Lecture 6

DEM Based Watershed & Stream Network Delineations

GIS in Water Resources
Spring 2015

Digital Elevation Model Based Watershed and Stream Network Delineation

• Conceptual Basis
• Eight direction pour point model (D8)
• Flow accumulation
• Pit removal and DEM reconditioning
• Stream delineation
• Catchment and watershed delineation
• Geomorphology, topographic texture and drainage density
• Generalized and objective stream network delineation
Readings

- Arc Hydro Chapter 4


Conceptual Basics

- Based on an information model for the topographic representation of downslope flow derived from a DEM
- Enriches the information content of digital elevation data.
  - Sink removal
  - Flow field derivation
  - Calculating of flow based derivative surfaces
  - Delineation of channels and subwatersheds
### Duality between Terrain and Drainage Network

- Flowing water erodes landscape and carries away sediment sculpting the topography.
- Topography defines drainage direction on the landscape and resultant runoff and streamflow accumulation processes.

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The terrain flow information model for deriving channels, watersheds, and flow related terrain information. Watersheds are the most basic hydrologic landscape elements.

Raw DEM → Pit Removal (Filling) → Flow Field → Channels, Watersheds, Flow Related Terrain Information
DEM Elevations

720 720

Contours
- 740
- 720
- 700
- 680

740 720 700 680

Hydrologic Slope
- Direction of Steepest Descent

Slope: \( \frac{67 - 48}{30\sqrt{2}} = 0.45 \)

Slope: \( \frac{67 - 52}{30} = 0.50 \)

ArcHydro Page 70
Eight Direction Pour Point Model

ESRI Direction encoding

Flow Direction Grid

ArcHydro Page 69

ArcHydro Page 71
Flow Direction Grid

Grid Network

ArcHydro Page 71
Flow Accumulation Grid. Area draining in to a grid cell

Flow Accumulation > 10 Cell Threshold

Stream Network for 10 cell Threshold Drainage Area
The area draining each grid cell includes the grid cell itself.

Streams with 200 cell Threshold

(>18 hectares or 13.5 acres drainage area)
Watershed Draining to Outlet

Automated method is more consistent than hand delineation
The Pit Removal Problem

- DEM creation results in artificial pits in the landscape
- A pit is a set of one or more cells which has no downstream cells around it
- Unless these pits are removed they become sinks and isolate portions of the watershed
- Pit removal is first thing done with a DEM

Pit Filling

Increase elevation to the pour point elevation until the pit drains to a neighbor
Parallel Approach

- Improved runtime efficiency
- Capability to run larger problems
- Row oriented slices
- Each process includes one buffer row on either side
- Each process does not change buffer row
Pit Removal: Planchon Fill Algorithm

Planchon, O., and F. Darboux (2001), A fast, simple and versatile algorithm to fill the depressions of digital elevation models, *Catena*(46), 159-176.

**Parallel Scheme**

D denotes the original elevation.
P denotes the pit filled elevation.
n denotes lowest neighboring elevation
i denotes the cell being evaluated
Improved runtime efficiency

Parallel Pit Remove timing for NEDB test dataset (14849 x 27174 cells ≈ 1.6 GB).

8 processor PC
Dual quad-core Xeon E5405 2.0GHz PC with 16GB RAM

128 processor cluster
16 diskless Dell SC1435 compute nodes, each with 2.0GHz dual quad-core AMD Opteron 2350 processors with 8GB RAM

The challenge of increasing Digital Elevation Model (DEM) resolution

1980’s DMA 90 m $10^2$ cells/km$^2$

1990’s USGS DEM 30 m $10^3$ cells/km$^2$

2000’s NED 10-30 m $10^4$ cells/km$^2$

2010’s LIDAR ~1 m $10^6$ cells/km$^2$
### Capabilities Summary

<table>
<thead>
<tr>
<th>Capability to run larger problems</th>
<th>Processors used</th>
<th>Grid size</th>
<th>Theoretical limit</th>
<th>Largest run</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006 TauDEM 4</td>
<td>1</td>
<td>0.22 GB</td>
<td>0.22 GB</td>
<td></td>
</tr>
<tr>
<td>Sept 2009 Partial implement-ation</td>
<td>8</td>
<td>4 GB</td>
<td>1.6 GB</td>
<td></td>
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<tr>
<td>June 2010 TauDEM 5</td>
<td>8</td>
<td>4 GB</td>
<td>4 GB</td>
<td></td>
</tr>
<tr>
<td>Sept 2010 Multifile on 48 GB RAM PC</td>
<td>4</td>
<td>Hardware limits</td>
<td>6 GB</td>
<td></td>
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<tr>
<td>Sept 2010 Multifile on cluster with 128 GB RAM</td>
<td>128</td>
<td>Hardware limits</td>
<td>11 GB</td>
<td></td>
</tr>
</tbody>
</table>

Single GeoTIFF file size limit 4GB

At 10 m grid cell size

### Carving

Lower elevation of neighbor along a predefined drainage path until the pit drains to the outlet point
“Burning In” the Streams

- Take a mapped stream network and a DEM
- Make a grid of the streams
- Raise the off-stream DEM cells by an arbitrary elevation increment
- Produces "burned in" DEM streams = mapped streams
AGREE Elevation Grid Modification Methodology – DEM Reconditioning

Stream Segments

Each link has a unique identifying number

ArcHydro Page 74
Vectorized Streams Linked Using Grid Code to Cell Equivalents

DrainageLines are drawn through the centers of cells on the stream links. DrainagePoints are located at the centers of the outlet cells of the catchments
Key Concepts

- DEM Reconditioning as an example of quantitative raster analysis
  - Vector to Raster
  - Distance
  - Raster Calculation
  - Volume removed analysis

\[
\text{"smdem"} - 10 \times \text{"flowLineReclas"} - 0.02 \times (500 - \text{"distance"}) \times (\text{"distance"} < 500)
\]

Add 10 at all stream grid cells

Only do taper when distance is less than 500, otherwise this is 0 and nothing is subtracted

3D Analyst Profiles
Catchments

- For every stream segment, there is a corresponding catchment
- Catchments are a tessellation of the landscape through a set of physical rules

Raster Zones and Vector Polygons

One to one connection

DEM GridCode → Catchment GridID

Raster Zones

Vector Polygons
Catchments, DrainageLines and DrainagePoints of the San Marcos basin

Watershed outlet points may lie within the interior of a catchment, e.g. at a USGS stream-gaging site.
Construct the Analysis Layer

- Fill
- Flow Direction
- Flow Accumulation
- Stream Definition
- Stream Links
- Catchments

Convert to Vector

- Vector streams
- Vector catchments
- Attribute feature with raster zonal statistics
- Geometric Network
- Tracing
- Selection statistics
Summary of Key Processing Steps

• [DEM Reconditioning]
• Pit Removal (Fill Sinks)
• Flow Direction
• Flow Accumulation
• Stream Definition
• Stream Segmentation
• Catchment Grid Delineation
• Raster to Vector Conversion (Catchment Polygon, Drainage Line, Catchment Outlet Points)

Delineation of Channel Networks and Catchments
How to decide on stream delineation threshold?

Drainage density (total channel length divided by drainage area) as a function of drainage area support threshold used to define channels for the three study watersheds.

Why is it important?

Hydrologic processes are different on hillslopes and in channels. It is important to recognize this and account for this in models.

Drainage area can be concentrated or dispersed (specific catchment area) representing concentrated or dispersed flow.
Examples of differently textured topography

Badlands in Death Valley.
from Easterbrook, 1993, p 140.

Coos Bay, Oregon Coast Range.
from W. E. Dietrich

Gently Sloping Convex Landscape

From W. E. Dietrich
“landscape dissection into distinct valleys is limited by a threshold of channelization that sets a finite scale to the landscape.” (Montgomery and Dietrich, 1992, Science, vol. 255 p. 826.)

Suggestion: One contributing area threshold does not fit all watersheds.

Let's look at some geomorphology.

- Drainage Density
- Horton’s Laws
- Slope – Area scaling
- Stream Drops
Drainage Density

• $D_d = \frac{L}{A}$
• Hillslope length $\approx \frac{1}{2}D_d$

Hillslope length = $B$

$A = 2B \cdot L$

$D_d = \frac{L}{A} = \frac{1}{2}B$

$\therefore B = \frac{1}{2}D_d$

Drainage Density for Different Support Area Thresholds

EPA Reach Files

100 grid cell threshold

1000 grid cell threshold

1 0 1 2 Kilometers
Drainage Density Versus Contributing Area Threshold

Hortons Laws: Strahler system for stream ordering
Length Ratio

![Graph showing the relationship between order and mean stream length, with a linear trend with a slope of Rs = 1.91.]

Slope Ratio

![Graph showing the relationship between order and mean stream slope, with a linear trend with a slope of Rs = 1.7.]

Length Ratio

<table>
<thead>
<tr>
<th>Order</th>
<th>Mean Stream Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>900</td>
</tr>
<tr>
<td>2</td>
<td>2000</td>
</tr>
<tr>
<td>3</td>
<td>4000</td>
</tr>
</tbody>
</table>

Slope Ratio

<table>
<thead>
<tr>
<th>Order</th>
<th>Mean Stream Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.10</td>
</tr>
<tr>
<td>1.5</td>
<td>0.05</td>
</tr>
<tr>
<td>2.0</td>
<td>0.05</td>
</tr>
<tr>
<td>2.5</td>
<td>0.05</td>
</tr>
<tr>
<td>3.0</td>
<td>0.05</td>
</tr>
<tr>
<td>3.5</td>
<td>0.05</td>
</tr>
<tr>
<td>4.0</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Constant Stream Drops Law

![Graph showing constant stream drops law](image)

Rd = 0.944


Stream Drop

Elevation difference between ends of stream

Note that a “Strahler stream” comprises a sequence of links (reaches or segments) of the same order
Suggestion: Map channel networks from the DEM at the finest resolution consistent with observed channel network geomorphology ‘laws’.

- Look for statistically significant break in constant stream drop property as stream delineation threshold is reduced
- Break in slope versus contributing area relationship
- Physical basis in the form instability theory of Smith and Bretherton (1972), see Tarboton et al. 1992
T-Test for Difference in Mean Values

<table>
<thead>
<tr>
<th>Order 1</th>
<th>Order 2-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean X</td>
<td>72.2</td>
</tr>
<tr>
<td>Std X</td>
<td>68.8</td>
</tr>
<tr>
<td>Var X</td>
<td>4740.0</td>
</tr>
<tr>
<td>Nx</td>
<td>268</td>
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</tbody>
</table>

T-test checks whether difference in means is large (> 2) when compared to the spread of the data around the mean values.

Constant Support Area Threshold

<table>
<thead>
<tr>
<th>Support Area threshold (30 m grid cells)</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>500</th>
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</thead>
<tbody>
<tr>
<td>Drainage Density (km(^{-1}))</td>
<td>3.3</td>
<td>2.3</td>
<td>1.7</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>t statistic for difference between lowest order and higher order drops</td>
<td>-8.8</td>
<td>-5</td>
<td>-1.8</td>
<td>-1.1</td>
<td>-0.72</td>
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</tbody>
</table>
100 grid cell constant support area threshold stream delineation

200 grid cell constant support area based stream delineation
Local Curvature Computation

Contributing area of upwards curved grid cells only
Upward Curved Contributing Area Threshold

<table>
<thead>
<tr>
<th>Strahler Stream Order</th>
<th>0</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>135</td>
<td>135</td>
<td>135</td>
<td>135</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

Upward curved support area threshold (30 m grid cells)

<table>
<thead>
<tr>
<th>Drainage Density (km⁻¹)</th>
<th>2.2</th>
<th>1.8</th>
<th>1.6</th>
<th>1.4</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>t statistic for difference between lowest order and higher order drops</th>
<th>-4.1</th>
<th>-2.2</th>
<th>-1.3</th>
<th>-1.2</th>
</tr>
</thead>
</table>

Curvature based stream delineation
Channel network delineation, other options

Contributing Area

Grid Order

Grid network pruned to order 4 stream delineation
Summary Concepts

• The eight direction pour point model approximates the surface flow using eight discrete grid directions
• The elevation surface represented by a grid digital elevation model is used to derive surfaces representing other hydrologic variables of interest such as
  – Slope
  – Flow direction
  – Drainage area
  – Catchments, watersheds and channel networks

Summary Concepts (2)

• Hydrologic processes are different between hillslopes and channels
• Drainage density defines the average spacing between streams and the representative length of hillslopes
• The constant drop property provides a basis for selecting channel delineation criteria to preserve the natural drainage density of the topography
• Generalized channel delineation criteria can represent spatial variability in the topographic texture and drainage density
Are there any questions?