# Digital Elevation Models and Hydrology

David G. Tarboton

Utah State University, Civil & Environmental Engineering Department, Logan, UT

## Abstract

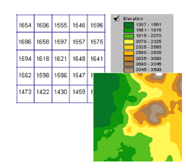
Digital elevation models (DEMs) are a useful data source for the automatic delineation of flow paths, sub watersheds and channel networks for hydrologic modeling. The scale (drainage density) of the flow network used, controls the scale of hillslope and channel model elements and the distinction between hillslope and channel processes. Although field mapping is acknowledged as the most accurate way to determine channel networks and drainage density, it is often impractical, especially for large watersheds, and DEM derived flow networks then provide a useful surrogate for channel or valley networks. There are a variety of approaches to delineating flow networks, using different algorithms such as single (drainage to a single neighboring cell) and multiple (partitioning of flow between multiple neighboring cells) flow direction methods for the computation of contributing area, and local identification of upwards curvature. The scale of the delineated network is sometimes controlled by a support area threshold, which may impose an arbitrary and spatially constant drainage density. This paper reviews methods for the delineation of flow networks using grid DEMs. The question of objective estimation of drainage density is addressed and a method based on terrain curvature that can accommodate spatially variable drainage density is presented. The spatial flow field determined from a DEM can also serve as a basis for routing overland and topographically driven subsurface flows useful in water quality, erosion and terrain stability modeling. New DEM derived quantities, such as downslope influence, upslope dependence, decayed accumulation, downslope accumulation and transport limited accumulation are illustrated. The methods presented have been incorporated into software (TauDEM) developed to support hydrologic and water quality modeling and available from the author's website.

## Purposes

1. Hillslope, channel partitioning and objective drainage density estimation
2. New DEM analysis concepts that may be useful in hydrology

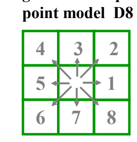
### Digital Elevation Model Based Flow Path Analysis

What is a digital elevation model (DEM) grid

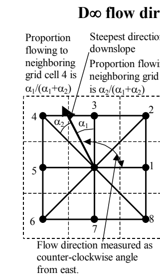


A grid of cells (square or rectangular) in some coordinate system having land surface elevation as the value stored in each cell

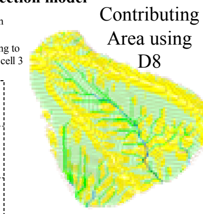
Eight direction pour point model D8



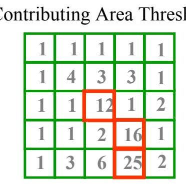

D∞ flow direction model



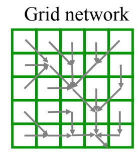

Contributing Area using D8



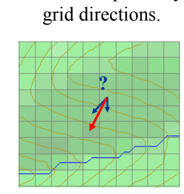
Contributing Area Threshold

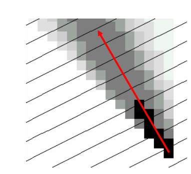



Grid network

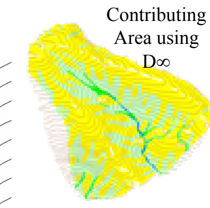


Limitation imposed by 8 grid directions.



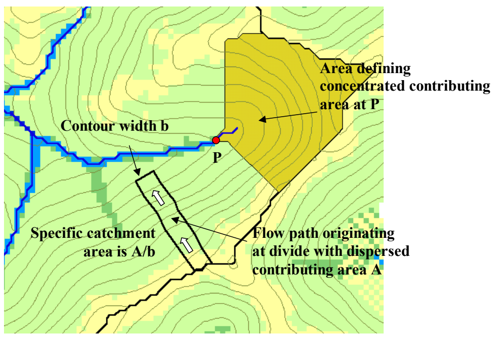


Contributing Area using D∞

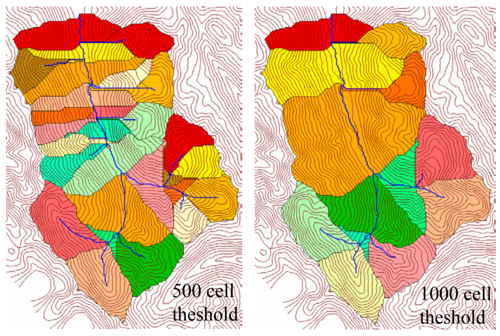


Tarboton, D. G., (1997), "A New Method for the Determination of Flow Directions and Contributing Areas in Grid Digital Elevation Models," Water Resources Research, 33(2): 309-319.)

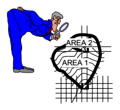
**Hydrologic processes are different on hillslopes and in channels. It is important to recognize this and delineate model elements that account for this.**




**Drainage area can be concentrated or dispersed (specific catchment area).**

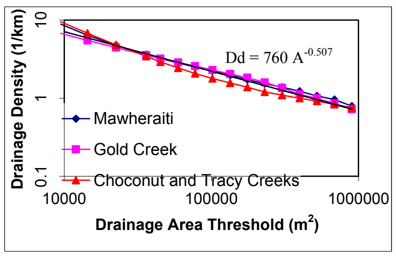



**Different subwatersheds (hydrologic model elements) are delineated with different support area thresholds.**

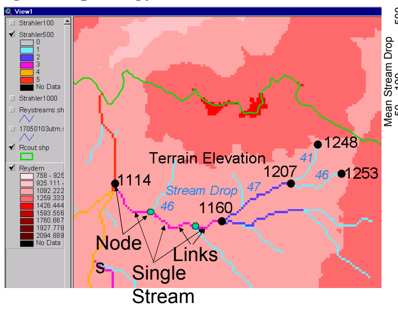


**How to decide on drainage area threshold ?**

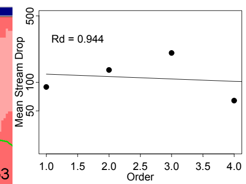
Constant Strahler Stream Drop Property as an empirical geomorphology 'law'




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.



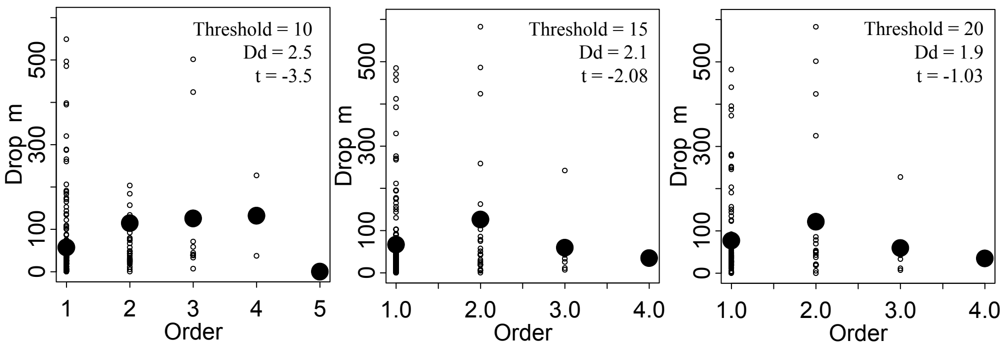

Note that a "Strahler stream" comprises a sequence of links (reaches or segments) of the same order




- most upstream is order 1
- when two streams of a order i join, a stream of order i+1 is created
- when a stream of order i joins a stream of order i+1, stream order is unaltered

**Suggestion: Map channel networks from the DEM at the finest resolution consistent with observed channel network geomorphology 'laws'. Here the constant drop property is used. We test for a statistically significant break in the 'constant' stream drops across stream orders.**

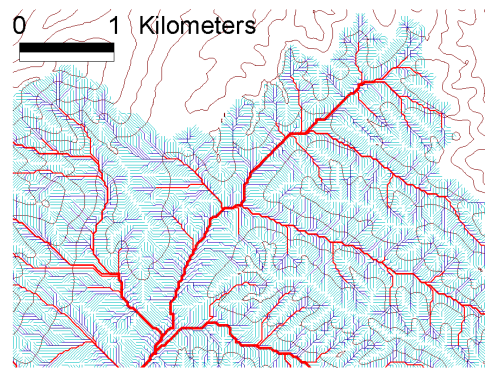
Statistical Analysis of Stream Drops



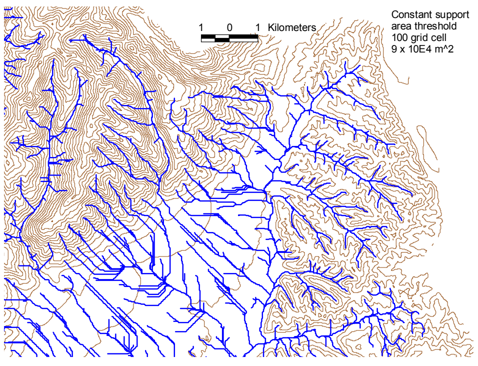

Stream drop test for Mawheraiti River. For each upward curved support area threshold the stream drop for each stream is plotted against Strahler stream order. The large circles indicate mean stream drop for each order The weighted support area threshold, drainage density (in km$^{-1}$) and t statistic for the difference in means between lowest order and all higher order streams is given.

### Flow Network Delineation Methods

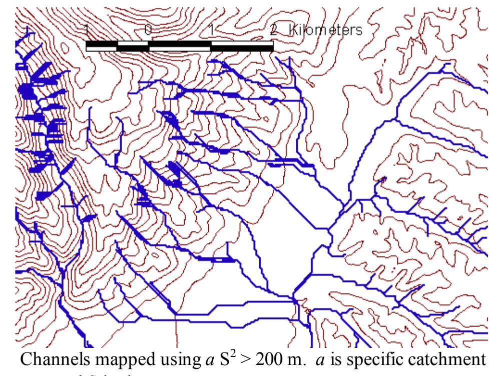
Grid Network Ordering Approach (Peckham, 1995)




100 grid cell constant drainage area threshold stream delineation

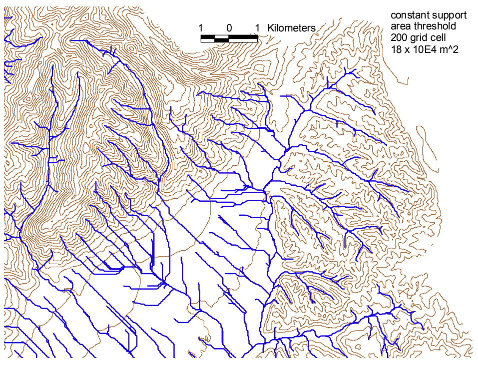



Slope area threshold (Montgomery and Dietrich, 1992).

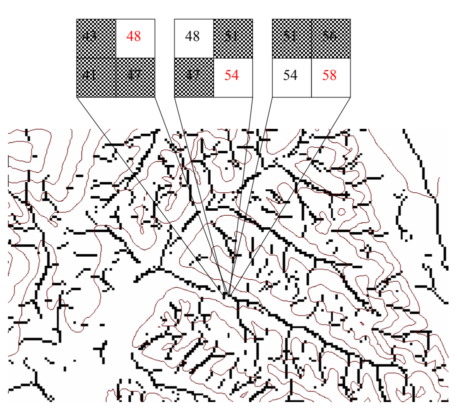


Channels mapped using $a\,S^2 > 200$ m. $a$ is specific catchment area and S is slope.

200 grid cell constant drainage area based stream delineation




**Accumulation of Local Curvature identified by Peuker and Douglas (1975, Comput. Graphics Image Proc. 4:375) algorithm used to account for spatially variable drainage density**




Curvature based stream delineation with threshold by constant drop analysis

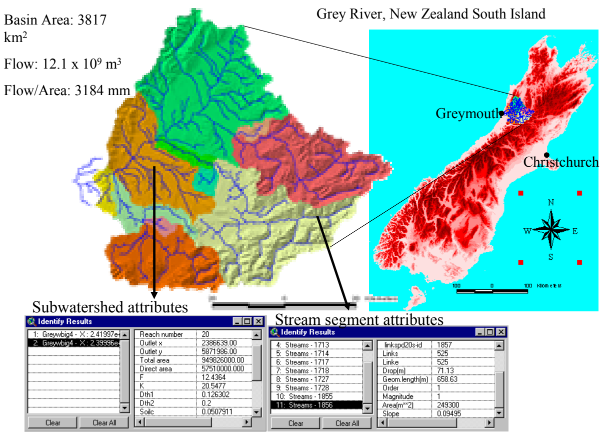
# New (and not so new) DEM Analysis Concepts and Uses

## Hydrologic Model Parameterization

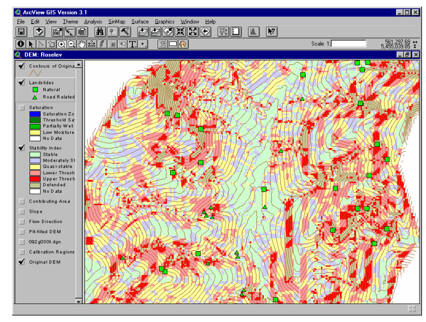
Basin Area: 3817 $km^2$

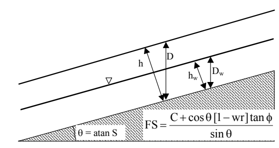
Flow: 12.1 x $10^9$ $m^3$

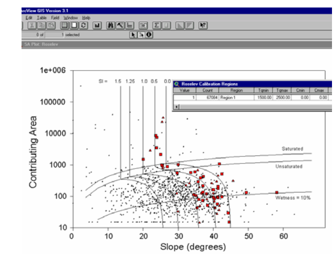
Flow/Area: 3184 mm




## Terrain Stability Mapping based on slope and specific catchment area.






SINMAP software available from http://www.engineering.usu.edu/dtarb

# Specialized Functions based on Generalization of D∞ Flow path analysis

### Notation and Methodology

Weighted contributing area accumulation

$$A[r(x)] = \int_{CA} r(x)dx$$

A[.] is a functional operator that takes as input a spatial field r(x), and the topographic flow direction field (not denoted) and produces a field A(x) representing the accumulation of r(x) up to each point x. Numerical evaluation

$$A[r(x)] = A(i,j) = r(i,j)\Delta^2 + \sum_{k \text{ contributing neighbors}} p_k A(i_k, j_k)$$

$p_k$ is the proportion of flow from neighbor k contributing to the grid cell (i,j). Δ is grid cell size.

$\sum p_k = 1$ is required to ensure 'conservation'.

Flow directions must not have loops.

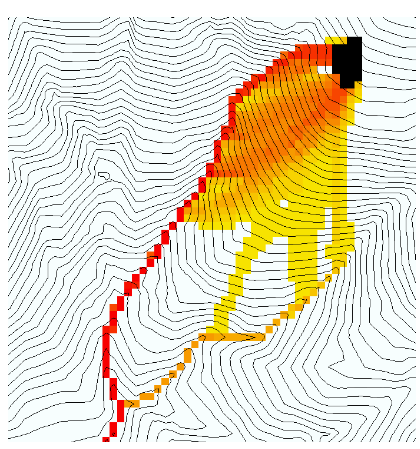
### Decayed Accumulation

A decayed accumulation operator DA[.] takes as input a mass loading field m(x) expressed at each grid location as m(i, j) that is assumed to move with the flow field but is subject to first order decay in moving from cell to cell. The output is the accumulated mass at each location DA(x). The accumulation of m at each grid cell can be numerically evaluated

$$DA[m(x)] = DA(i,j) = m(i,j)\Delta^2 + \sum_{k \text{ contributing neighbors}} p_k d(i_k, j_k) DA(i_k, j_k)$$

Here d(x) = d(i ,j) is a decay multiplier giving the fractional (first order) reduction in mass in moving from grid cell x to the next downslope cell. If travel (or residence) times t(x) associated with flow between cells are available d(x) may be evaluated as $\exp(-\lambda t(x))$ where λ is a first order decay parameter

Useful for a tracking contaminant or compound subject to decay or attenuation

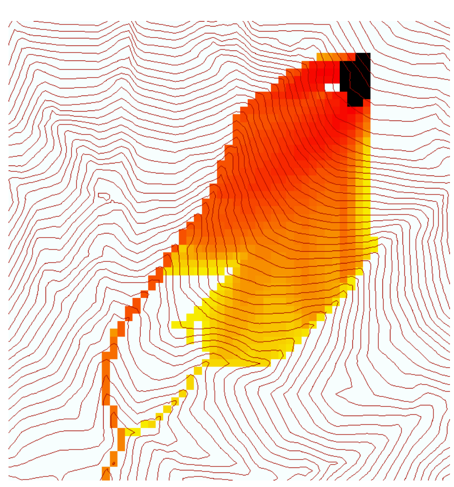


### Concentration Limited Accumulation

An unlimited supply of a substance that is loaded into flow at a concentration or solubility threshold $C_{sol}$. The set of points y, delineating the area of the substance supply are mapped using the (0,1) indicator field i(x;y)

1. **Flow** (weighted accumulation)
   Q(x)=A[w(x)]
2. **Supply area** concentration at threshold
   If i(x; y) = 1
   $C(x) = C_{sol}$
   $L(x) = C_{sol} Q(x)$
3. **Remaining locations** by load accumulation and dilution
   $L(x) = L(i,j) = \sum_{k \text{ contributing neighbors}} p_k L(i_k, j_k)$
   C(x) = L(x)/Q(x)

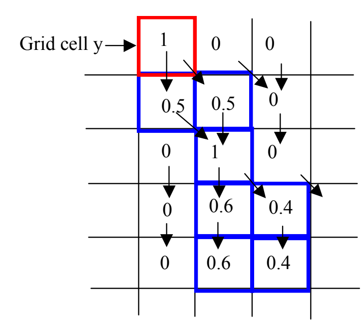
Useful for a tracking a contaminant released or partitioned to flow at a fixed threshold concentration



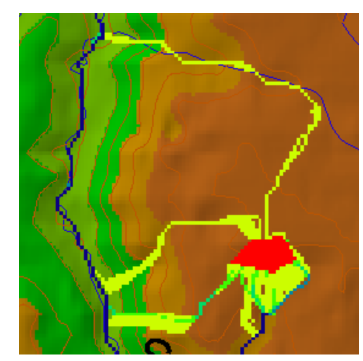
### Downslope Influence function (or influence zone) of y is

I(x;y) = A[i(x;y)]

I(x;y) says what the contribution from the set of points y is at each point x in the map. i(x;y) is an indicator (1,0) function on the set y and I is evaluated using the weighted contributing area function only on points in the set y.



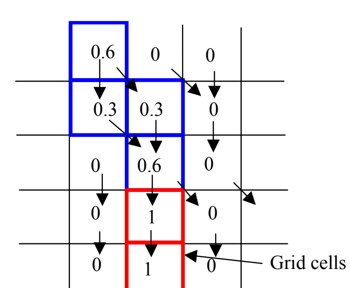

Influence function of grid cell y



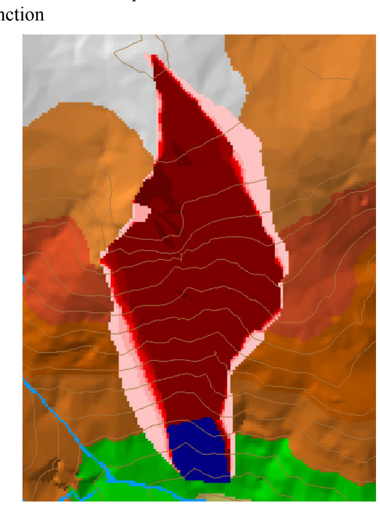
**Useful for example to track where sediment or contaminant moves**

### Upslope Dependence function. Quantifies the amount a point x contributes to the point or zone y. The inverse of the influence function

D(x;y) = I(y;x)

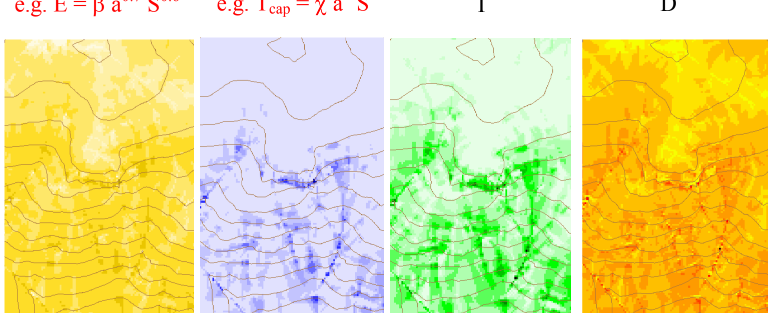



Dependence function of grid cells y



**Useful for example to track where a contaminant may come from**

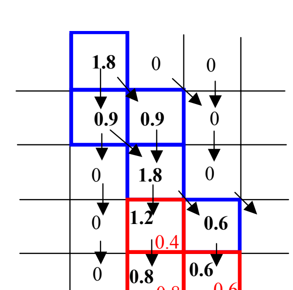
### Transport limited accumulation




$$T_{out} = \min(E + \sum T_{in}, T_{cap}) \qquad D = E + \sum T_{in} - T_{out}$$

**Useful for modeling erosion and sediment delivery, the spatial dependence of sediment delivery ratio and contaminant that adheres to sediment**

### Reverse Accumulation




Reverse accumulation of field weights indicated in red

Useful for destabilization sensitivity in landslide hazard assessment

TauDEM software available from http://www.engineering.usu.edu/dtarb