated over 0.5-meter vertical intervals, which represents the finest scale that can be resolved due to local noise in the elevation of the water surface on the lidar DEMs. These measurements compare well with high-precision field surveys. Furthermore, morphologic features such as banks and floodplains can be identified and measured within the lidar DEMs in channels where the width is larger than a few pixels. These features cannot be resolved with 10-meter DEMs.

Lidar DEMs allow researchers to make measurements of morphologic parameters over entire stream networks, at a resolution previously available only via time-consuming field surveying [*McKean et al.*, 2008]. Yet unlike widely available traditional DEMs, most high-resolution lidar DEMs to date have been collected for individual study areas and funded by specific research projects. This piecemeal approach is expensive but allows for repeat lidar surveys in the event of large-scale land disturbances, such as major floods.

Applications of Airborne Lidar DEMs

High-resolution elevation data sets generated through airborne lidar studies allow researchers to address new questions. *Hilley and Arrowsmith* [2008] used a lidar DEM to study the uplift and response of a series of small (<1 square kilometer) catchments along a tectonically active pressure ridge. The 1-meter DEM enabled them to measure reach-scale variations in channel gradient and other geomorphic parameters in the small basins. Similarly, lidar DEMs are useful in low-relief watersheds where traditional DEMs do not adequately resolve channel changes (see Figures 2b and 2c).

Lidar DEMs can provide boundary conditions for hydrologic models and are particularly useful in studying urban flooding because they represent the influence of roads, ditches, and buildings [e.g., *McMillan and Brasington*, 2007]. Such models also benefit from watershed land cover information (e.g., tree canopy height and structure) available from lidar data sets.

Another opportunity, facilitated by lidar DEMs, is to investigate links between channel morphology and riparian ecology (see Figure 2). In an exciting new direction, *McKean et al.* [2008] used a water-penetrating lidar system to study spatial patterns of riverbed morphology, hydraulics, and Chinook salmon spawning habitat. Studies using lidar DEMs may guide stream restoration processes by identifying reaches with potential high-quality habitat.

Research Challenges

In addition to the new varied applications, lidar DEMs present new research challenges for channel studies, including sparse laser returns off surface water, and the need for new flow-routing algorithms.

The 1064-nanometer laser used in most lidar mapping systems can be absorbed by water, limiting returns from surface water bodies. Gridding algorithms that produce bare-earth DEMs (i.e., with vegetation removed) from raw laser returns seek the lowest elevation in a given search window, so typically they sample the water surface or adjacent locations low on river banks, but in some areas the density of returns may be too sparse, causing DEM data gaps. A simple solution is to interpolate longitudinal profiles based on available data, which can be done with reasonable accuracy because water surface elevations change little across rivers and over short intervals in the downstream direction (<50 meters). For detailed, reach-scale studies, researchers may work with laser point clouds, rather than gridded DEMs, but this method is computationally expensive.

Additionally, flow-routing algorithms based on adjacent pixels typically overestimate channel length because the pixel size is less than channel width, resulting in overly sinuous estimates of channel paths. These algorithms are also computationally intensive and therefore impractical in large (>100 square kilometer) drainage basins. At present, researchers are developing new flow-routing algorithms, which will also improve the measurement of contributing drainage area from high-resolution DEMs. Another solution is to hand-digitize channel paths on lidar images [*McKean et al.*, 2008].

Future of Airborne Lidar

At present, maps generated from airborne lidar cover a small fraction of the Earth's total land area. However, as the value of high-resolution DEMs is becoming more recognized, several groups are working to increase spatial coverage and make maps readily available.

The National Center for Airborne Laser Mapping (NCALM; http://www.ncalm.ufl.edu/) collects and archives research-grade data from 10–20 study areas per year, mostly as part of projects funded by the U.S. National Science Foundation. Government agencies are conducting laser altimetry surveys over large areas (including entire U.S. states), often motivated by flood hazard mapping. Lidar processing algorithms are also being developed and made available online (see links compiled at the U.S. Geological Survey lidar information Web site, http://lidar.cr.usgs.gov/) and in remote-sensing and GIS software packages.

This expanding availability of data and processing algorithms will fuel advances in understanding river systems. Lidar DEMs hold great promise for unraveling relationships among stream physical, chemical, and biological processes, and changes in tectonics, climate, and land use.

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Archive Compiles New Resource for Global Tropical Cyclone Research

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The International Best Track Archive for Climate Stewardship (IBTrACS) compiles tropical cyclone best track data from 11 tropical cyclone forecast centers around the globe, producing a unified global best track data set (M. C. Kruk et al., A technique for merging global tropical cyclone best track data, submitted to *Journal of Atmospheric and Oceanic Technology*, 2008). Best track data (so called because the data generally refer to the best estimate of a storm's characteristics) include the position, maximum sustained winds, and minimum central pressure of a tropical cyclone at 6-hour intervals.

Despite the significant impact of tropical cyclones on society and natural systems, there had been no central repository maintained for global best track data prior to the development of IBTrACS in 2008. The data set, which builds upon the efforts of the international tropical forecasting community, has become the most comprehensive global best track data set publicly available. IBTrACS was created by the U.S. National Oceanic and Atmospheric Administration's National Climatic Data Center (NOAA NCDC) under the auspices of the World Data Center for Meteorology.

While IBTrACS is archived using the network common data format (NetCDF [*Rew and Davis*, 1990]), NCDC also provides best track data in a variety of other formats. NetCDF allows for the storage of many variables along with their descriptions, is actively supported by its developers, and has software interfaces readily available for many programming languages. Because NetCDF is not widely used by the tropical cyclone research community, NCDC has translated the IBTrACS into a variety of traditional formats such as NOAA's 80-column format [*Jarvinen et al.*, 1984], Automatic Tropical Cyclone Forecast, and other ASCII code formats; and into newer formats such as cyclone XML (cXML), which was designed in 2008 to facilitate the interchange of cyclone data within the modeling community.

Additionally, NCDC has made IBTrACS available through Open Geospatial Consortium, Inc., service interface standards such as Web Map Services and Web Feature Services, which will facilitate geographic information system (GIS) analysis of the data and allow for portability between systems and users. Through this family of services, conditional queries can be constructed to highlight storms, regions, or situations. For example, with conditional queries, one can determine the historical probability of a storm affecting a certain location given its current position (Figure 1).

IBTrACS is unique in that it incorporates best track data from numerous forecast centers. Therefore, researchers no longer need to contact each center to obtain best track data, nor do they need to write user-defined tools to determine, for example, which storms were reported by multiple forecast centers. In the process of merging storm data for IBTrACS, information about the range of a storm's position and intensity (pressure and/or wind) reported by various centers is maintained and provided to the user. Additionally, data quality assessments provide information on the quality of the best track data.

IBTrACS is an ongoing project and will be updated semiannually. Though numerous capabilities currently exist to utilize IBTrACS, the full range of potential uses of the data set has yet to be realized. It is anticipated that with the availability of IBTrACS data, these formats will further expand the user base and allow applications of the IBTrACS data set to be shared by those studying tropical cyclones: