Reflections on Geomorphometry and Hydrology

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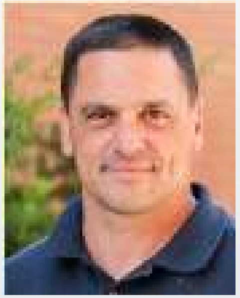
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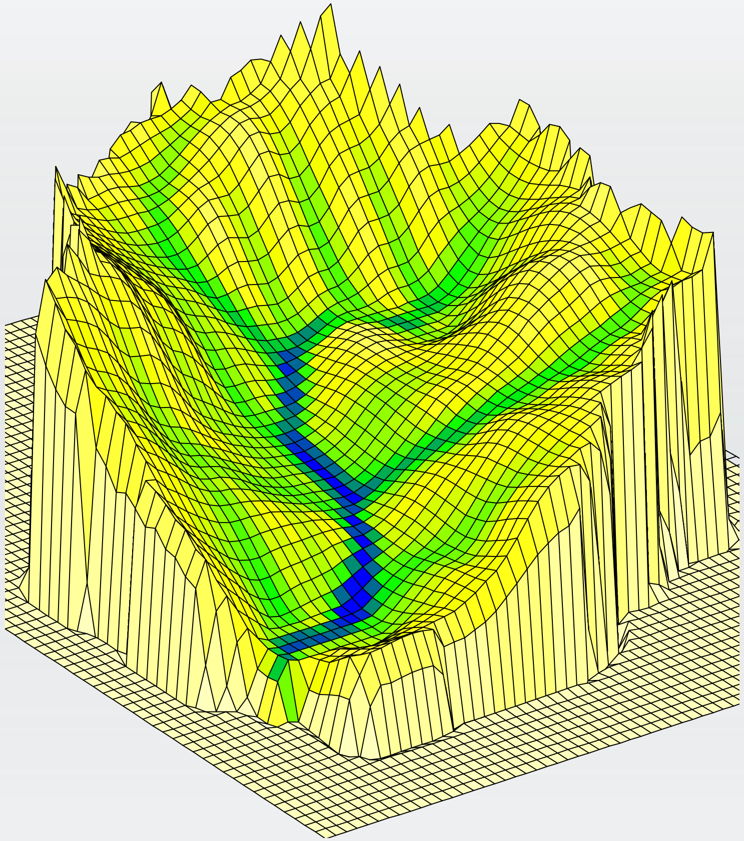
Outline

- Watershed and channel network delineation and objective channelization threshold determination
- D-infinity and multiple flow directions
- Generalized terrain-based flow analysis (flow algebra)
- Height above nearest drainage (HAND) and flood inundation mapping
- TauDEM software and parallel programming (speeding it up)



Topography and Hydrology

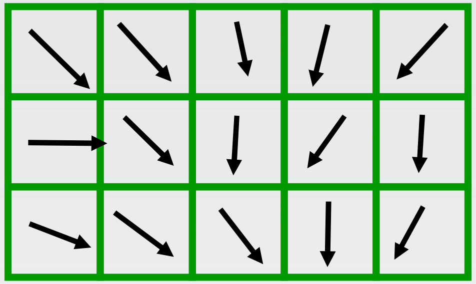
- Watersheds are fundamentally the most basic hydrologic landscape elements
- Topography dictates the flow of water across the landscape
- Flowing water sculpts the landscape
- This synergy is at the heart of much hydrologic modeling relating to questions of runoff generation important for flooding and water resources
- Representing hydrologic processes at high resolution is important to help solve these problems

General Terrain Flow Model

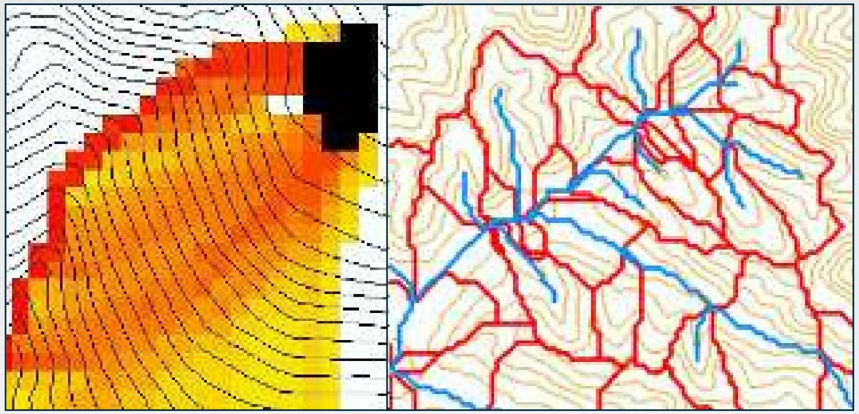
Input Digital Elevation Model

Hydrologic Conditioning (Often Filling)

Flow Field



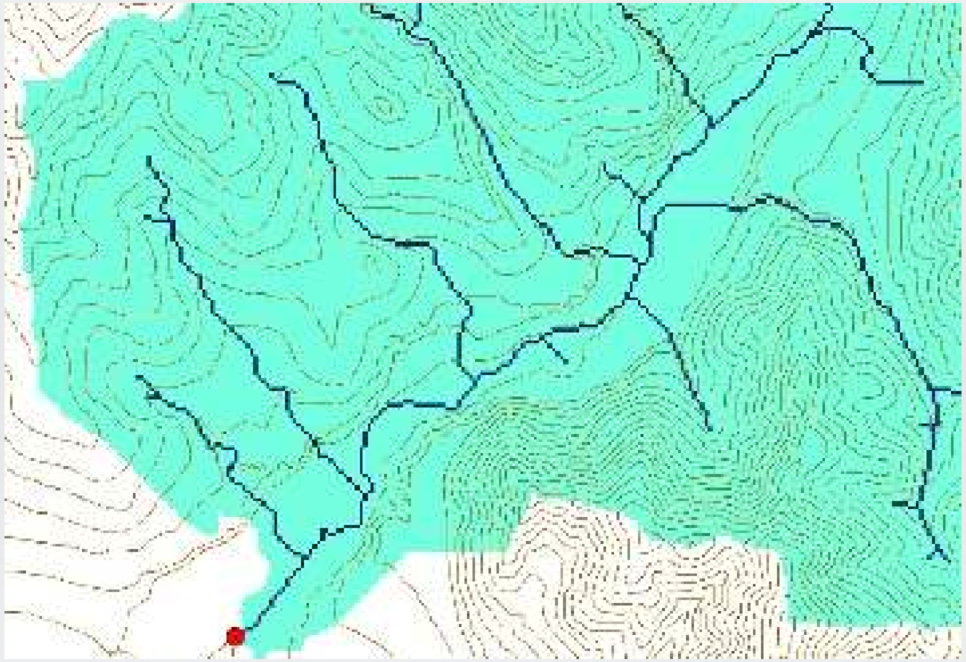
Flow Related Terrain Information



“In the most simple terms, geomorphometry is everything you can extract from DEMs”
www.geomorphometry.org

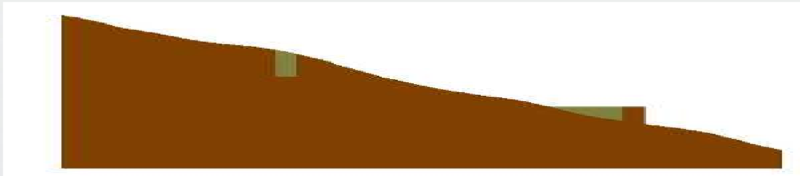
Basic Watershed and Channel Network Delineation

- Pit Removal (Filling)
- Flow direction calculation (D8)
- Flow accumulation (may be weighted)
- Channel (Stream) definition using a threshold
- Channels and watersheds (catchments/basins)



Conditioning the DEM - Pit Filling

Increase elevation until the pit drains to a neighbor and ultimately out of the domain



Original DEM

7	7	6	7	7	7	7	5	7	7
9	9	8	9	9	9	9	7	9	9
11	11	10	11	11	11	11	9	11	11
12	12	8	12	12	12	12	10	12	12
13	12	7	12	13	13	13	11	13	13
14	7	6	11	14	14	14	12	14	14
15	7	7	8	9	15	15	13	15	15
15	8	8	8	7	16	16	14	16	16
15	11	11	11	11	17	17	6	17	17
15	15	15	15	15	18	18	15	18	18

Pits Filled

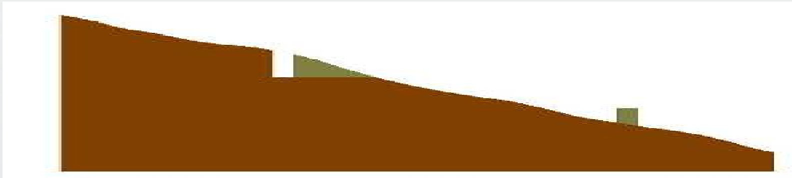
7	7	6	7	7	7	7	5	7	7
9	9	8	9	9	9	9	7	9	9
11	11	10	11	11	11	11	9	11	11
12	12	10	12	12	12	12	10	12	12
13	12	10	12	13	13	13	11	13	13
14	10	10	11	14	14	14	12	14	14
15	10	10	10	10	15	15	13	15	15
15	10	10	10	10	16	16	14	16	16
15	11	11	11	11	17	17	14	17	17
15	15	15	15	15	18	18	15	18	18

Pits

Grid cells or zones completely surrounded by higher terrain

Conditioning the DEM - Carving

Lower elevation of neighbor along a predefined drainage path until the pit drains to the outlet point



Original DEM

7	7	6	7	7	7	7	5	7	7
9	9	8	9	9	9	9	7	9	9
11	11	10	11	11	11	11	9	11	11
12	12	8	12	12	12	12	10	12	12
13	12	7	12	13	13	13	11	13	13
14	7	6	11	14	14	14	12	14	14
15	7	7	8	9	15	15	13	15	15
15	8	8	8	7	16	16	14	16	16
15	11	11	11	11	17	17	6	17	17
15	15	15	15	15	18	18	15	18	18

Pits

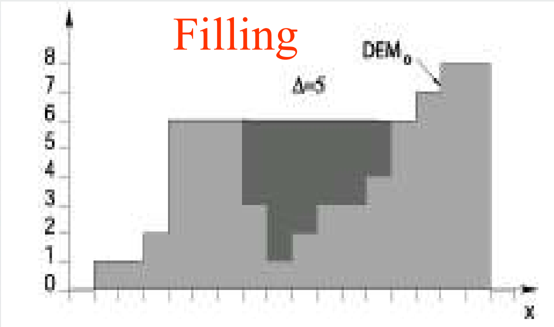
Carved DEM

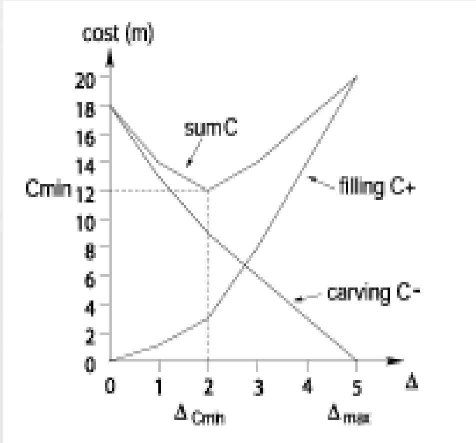
7	7	6	7	7	7	7	5	7	7
9	9	6	9	9	9	9	6	9	9
11	11	6	11	11	11	11	6	11	11
12	12	6	12	12	12	12	6	12	12
13	12	6	12	13	13	13	6	13	13
14	7	6	11	14	14	14	6	14	14
15	7	7	7	9	15	15	6	15	15
15	8	8	8	7	16	16	6	16	16
15	11	11	11	11	17	17	6	17	17
15	15	15	15	15	18	18	15	18	18

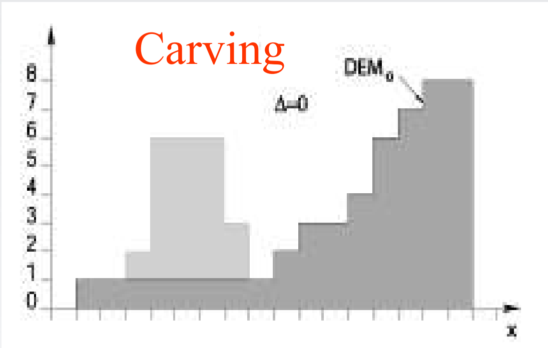
Carve outlets

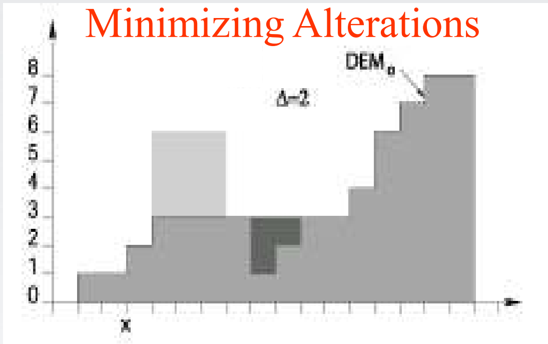
Optimal removal of spurious pits in grid digital elevation models

Pierre Soille, WRR 2004, http://doi.org/10.1029/2004WR003060









Conditioning the DEM – Optimally adjusted

Original DEM

7	7	6	7	7	7	7	5	7	7
9	9	8	9	9	9	9	7	9	9
11	11	10	11	11	11	11	9	11	11
12	12	8	12	12	12	12	10	12	12
13	12	7	12	13	13	13	11	13	13
14	7	6	11	14	14	14	12	14	14
15	7	7	8	9	15	15	13	15	15
15	8	8	8	7	16	16	14	16	16
15	11	11	11	11	17	17	6	17	17
15	15	15	15	15	18	18	15	18	18

Pits

Optimally adjusted

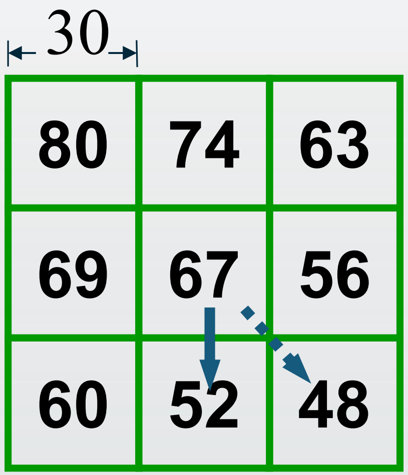
Carved

7	7	6	7	7	7	7	5	7	7
9	9	7	9	9	9	9	7	9	9
11	11	7	11	11	11	11	9	11	11
12	12	7	12	12	12	12	10	12	12
13	12	7	12	13	13	13	11	13	13
14	7	7	11	14	14	14	12	14	14
15	7	7	7	9	15	15	13	15	15
15	8	8	8	7	16	16	14	16	16
15	11	11	11	11	17	17	14	17	17
15	15	15	15	15	18	18	15	18	18

Filled

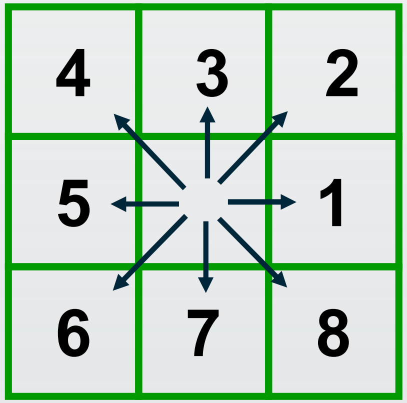
D8 Flow Direction Model

Direction of steepest descent



$$\frac{67-52}{30} = 0.50$$

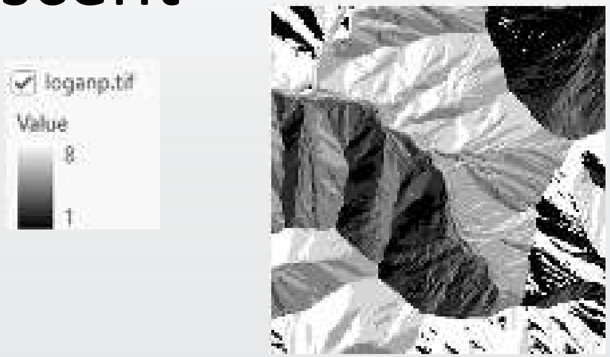
$$\frac{67-48}{30\sqrt{2}} = 0.45$$



Slope = Drop/Distance

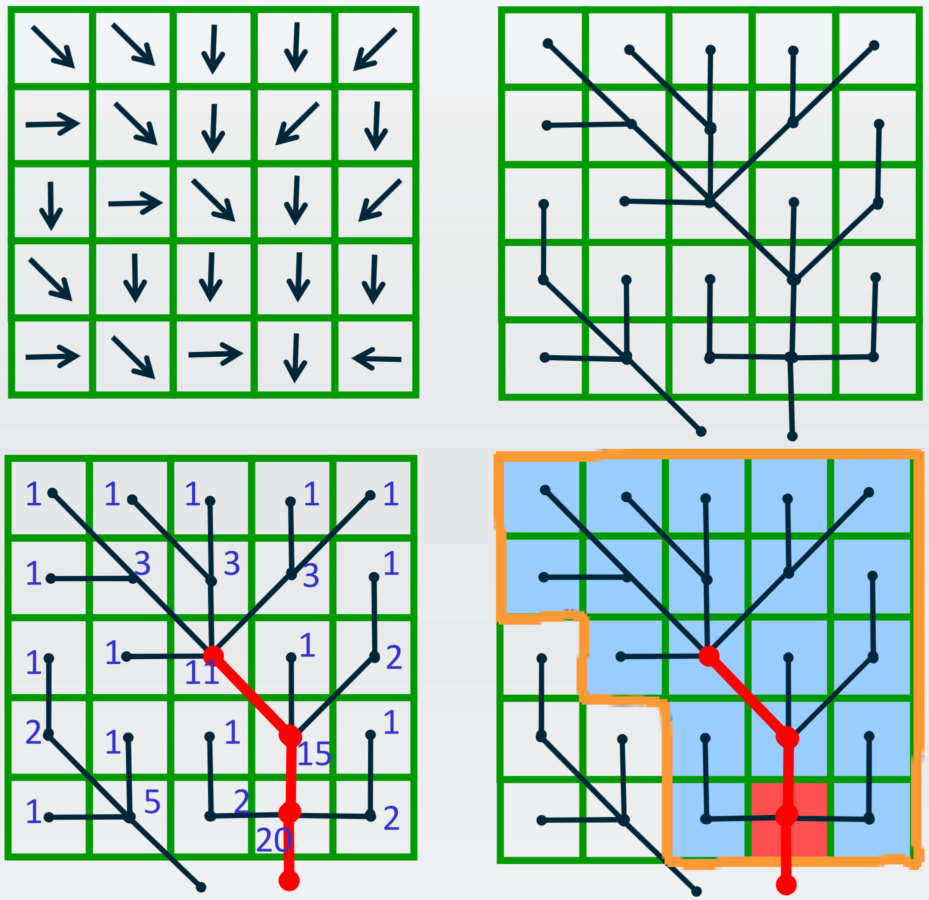
Steepest down slope direction

Note that this is different from the 3x3 or 5x5 slope that Peter Guth discussed Monday. It only looks down to where water may flow.

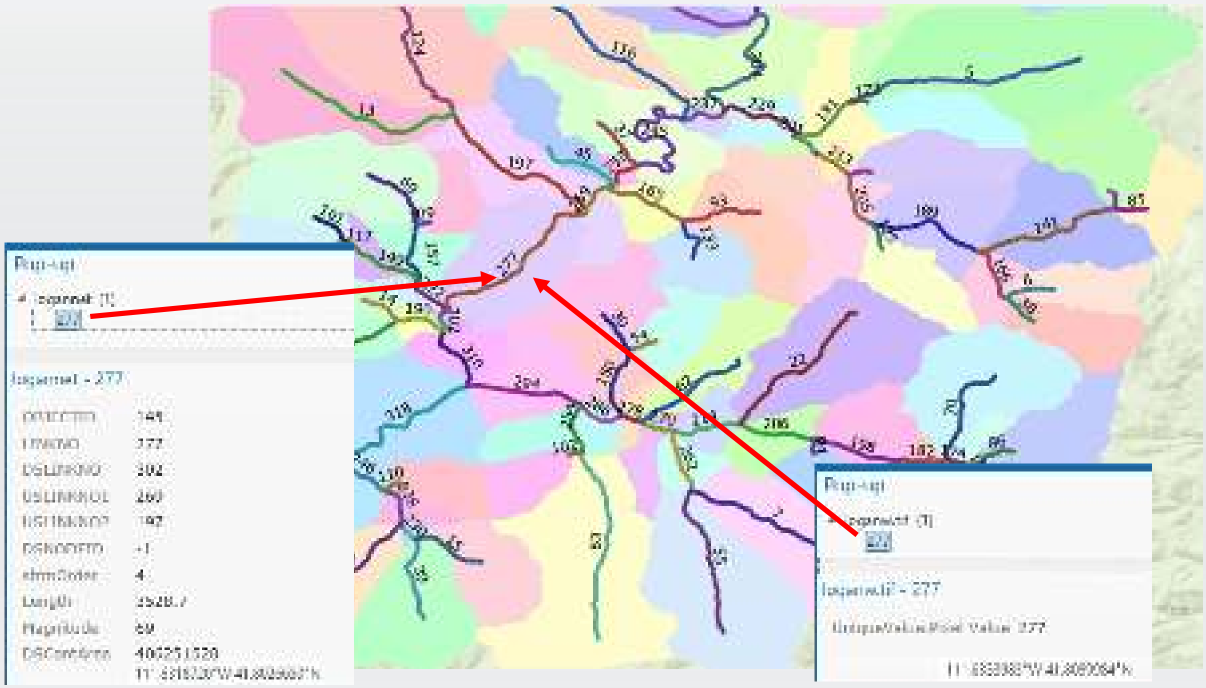


O'Callaghan, J. F. and D. M. Mark, (1984), https://doi.org/10.1016/S0734-189X(84)80011-0.

Grid Network, Flow Accumulation, Streams and Watersheds

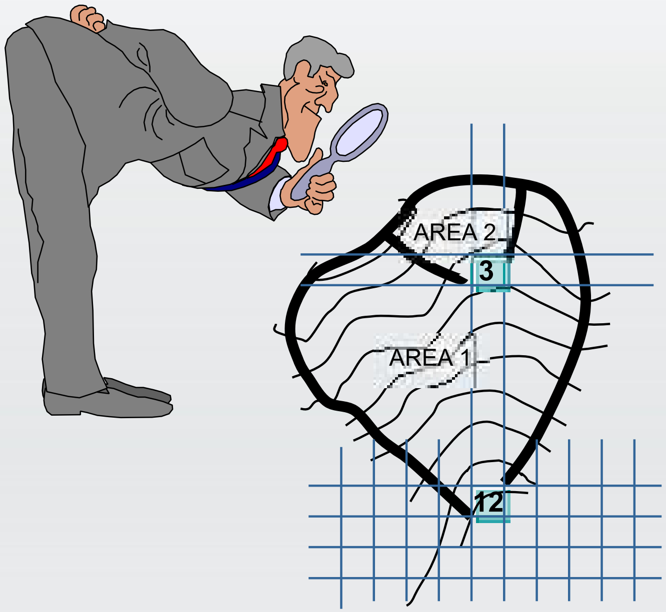


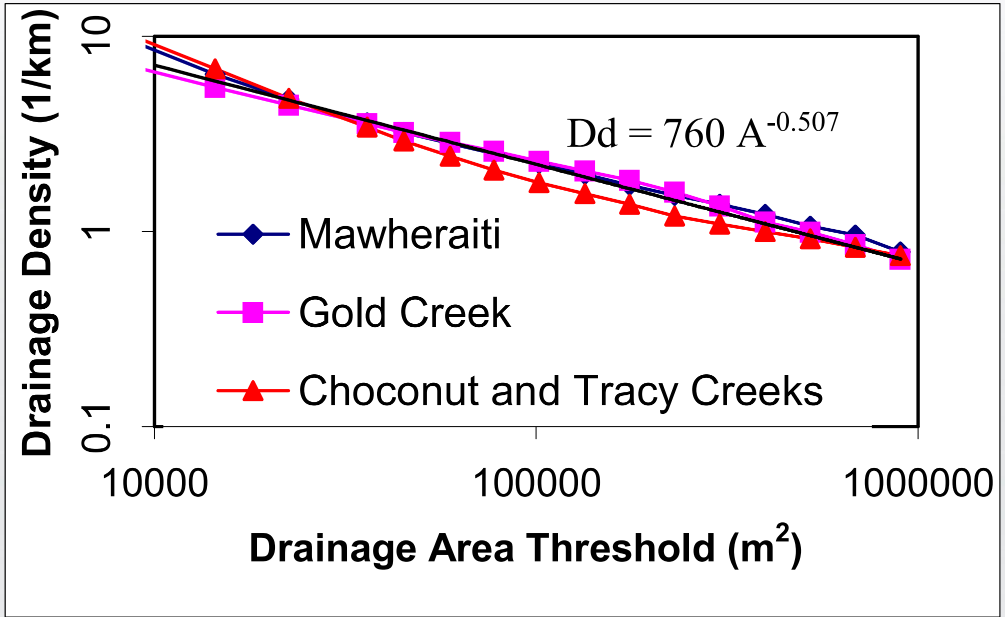
Streams linked to associated catchments



The starting point for catchment based distributed hydrologic modeling

Where do Channels Begin?

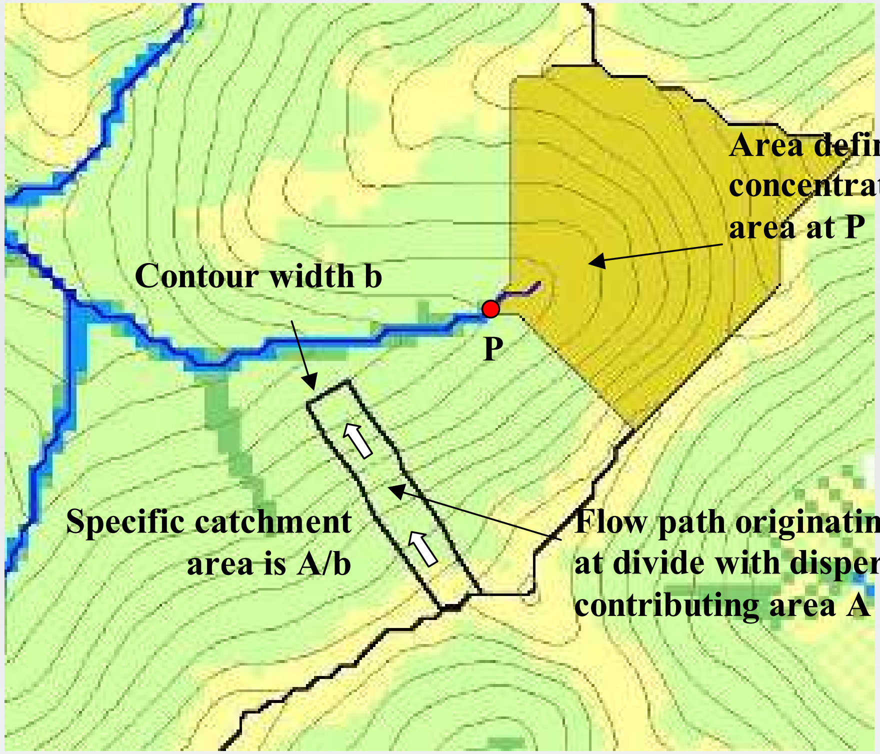




Drainage density (total channel length divided by drainage area) as a function of drainage area support threshold used to define channels for the three study watersheds.

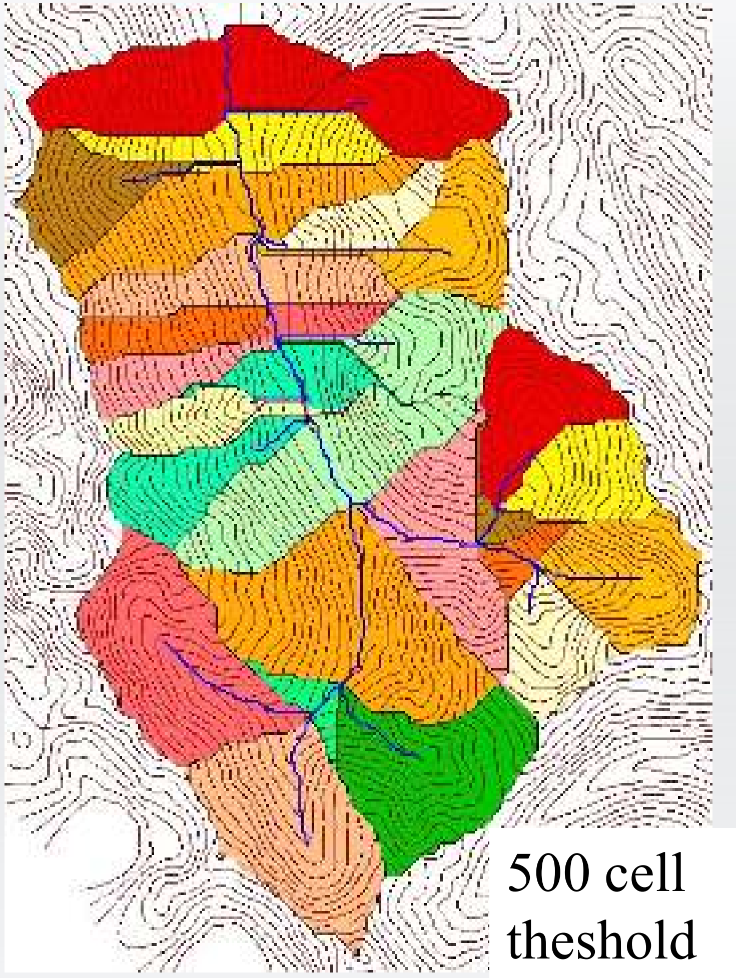
How to decide on stream delineation threshold ?
Why is this important ?

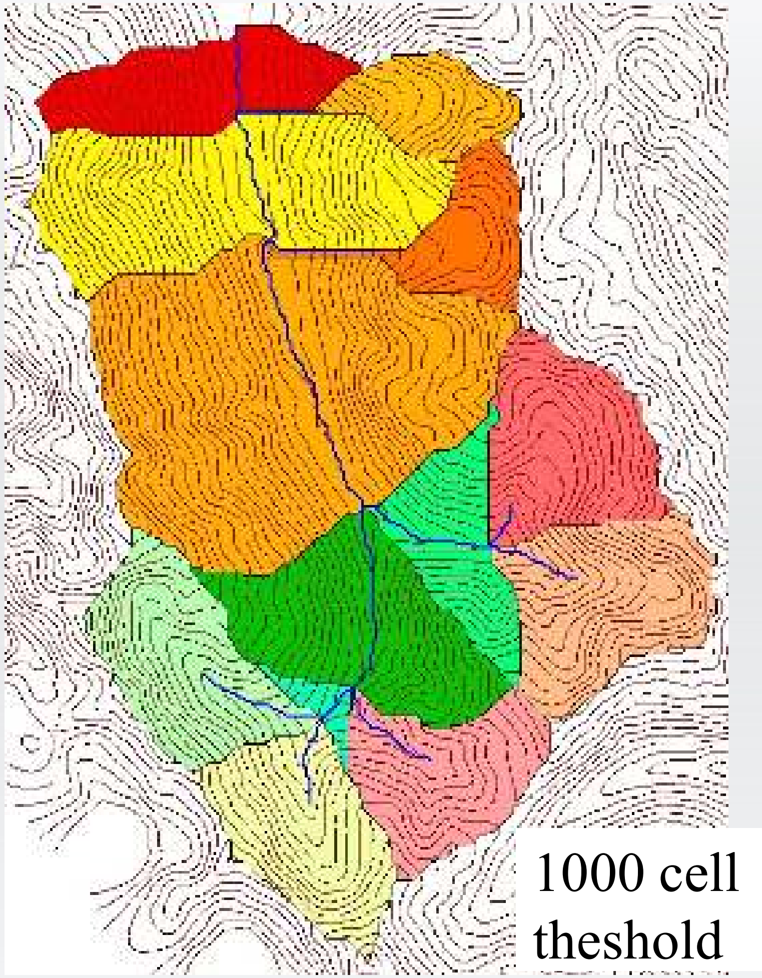
Hydrologic processes are different on hillslopes and in channels. It is important to recognize this and account for this in the delineation of streams.



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

The scale of catchment model elements is sensitive to channelization support area threshold





Alternative views

Although the river and hill-side waste do not resemble each other at first sight, they are only the extreme members of a continuous series, and when this generalization is appreciated, one may fairly extend the "river" all over its basin and up to its very divides. Ordinarily treated, the river is like the veins of a leaf; broadly viewed it is like the entire leaf.

Davis, W. M., (1899), "The geographical cycle," Geogr. J., 14: 481-504 (reproduced in Geographical Essays, edited by W. M. Davis, Ginn, Boston, 1909).

landscape dissection into distinct valleys is limited by a threshold of channelization that sets a finite scale to the landscape.

Montgomery, D. R. and W. E. Dietrich, (1992), "Channel Initiation and the Problem of Landscape Scale," Science, 255: 826-830.

Examples of differently textured topography

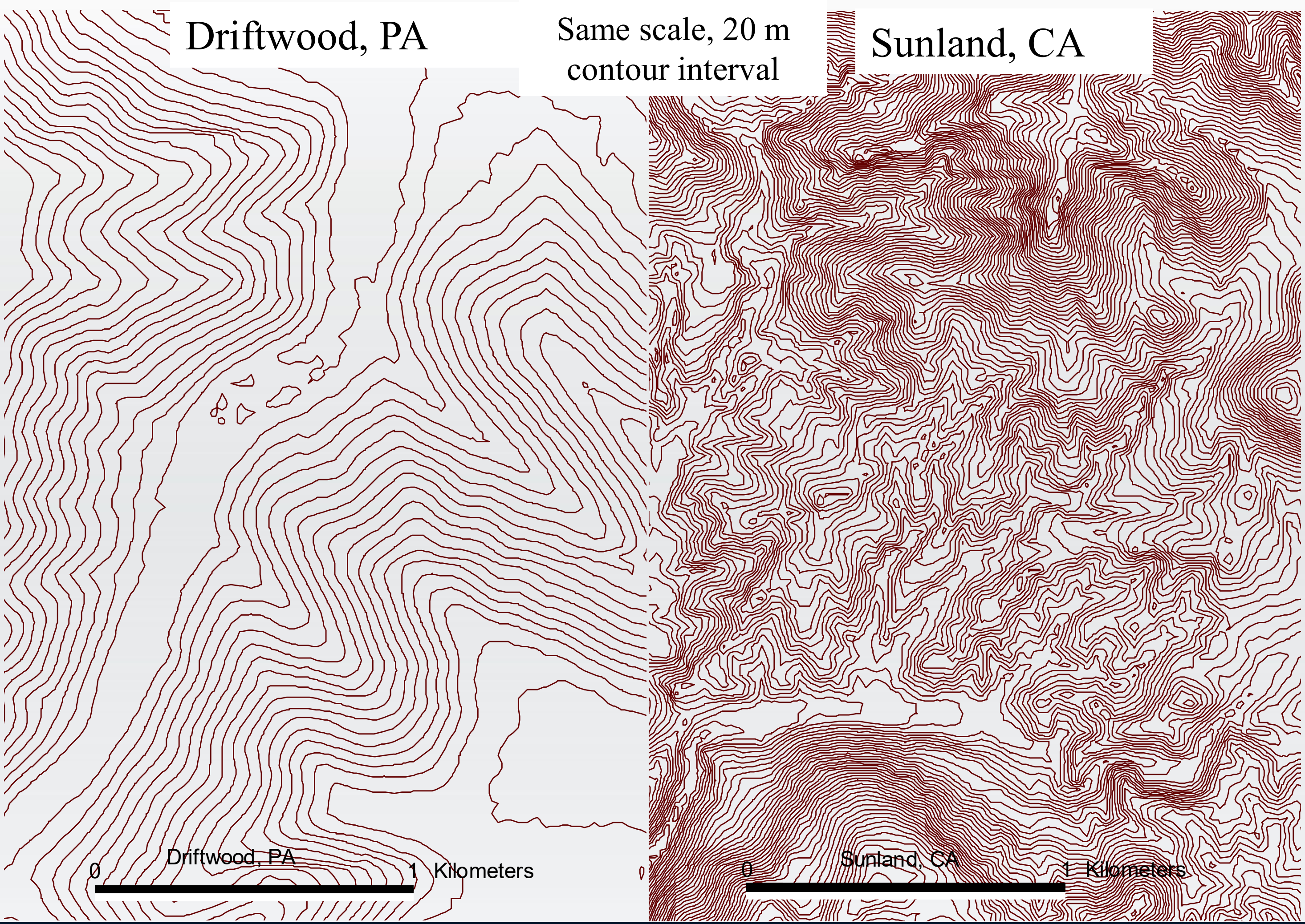
Badlands in Death Valley.
from Easterbrook, 1993, p 140.

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

Gently Sloping Convex Landscape

From W. E. Dietrich

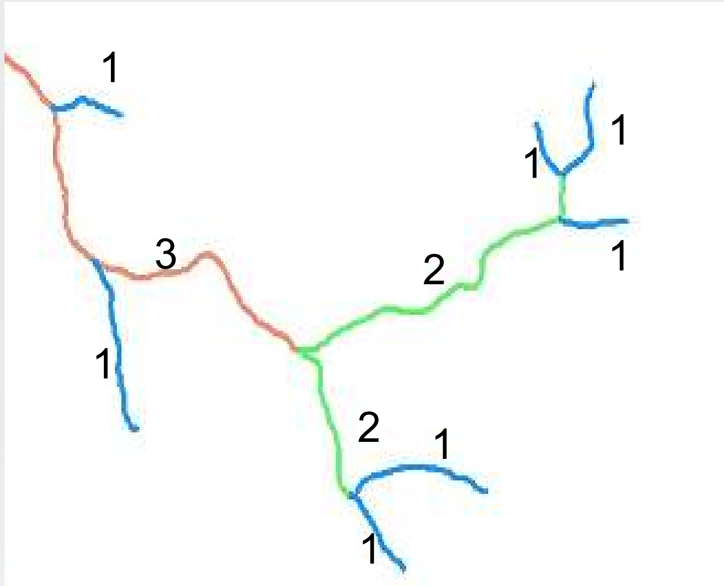
Contours indicate topographic texture



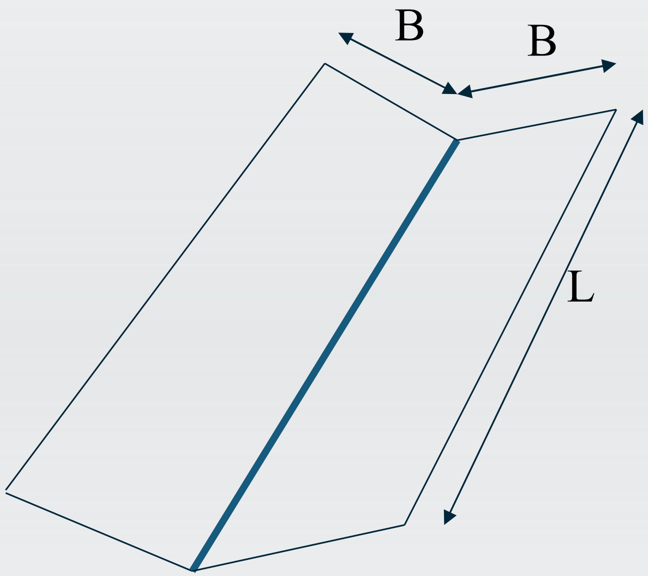
Topographic texture, drainage density and "laws" of geomorphology

Horton/Strahler stream ordering

Stream networks obey (approximately) the empirically established Hortons "laws"



Drainage density "measures" the scale of topographic texture



$D_d = L/A$

Hillslope length = B

A = 2B L

$D_d = L/A = 1/(2B)$

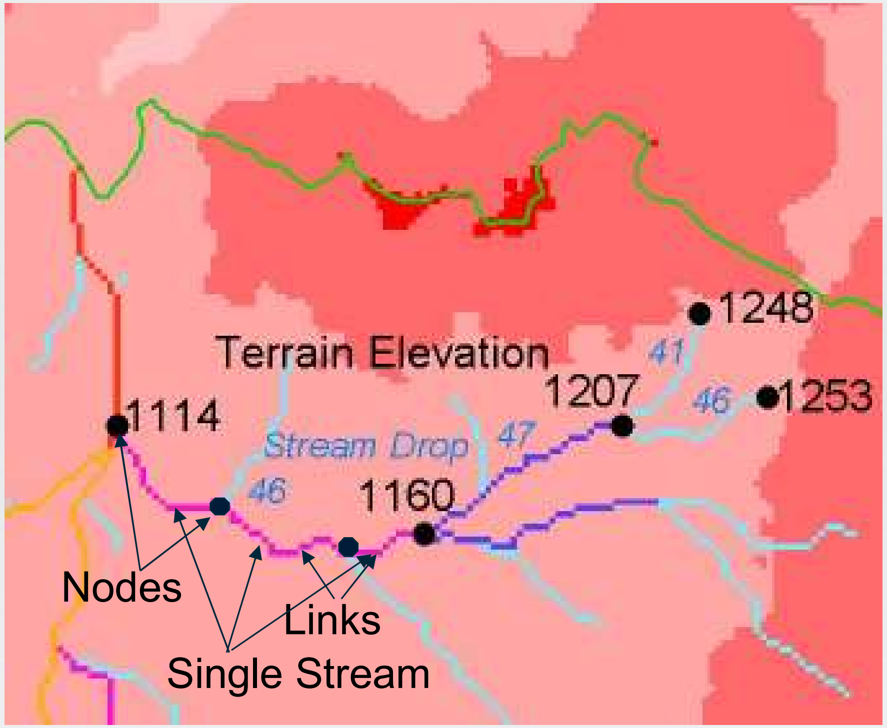
$\therefore$ $B = 1/(2D_d)$

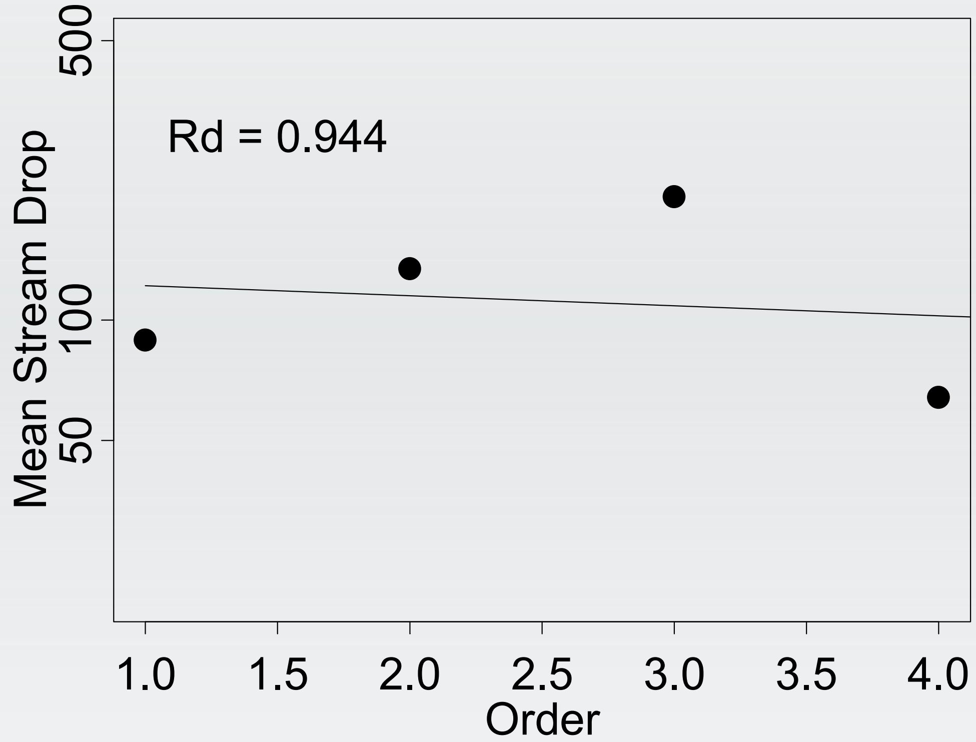
Hillslope length $\approx 1/(2D_d)$

Related concepts: Topographic grain, contour crenulations, ruggedness, topographic roughness

Constant Stream Drops Law

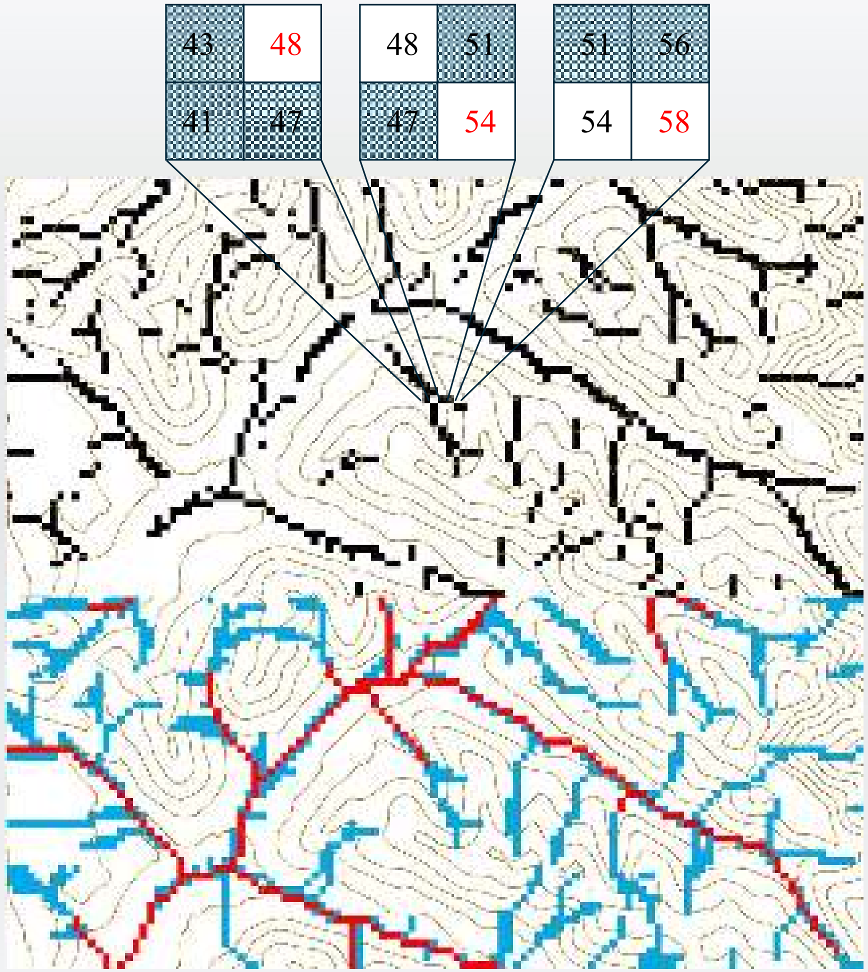
Broscoe, A. J., (1959), "Quantitative analysis of longitudinal stream profiles of small watersheds," Office of Naval Research, Project NR 389-042, Technical Report No. 18, Department of Geology, Columbia University, New York.





Approaching the objective mapping of channel networks

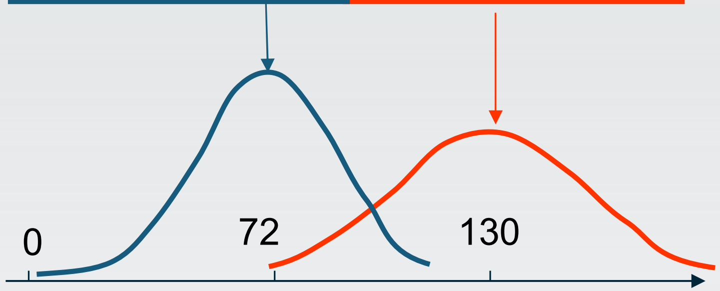
- Adjust for spatially variable drainage density
- Local valley grid cells (Peuker and Douglas, 1975, Comput. Graphics Image Proc. 4:375)
- Connect by taking valley grid cells as weights for flow accumulation
- Threshold the weighted flow accumulation grid



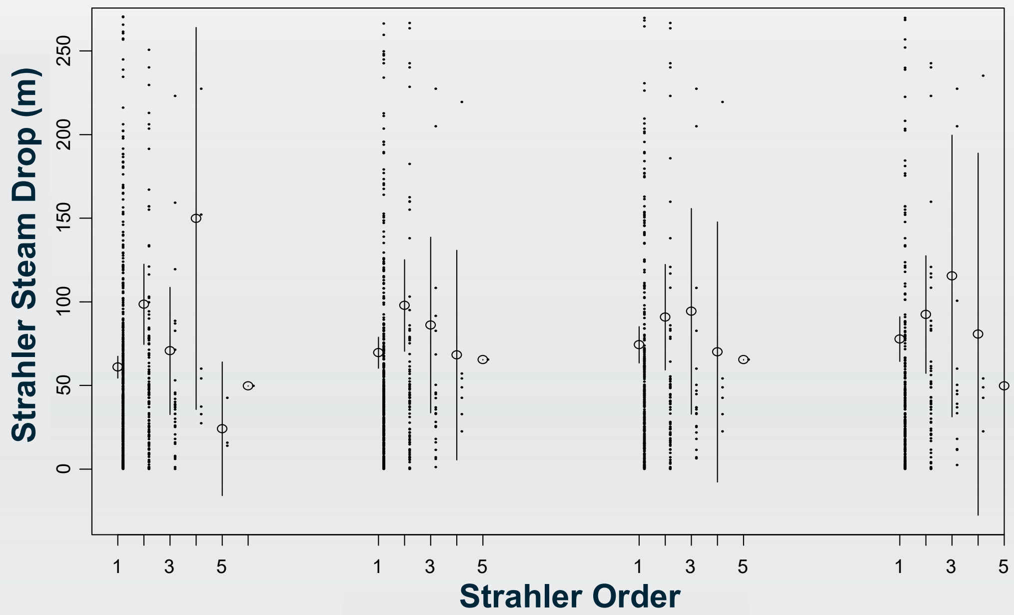
Select threshold to map channel networks at the finest resolution consistent with empirical constant drop “law”

t-test for difference in mean between first and higher order stream drops

	Order 1		Order 2-4
Mean X	72.2	Mean Y	130.3
Std X	68.8	Std Y	120.8
Var X	4740.0	Var Y	14594.5
Nx	268	Ny	81



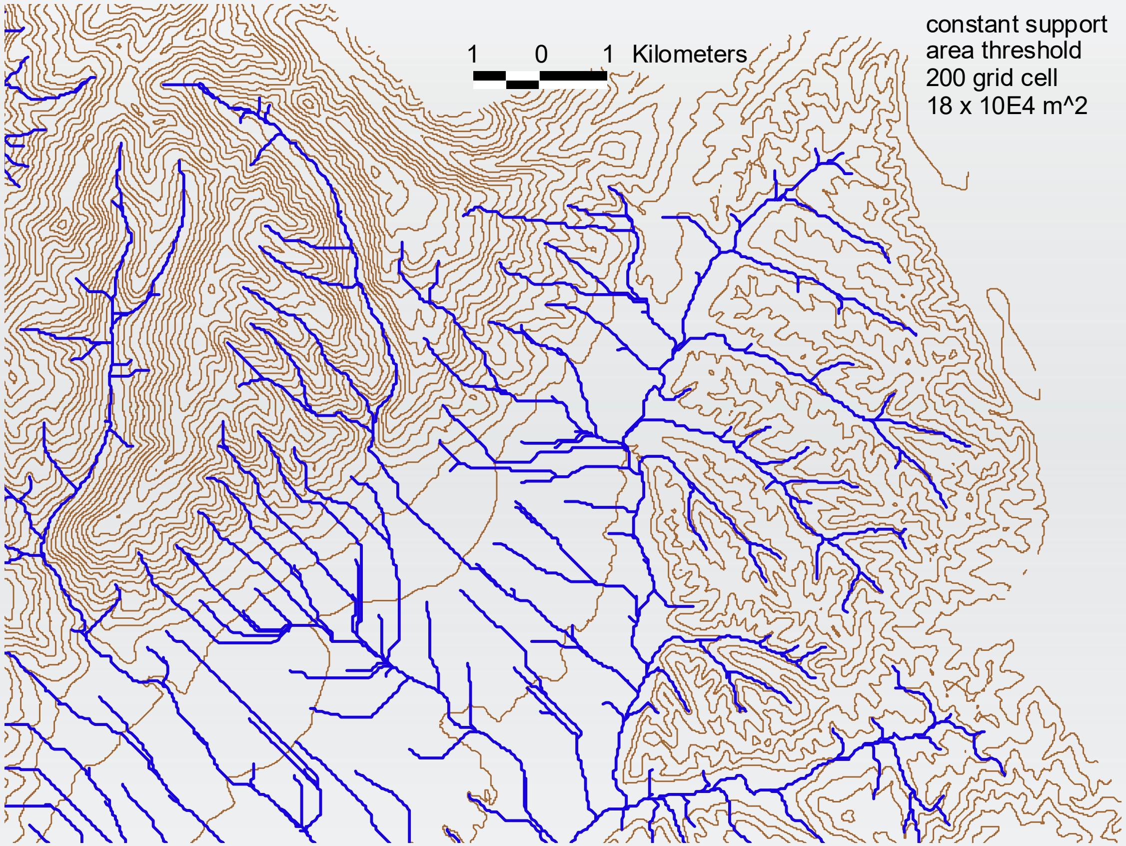
Use smallest threshold for which |t| < 2 (p=0.05) to map channels

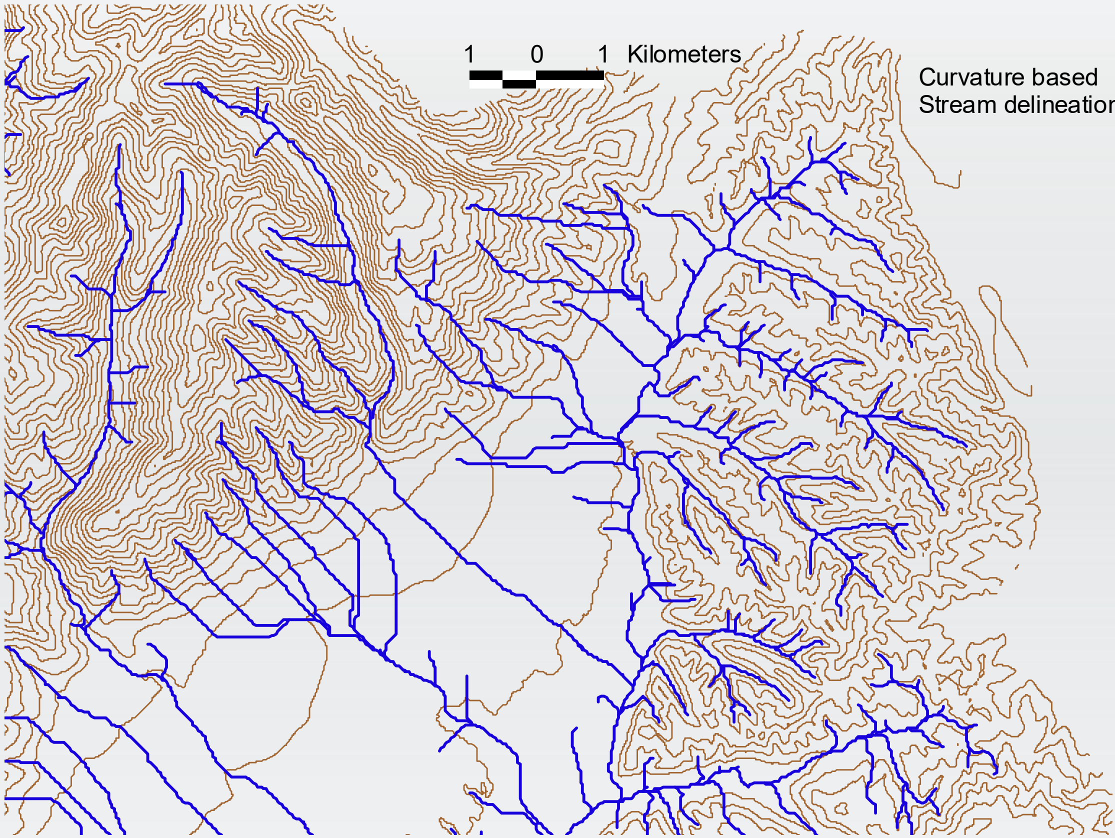


Weighted valley grid cell threshold	10	15	20	30
Drainage Density (km^{-1})	2.2	1.8	1.6	1.4
T for diff of first and higher order drop means	-4.1	-2.2	-1.3	-1.2

Channels mapped using contributing area and optimal threshold

Channels mapped using valley grid cells as weight and optimal threshold





Summary so far

- A simple grid DEM is the starting point for watershed delineation that produces structured information on watersheds and connected stream networks useful for hydrologic modeling
- Knowledge from geomorphology offers an approach towards objective selection of channel network delineation threshold
- Curvature and valley cell identification adapt for spatially variable drainage density and topographic texture
- Watershed delineation based on D8

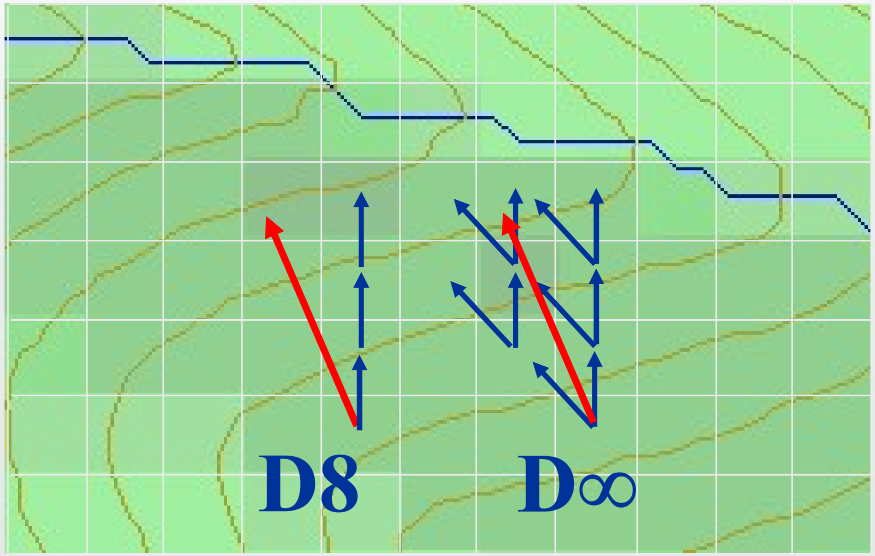
- Results are limited by being scale dependent and objective approach to finding a channelization threshold does not always work well
- Opportunities to extend using other valley classification approaches (some seen at this conference)

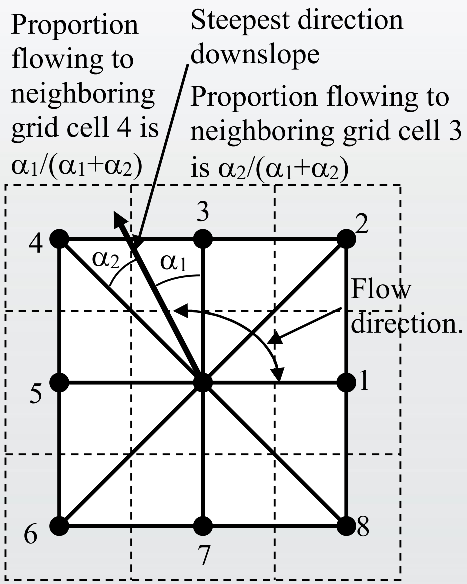
Representation of Flow Field

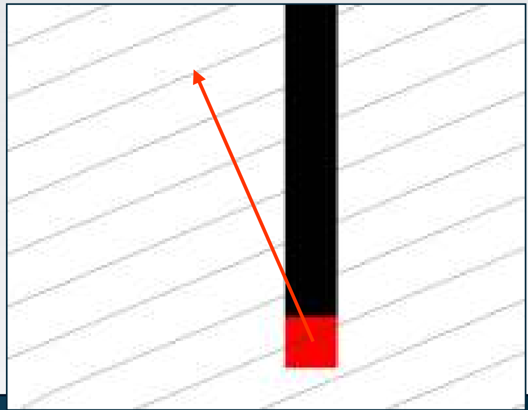
Steepest single direction

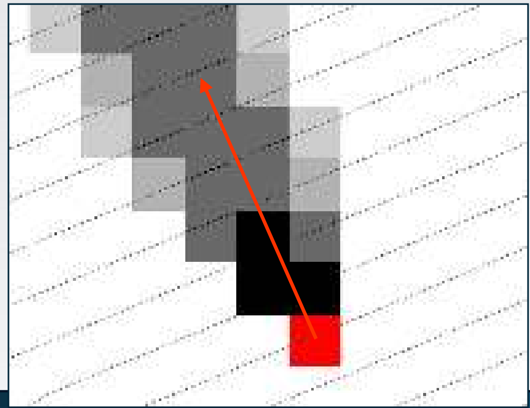
48	52
56	67

$$\frac{67-52}{30}=0.50$$









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, http://doi.org/10.1029/96WR03137.

Contributing Area

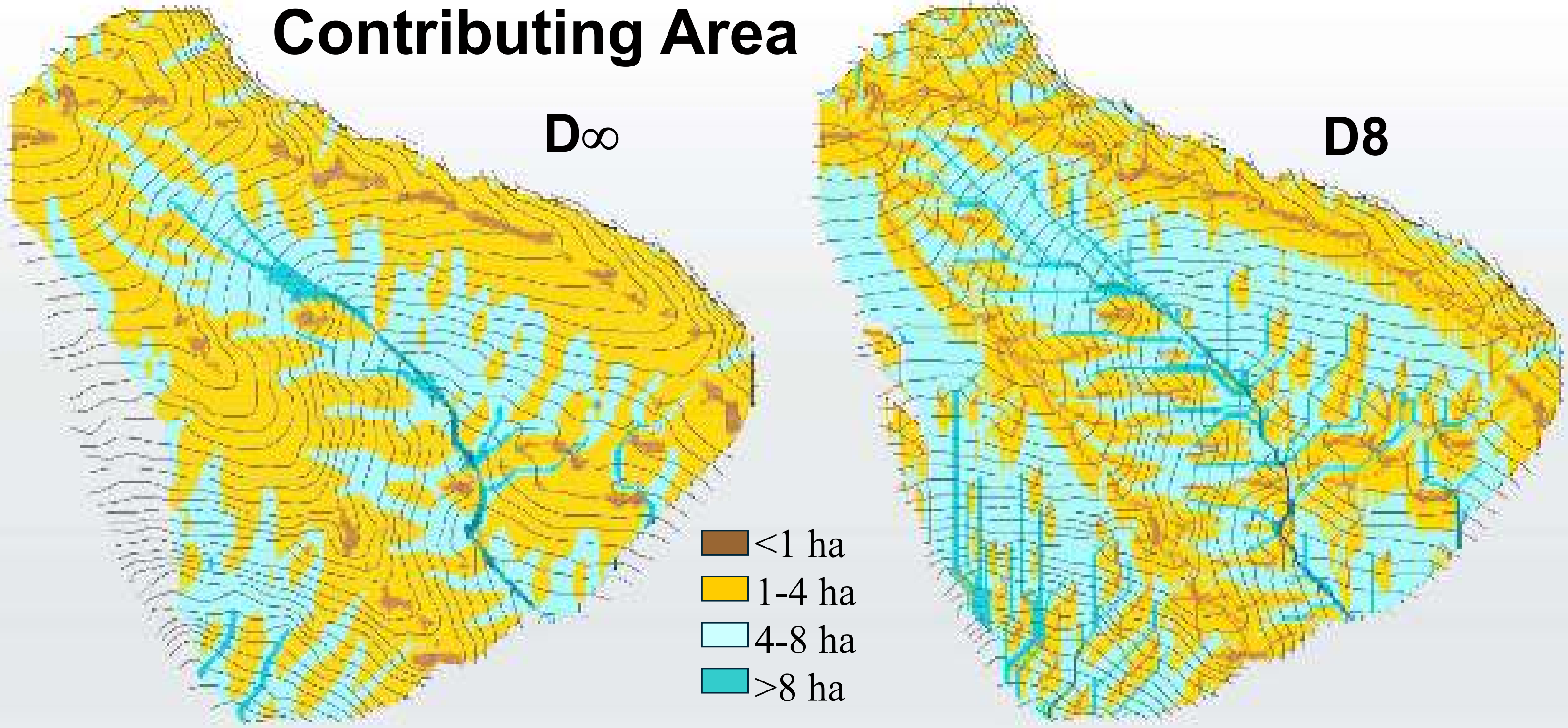
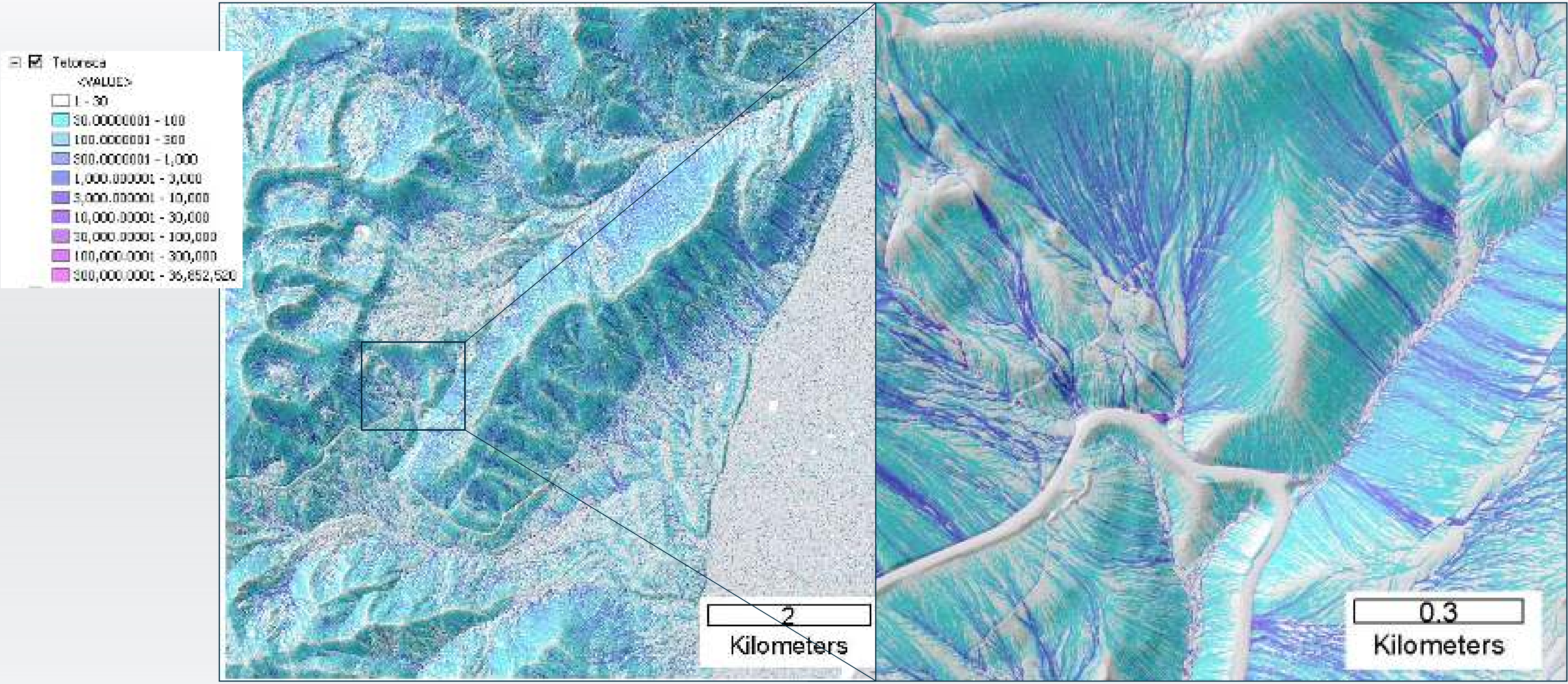


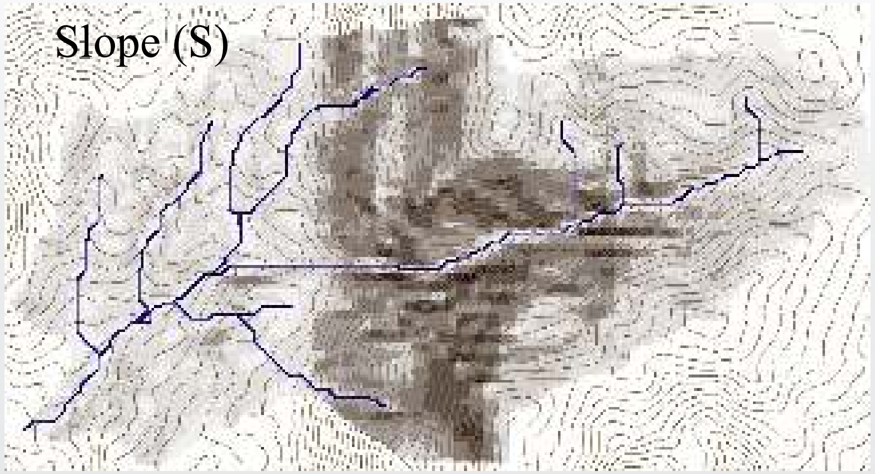
Table 2. Differences Between Theoretical and DEM-Computed Upslope Area for Test Examples Expressed in Terms of the Mean Error and Mean Square Error

	Outward Cone		Inward Cone		Plane	
	Bias Mean $(A - \hat{A})$	MSE Mean $((A - \hat{A})^2)$	Bias Mean $(A - \hat{A})$	MSE Mean $((A - \hat{A})^2)$	Bias Mean $(A - \hat{A})$	MSE Mean $((A - \hat{A})^2)$
D8	−0.13	2.13	1.76	118.88	−0.17	0.065
MS	−0.81	0.69	−1.07	5.70	−1.37	2.065
Lea's [1992] method	−1.29	2.41	−4.05	44.00	−2.57	7.912
DEMON	−0.37	0.17	−0.37	19.23	−0.40	0.161
D∞	−0.13	0.20	1.87	30.58	−0.17	0.065

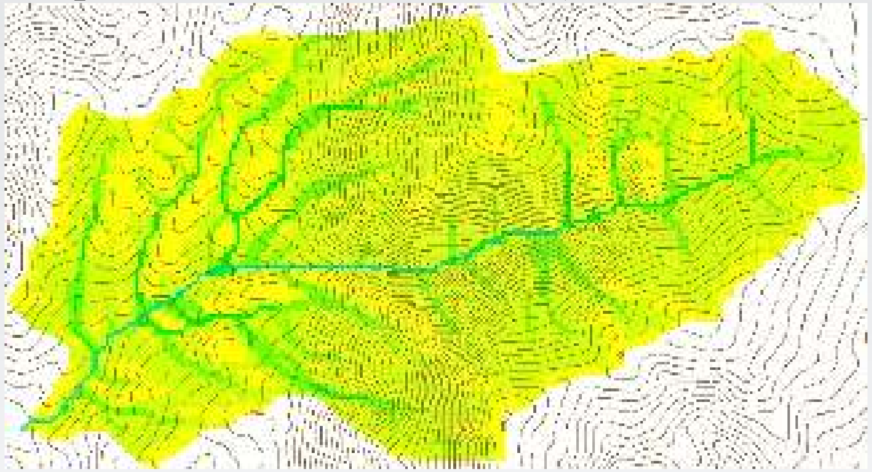
Contributing area from D-Infinity



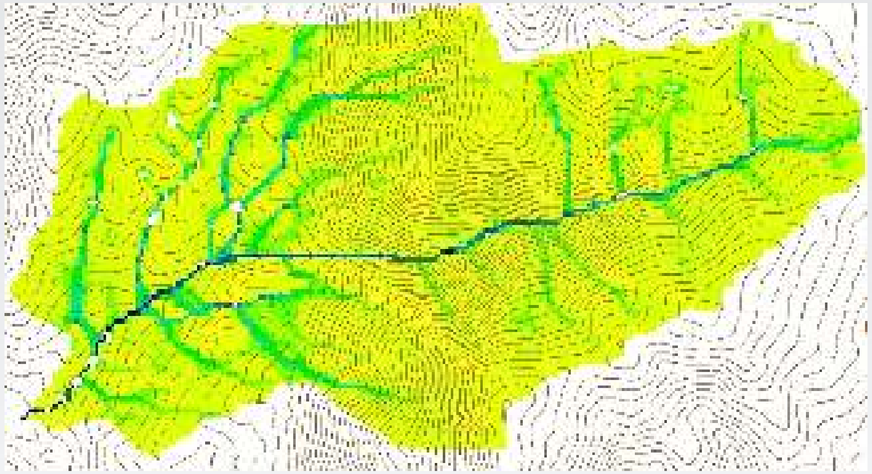
Wetness Index


Slope (S)

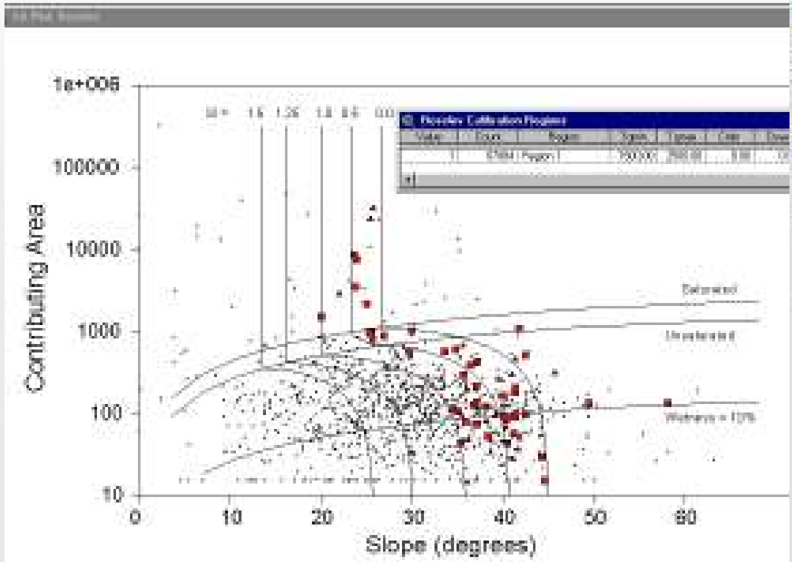
Specific Catchment Area (a)

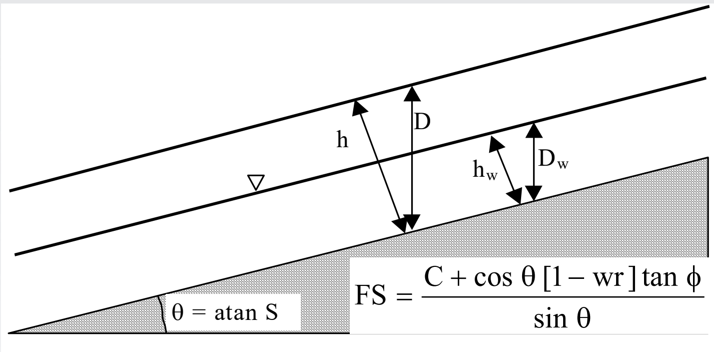


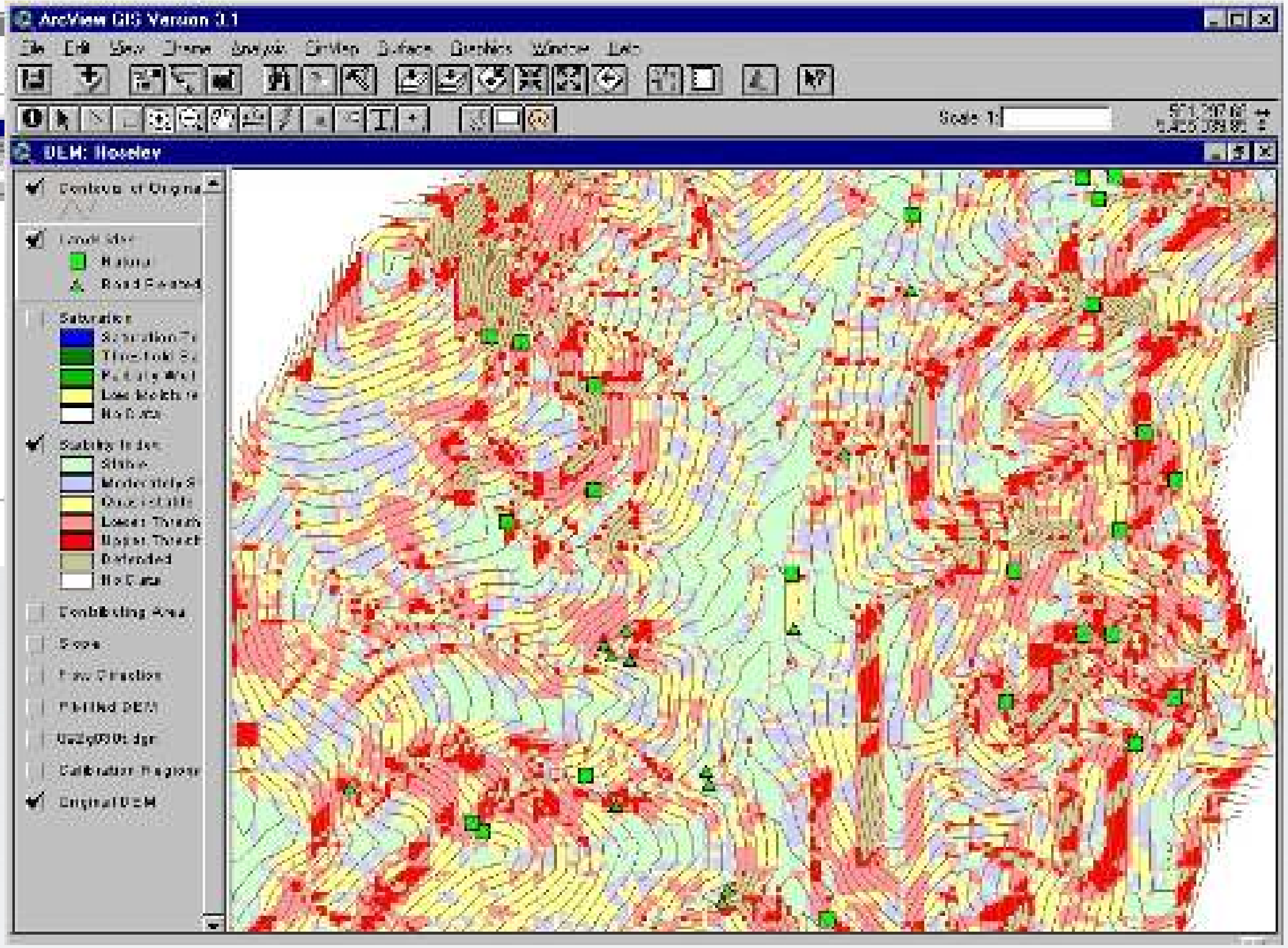
Wetness Index ln(a/S)



Terrain Stability Mapping

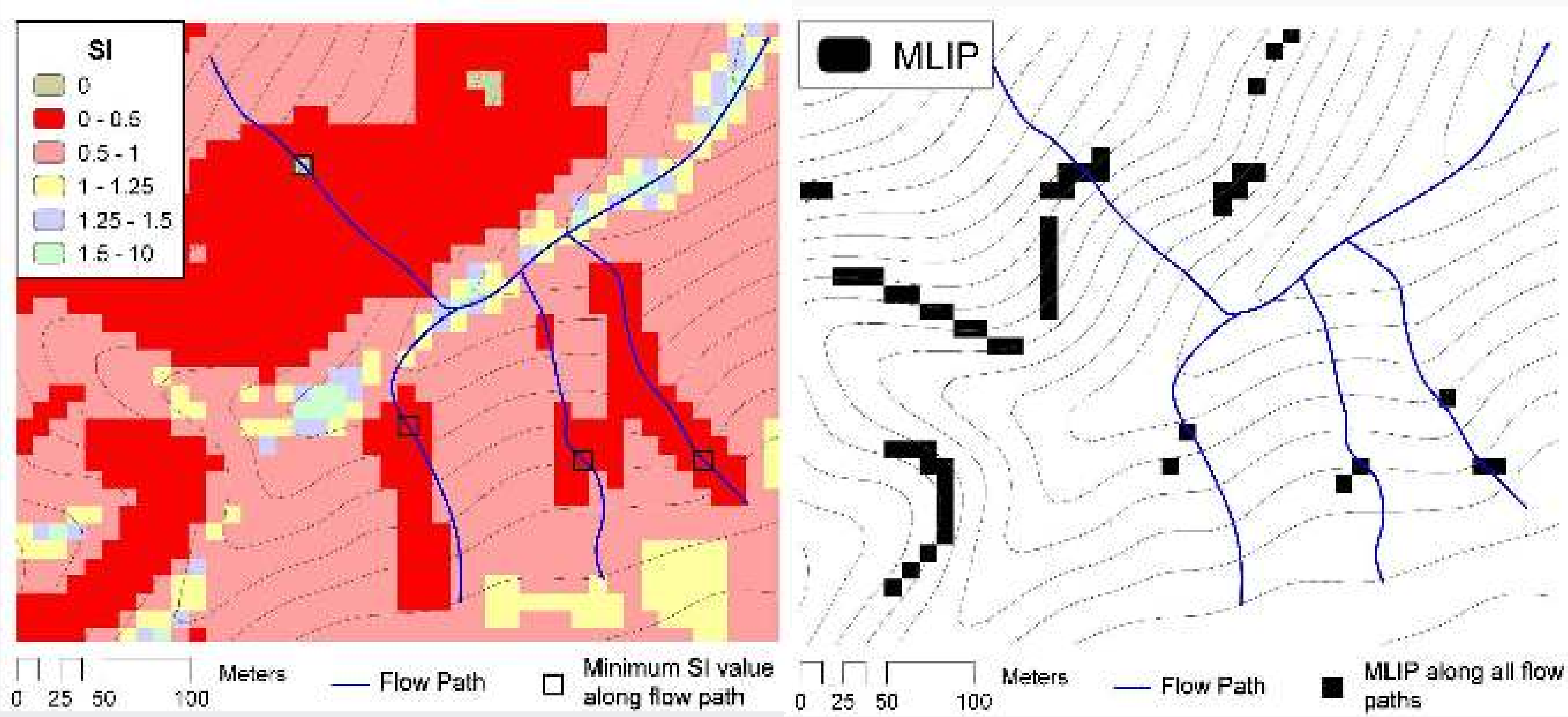






SINMAP: https://hydrology.usu.edu/sinmap2/

Most Likely Landslide Initiation Points



The location of the lowest SI value along a flow path

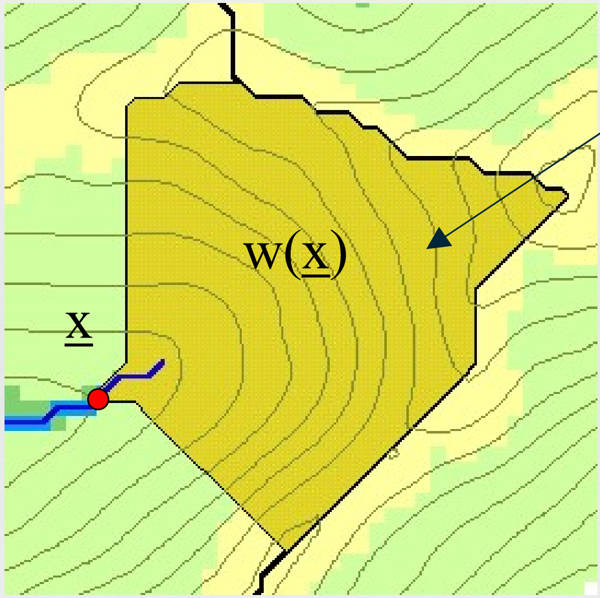
Tarolli, P. and D. G. Tarboton, (2006), HESS https://doi.org/10.5194/hess-10-663-2006

Other contributions, considerations and outstanding questions

- Seibert and McGlynn, 2007, MD∞, http://dx.doi.org/10.1029/2006WR005128
- Gallant and Hutchinson, 2011, differential equation approach, http://doi.org/10.1029/2009wr008540
- Gruber, S. and S. Peckham, 2009, https://doi.org/10.1016/S0166-2481(08)00007-X (Mass flux method)
- Lindsay (this conference) Minimal Dispersion Flow Algorithm
- Quinn et al., 1991; Fairfield and Leymarie, 1991

- Reduce angle/direction dispersion dependency
- Flow width. What cell dimension to use for specific catchment area calculation?
- Test cases beyond specific catchment area are needed

Flow accumulation calculation can be generalized to compute a broad class of terrain flow related quantities



$$A(\underline{x}) = \int_{CA} w(\underline{x})\, d\underline{x}$$

The flow accumulation function takes as input a spatial field w(x), and the topographic flow direction field and produces a field A(x) representing the accumulation of w(x) up to each point x.

Numerical evaluation

$$A(i,j) = w(i,j)\Delta + \sum_{k \text{ contributing neighbors}} p_k A(i_k, j_k)$$

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

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

Flow directions must not have loops.

Generalization to Flow Algebra

Replace

$$A_i = w_i \Delta + \sum_{contributing\ k} P_{ki} A_k$$

by general function

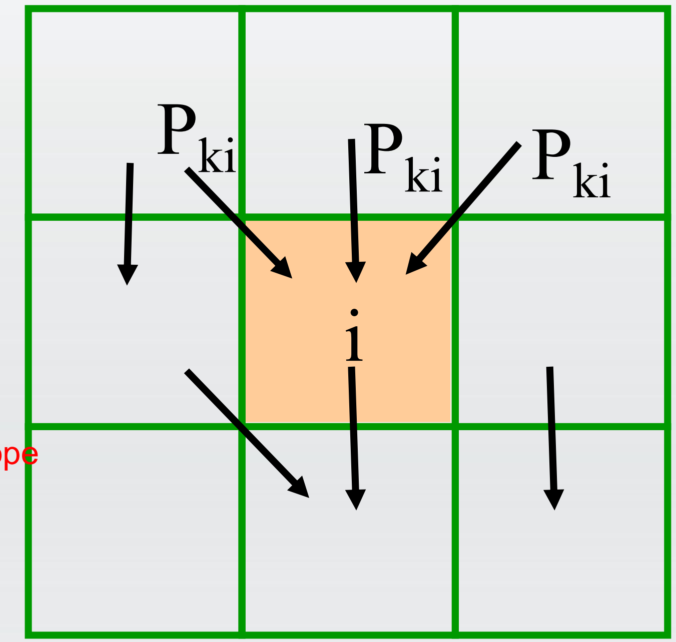
Flow direction proportions

Input Results from upslope

$$\theta_i = F(\gamma_i, P_{ki}, \theta_k, \gamma_k)$$

Output Result,
Quantity being calculated

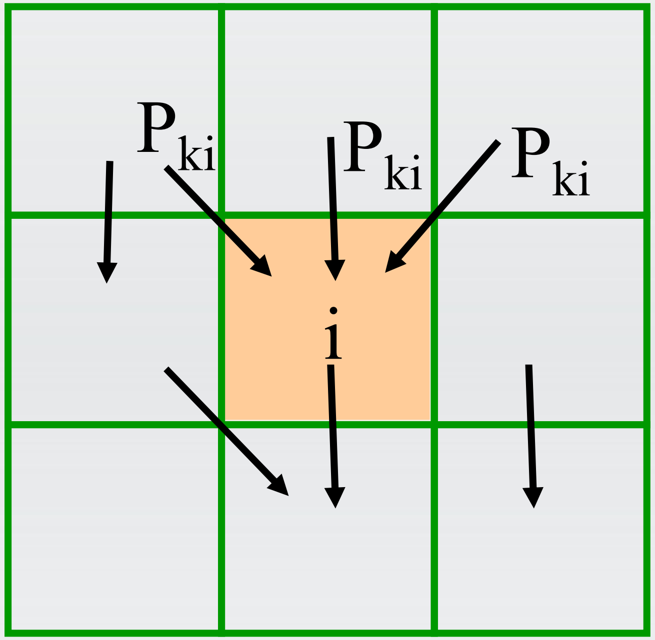
Other inputs at cell and upslope



Tarboton, D. G. and M. E. Baker, (2008), "Towards an Algebra for Terrain-Based Flow Analysis," in Representing, Modeling and Visualizing the Natural Environment: Innovations in GIS 12, Edited by N. J. Mount, G. L. Harvey, P. Aplin and G. Priestnall, CRC Press, Florida, p.496, http://dx.doi.org/10.1201/9781420055504.ch12.

General Pseudocode Upstream Flow Algebra Evaluation

Global $\underline{P}, \underline{\gamma}, \underline{\theta}$
FlowAlgebra(i)
for all k neighbors of i
  if $P_{ki}>0$
    FlowAlgebra(k)
next k
$\underline{\theta}_i = FA(\underline{\gamma}_i, \underline{P}_{ki}, \underline{\theta}_k, \underline{\gamma}_k)$
return

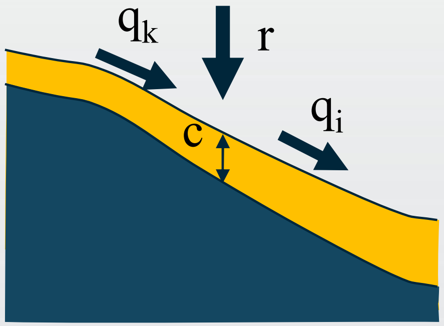


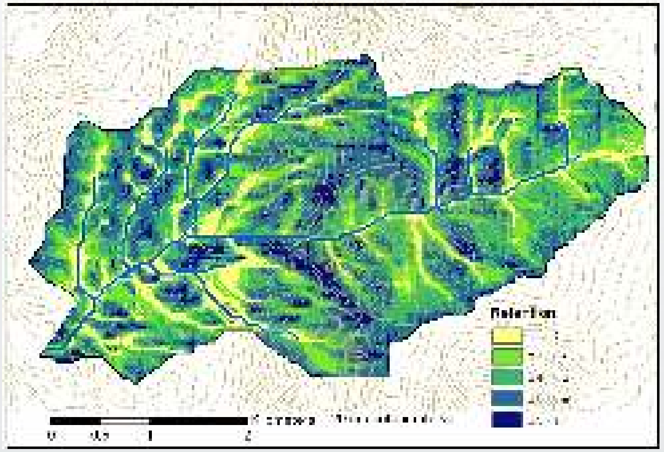
Example: Retention limited runoff generation with run-on

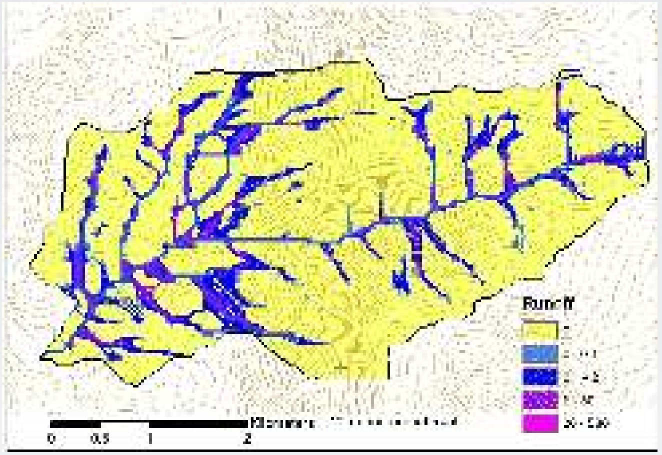
Global $\underline{P}$, ($\underline{r}$,$\underline{c}$), $\underline{q}$
FlowAlgebra(i)
for all k neighbors of i
    if P_{ki}>0
        FlowAlgebra(k)
next k

$$q_i = \max\left(\sum_{\{k:P_{ki}>0\}} P_{ki} q_k + r_i - c_i, 0\right)$$

return





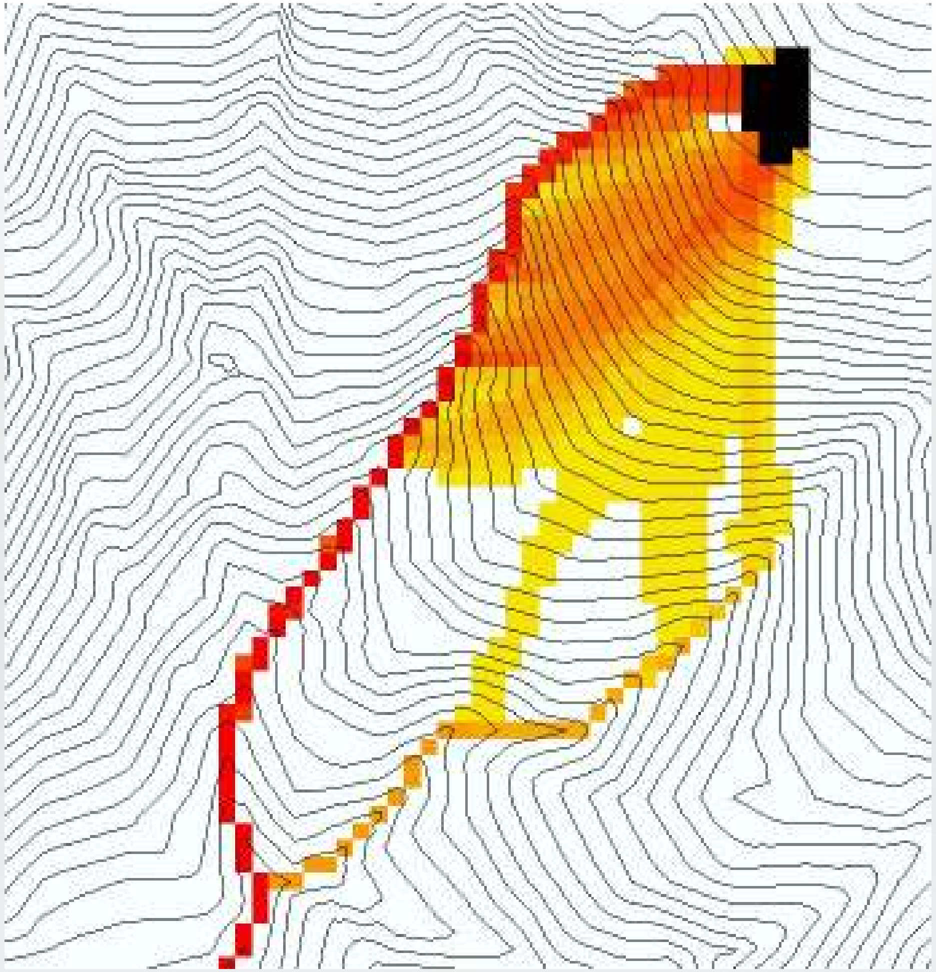


Decaying Accumulation

Mass loading field m(x) assumed to move with the flow field but is subject to first order decay

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

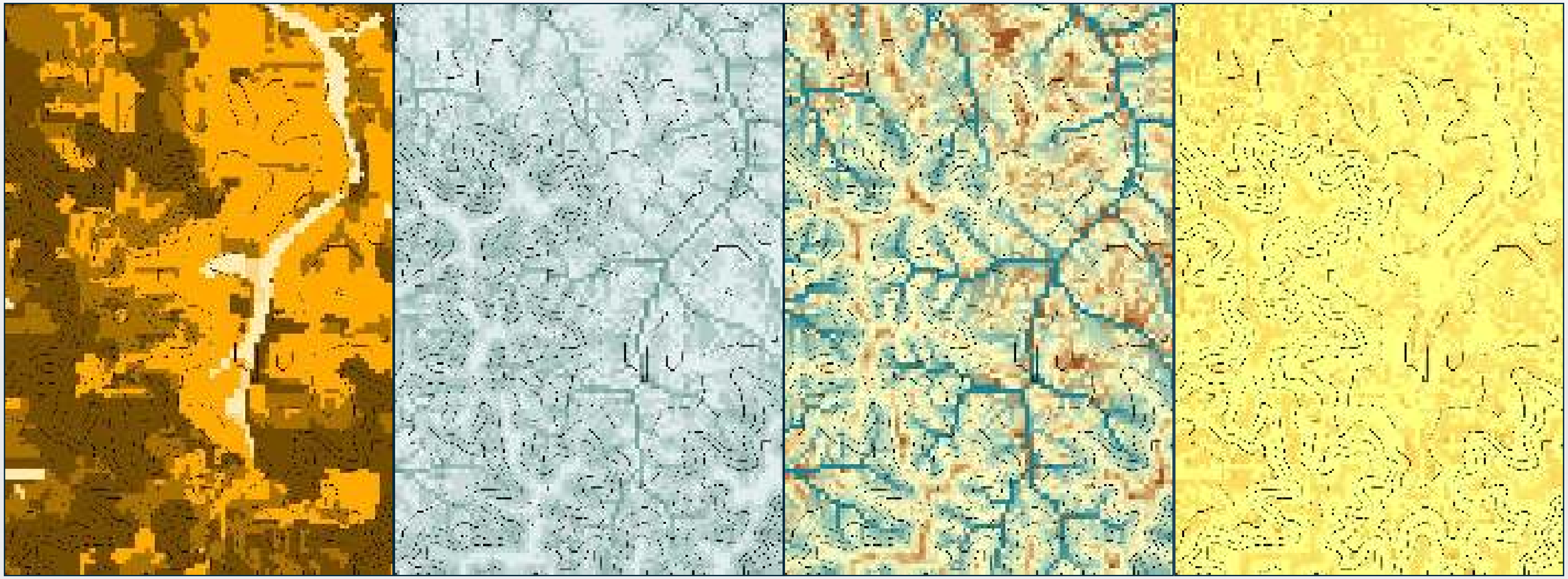
d(i ,j) is a decay multiplier giving the reduction in mass in moving from one grid cell to the next. d(i,j) may be related to travel time, e.g. as $d(i,j) = \exp(-\lambda t(i,j))$ where λ is a first order decay parameter.



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

Transport limited accumulation

Supply | Capacity | Transport | Deposition



$$S \qquad T_{cap} = \chi a^2 \tan(b)^2 \qquad T_{out} = \min\{S + \sum T_{in}, T_{cap}\} \qquad D = S + \sum T_{in} - T_{out}$$

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

General Pseudocode Downstream Flow Algebra Evaluation

Global $\underline{P}$, $\underline{\gamma}$, $\underline{\theta}$

FlowAlgebra(i)

for all k neighbors of i

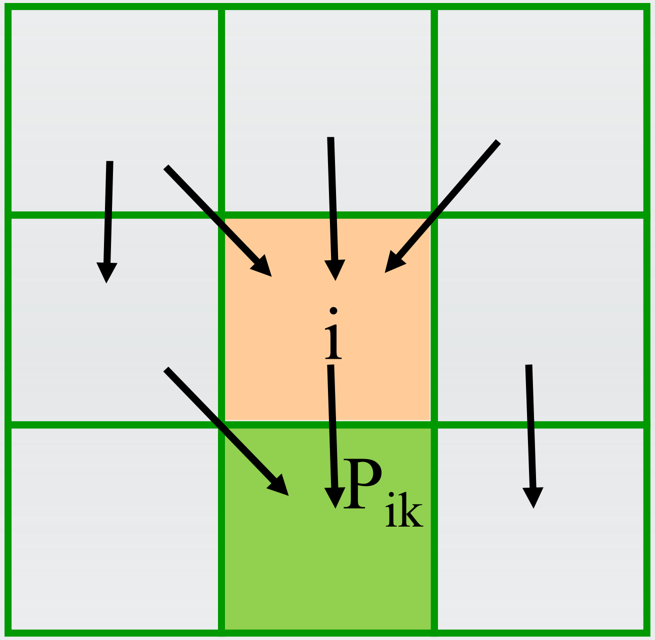
  if $P_{ik}>0$

    FlowAlgebra(k)

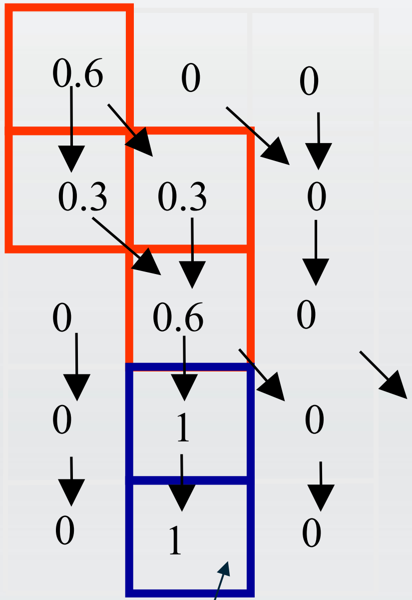
next k

$\underline{\theta}_i = \mathbf{FA}(\underline{\gamma}_i, \underline{\mathbf{P}}_{ik}, \underline{\theta}_k, \underline{\gamma}_k)$

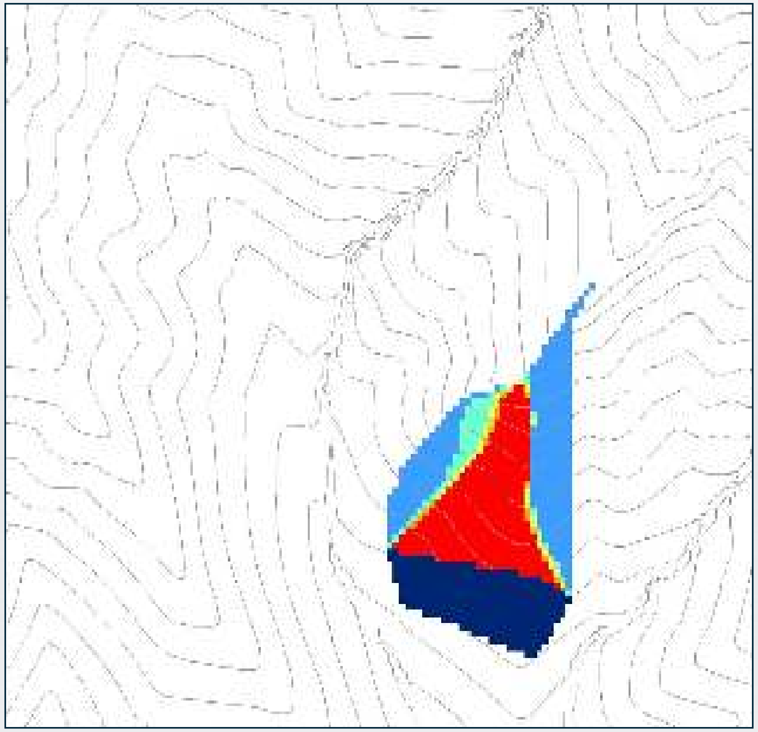
return



Dependence function. Quantifies the amount a point x contributes to the point or zone y.

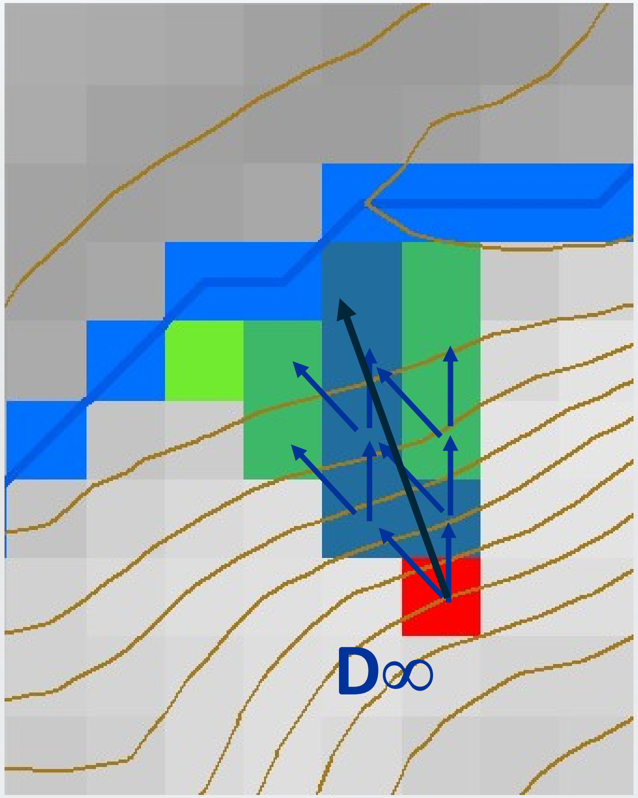


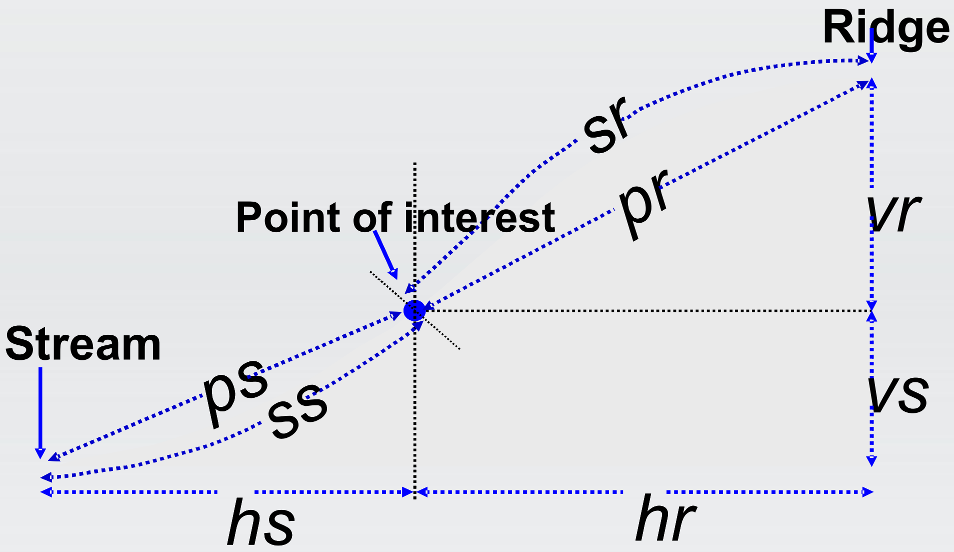
Dependence function of grid cells y



Useful for example to track where a contaminant may come from

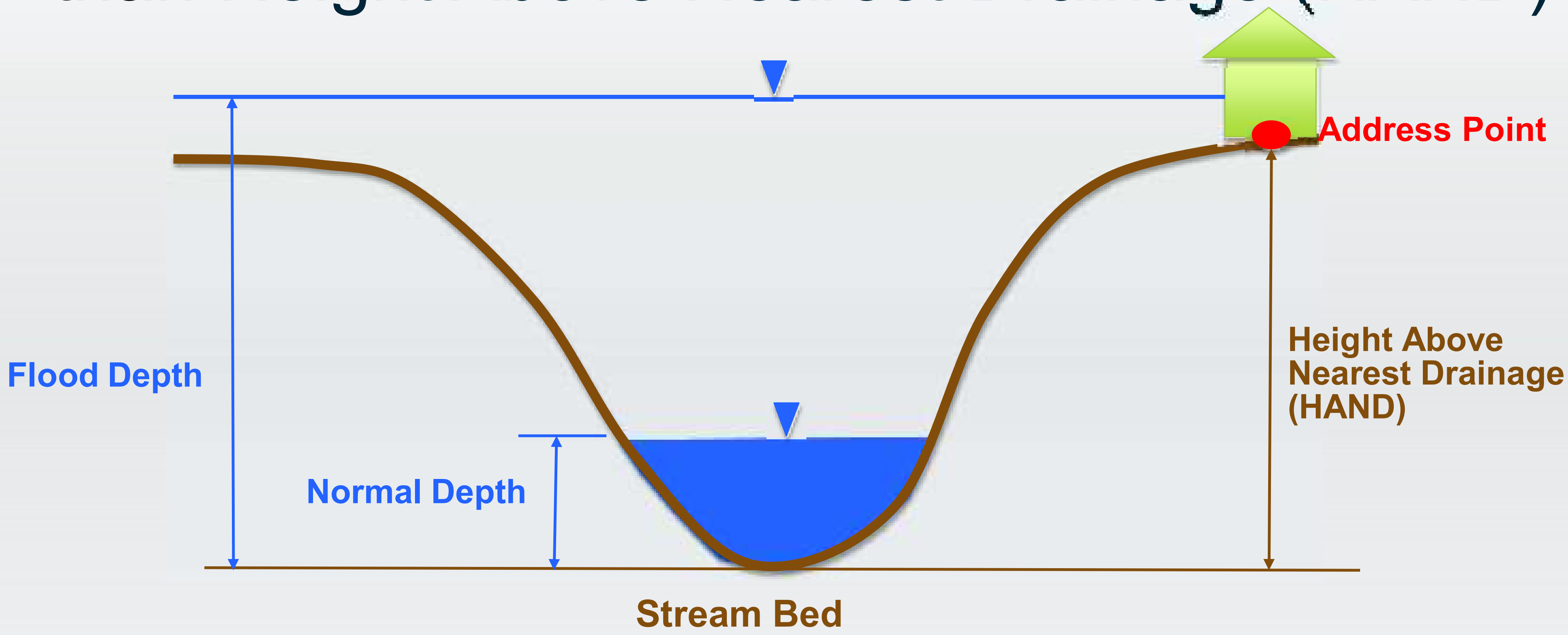
General Proximity Functions as weighted distance to a target set along Dinfinity Flow Directions





Tesfa, T. K., D. G. Tarboton, D. W. Watson, K. A. T. Schreuders, M. E. Baker and R. M. Wallace, (2011), "Extraction of hydrological proximity measures from DEMs using parallel processing," Environmental Modelling & Software, 26(12): 1696-1709, http://dx.doi.org/10.1016/j.envsoft.2011.07.018.

Flooding occurs when Water Depth is greater than Height Above Nearest Drainage (HAND)



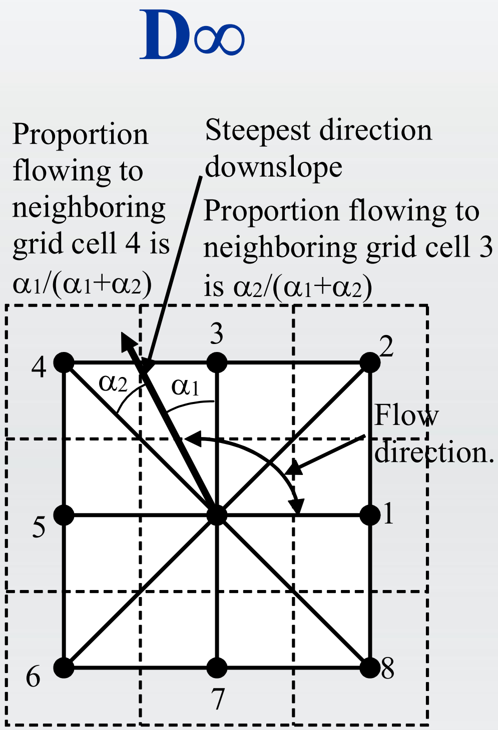
May be used to determine flood risk

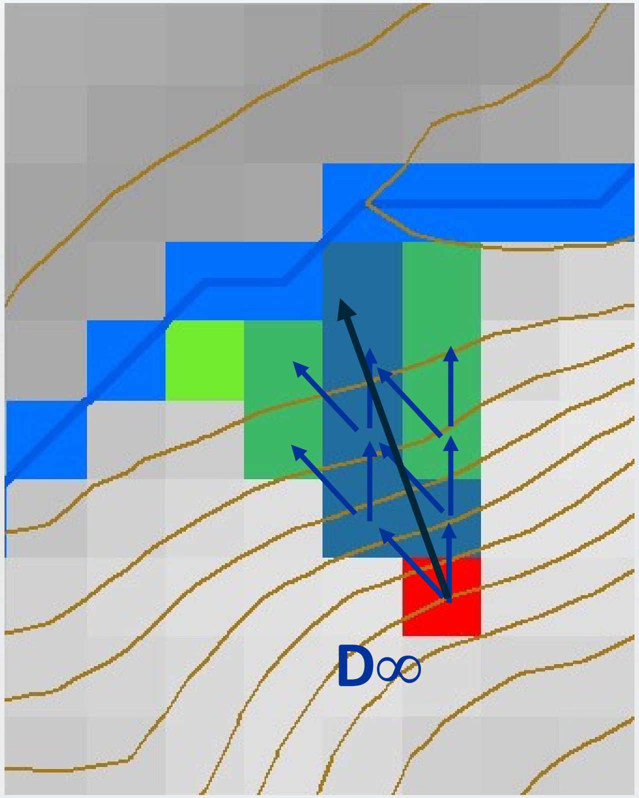
Slide from David Maidment

Literature on HAND

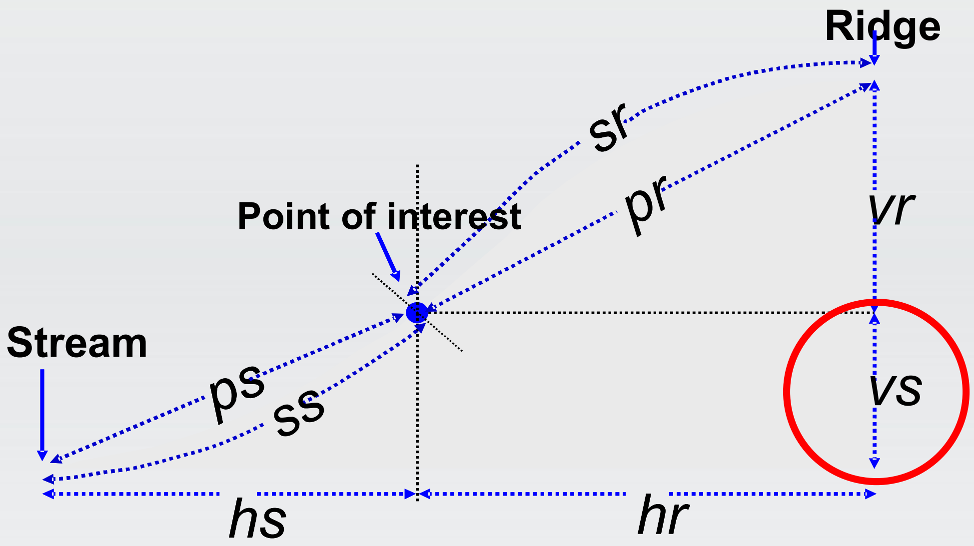
- Rodda, H. J. E., (2005), "The Development and Application of a Flood Risk Model for the Czech Republic," Natural Hazards, 36(1): 207-220, http://dx.doi.org/10.1007/s11069-004-4549-4.
- Rennó, C. D., A. D. Nobre, L. A. Cuartas, J. V. Soares, M. G. Hodnett, J. Tomasella and M. J. Waterloo, (2008), "HAND, a new terrain descriptor using SRTM-DEM: Mapping terra-firme rainforest environments in Amazonia," Remote Sensing of Environment, 112(9): 3469-3481, http://doi.org/10.1016/j.rse.2008.03.018.
- Nobre, A. D., L. A. Cuartas, M. Hodnett, C. D. Rennó, G. Rodrigues, A. Silveira, M. Waterloo and S. Saleska, (2011), "Height Above the Nearest Drainage – a hydrologically relevant new terrain model," Journal of Hydrology, 404(1–2): 13-29, http://dx.doi.org/10.1016/j.jhydrol.2011.03.051.
- Nobre, A. D., L. A. Cuartas, M. R. Momo, D. L. Severo, A. Pinheiro and C. A. Nobre, (2016), "HAND contour: a new proxy predictor of inundation extent," Hydrological Processes, 30(2): 320-333, http://dx.doi.org/10.1002/hyp.10581.

Height above Nearest Drainage (HAND) evaluated using TauDEM Dinfinity vertical distance down function



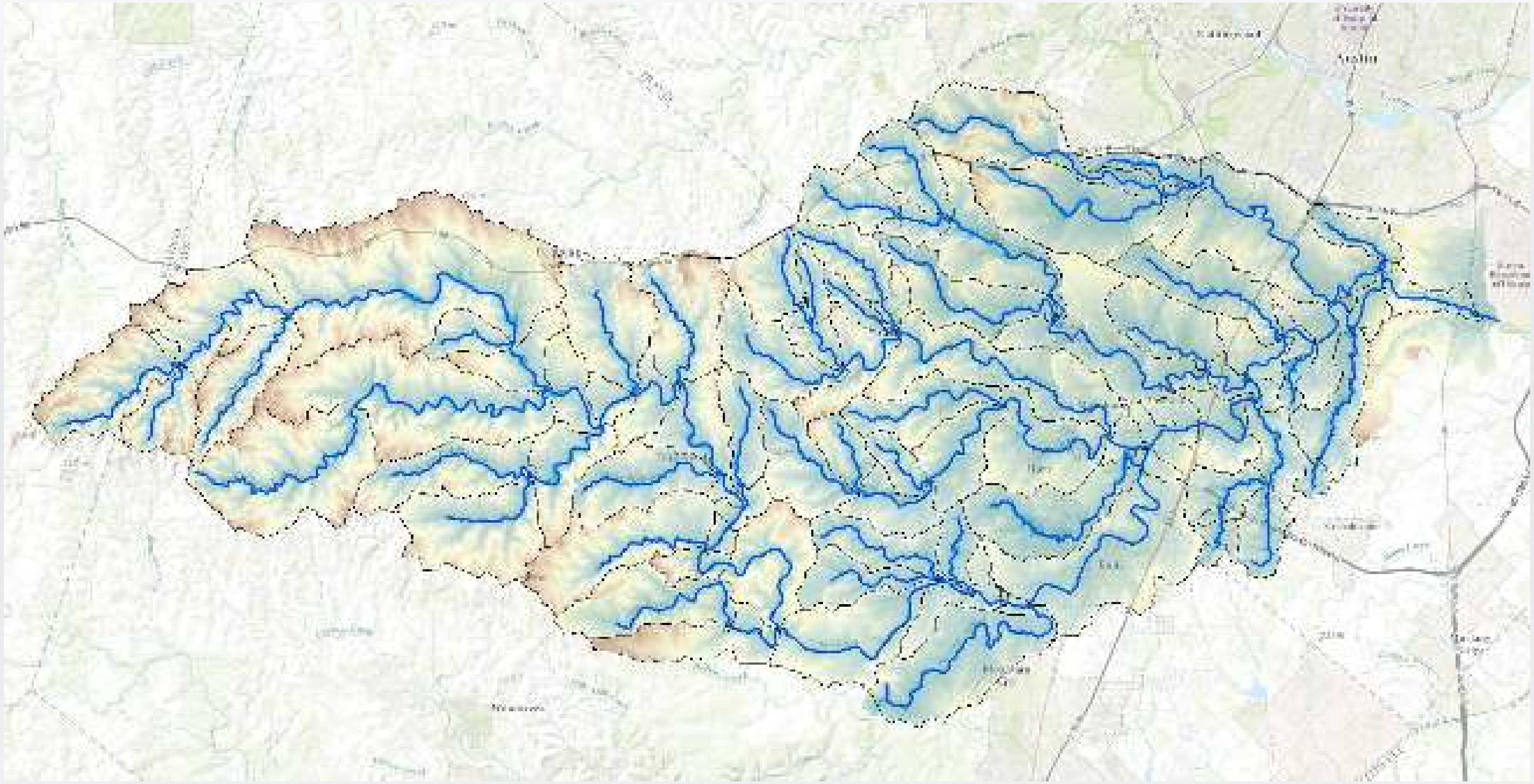


A special case of a general hydrological proximity measure



Vertical distance to stream evaluated as weighted average over multiple flow paths. This results in a "smooth" height above nearest drainage layer

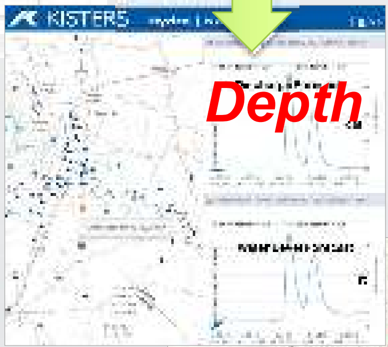
HAND from TauDEM for Onion Creek near Austin Texas



1/3 arc second NED DEM

Flood Inundation Mapping from National Water Model Discharges

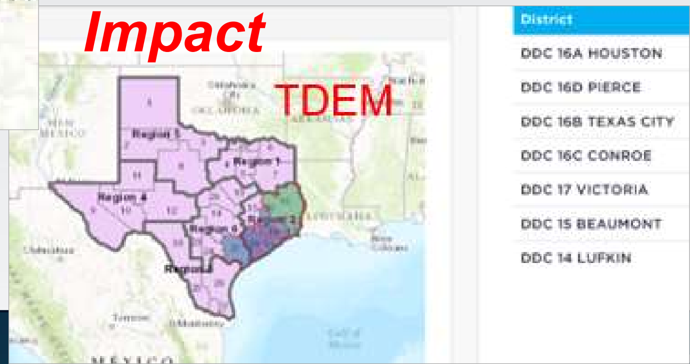
Take discharge forecast from the National Water Model



Transform discharge to depth by rating curve or hydraulic model

Create flood inundation map from water depth

Assess impact on people and property



Slide from David Maidment

Implementation

- Each stream reach has a discharge
- Each stream reach has a water depth calculated from discharge, h_w
- Each stream reach has a unique ID
- Each catchment has a unique ID for the reach to which it drains
- Each grid cell has the ID of the catchment it is in (reach it drains to) and height above the nearest drainage, h_d
- Evaluate inundation using

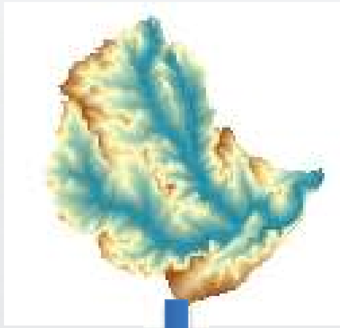
  if(h_w(id) > h_d(id))

  Inundation depth = h_w(id) - h_d(id)

  else

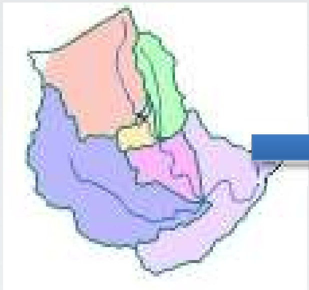
  Inundation depth = 0

Height above drainage
(relative elevation of land surface cell above cell in stream to which it flows)



Streams

Catchments



Inundation map

Reach Scale Flood Depth

Comid	Depth (ft)
5781365	8
5781381	9
5781405	10
5781401	15
5781399	14
5781383	12
5781933	11

Using HAND to determine reach average hydraulic properties

For each Catchment
For each height h
Identify cells where HAND $h_d < h$

Single Cell Plan Area $A_c = dx * dy$

Surface area $A_s = \sum A_c$

Bed Area $A_b = \sum A_c \sqrt{1 + slp^2}$

Approximates each cell as sloping plane

Volume $V = \sum A_c (h - h_d)$

$A = \frac{V}{L}$ Cross Section Area

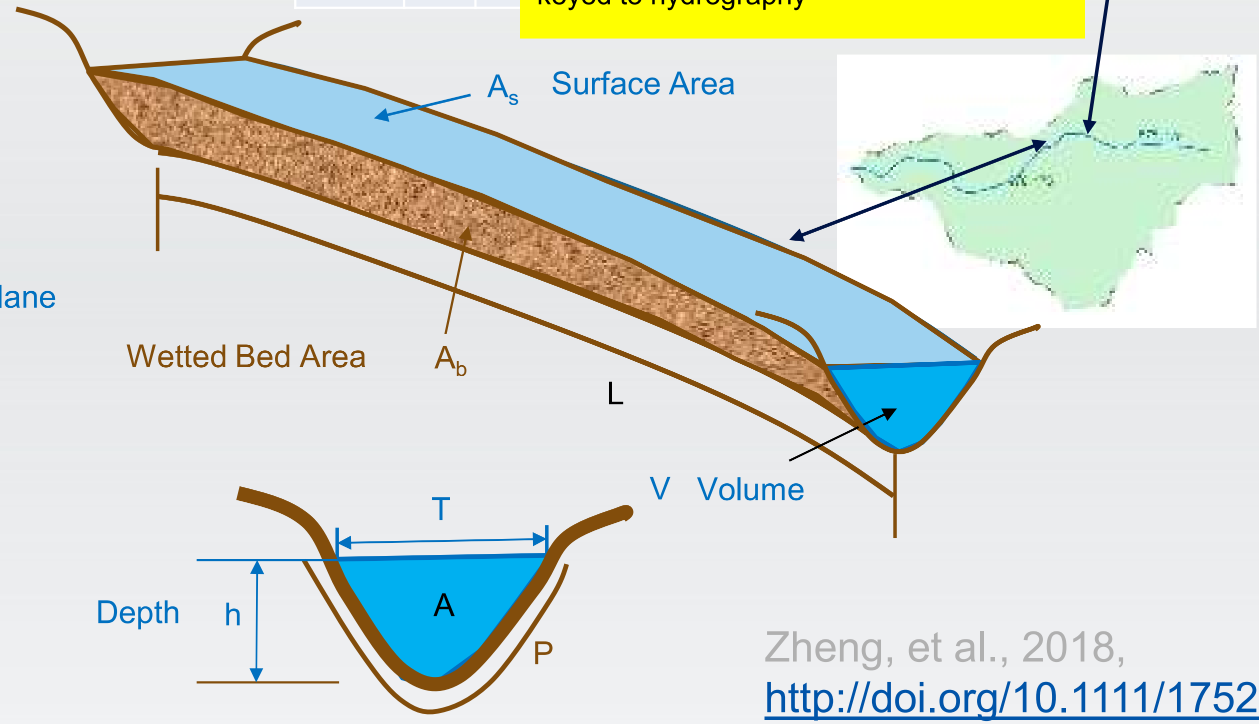
$P = \frac{A_b}{L}$ Wetted Perimeter

$T = \frac{A_s}{L}$ Top Width

$R = \frac{A}{P}$ Hydraulic Radius

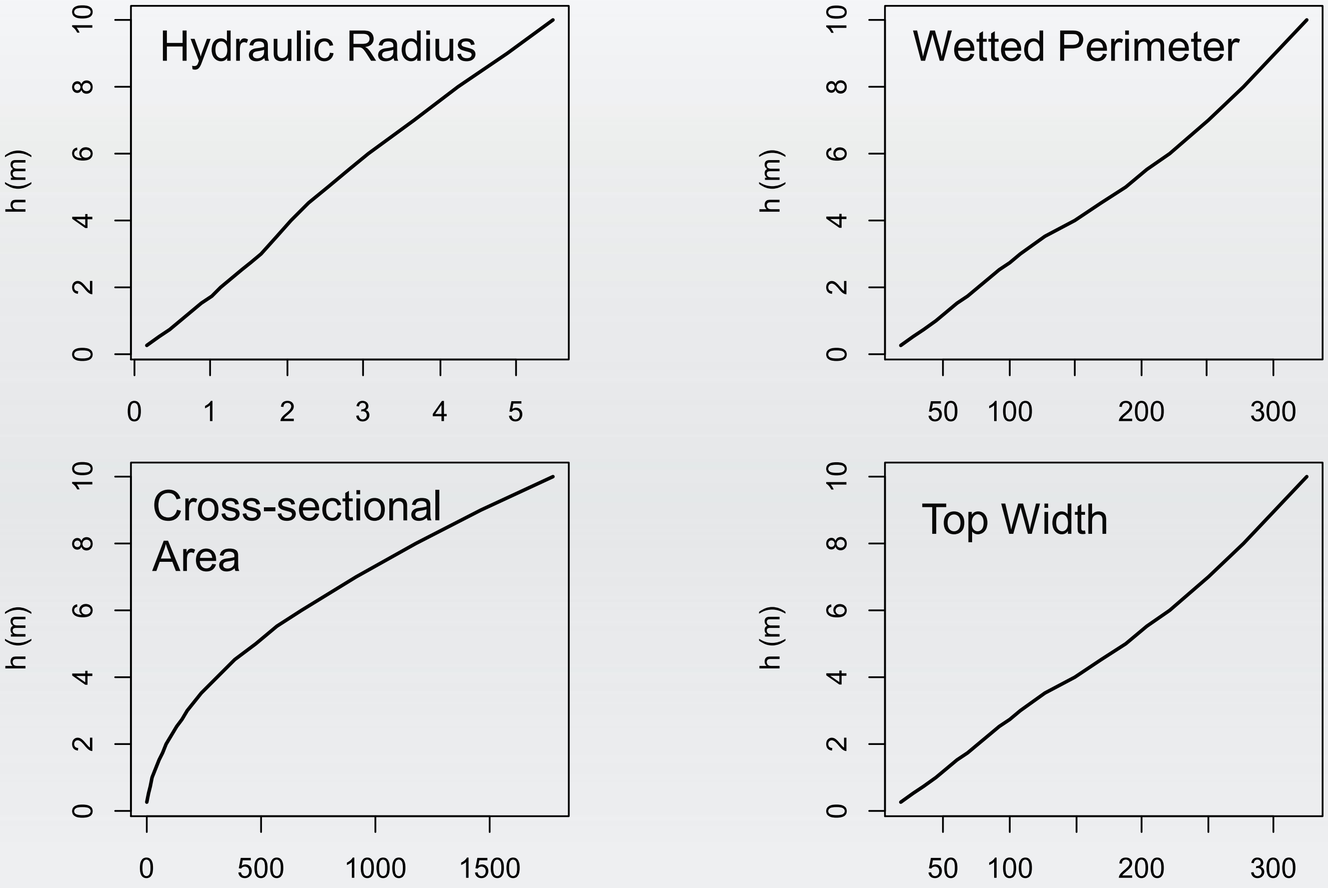
Comid	H	A	R	P	T	V	Ab	As
5781175	3							
5781175	4							

A table with reach hydraulic parameters keyed to hydrography



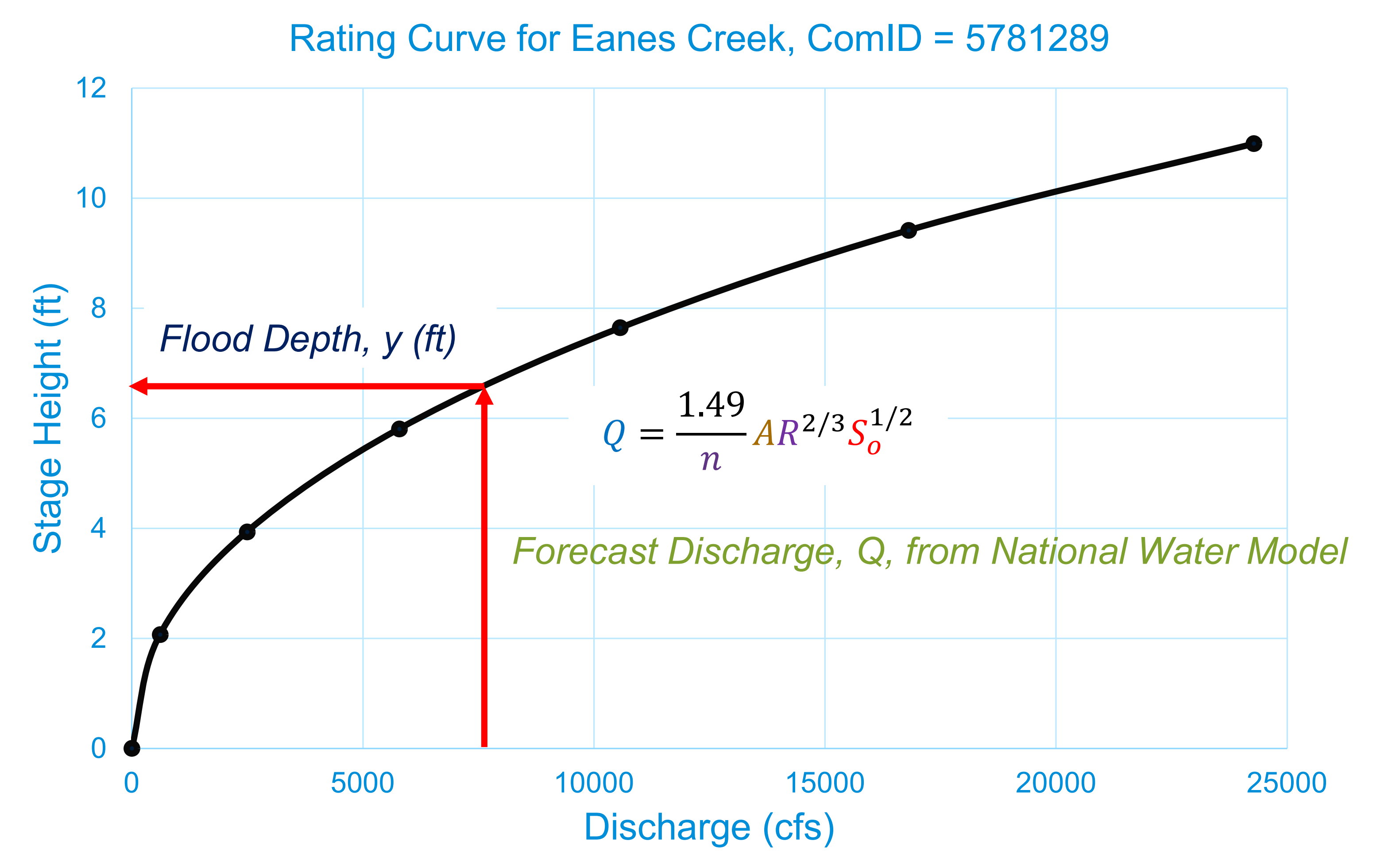
Zheng, et al., 2018, http://doi.org/10.1111/1752-1688.12661.

Terrain Approximated Reach Average Hydraulic Properties



Used for input to reach scale hydraulic model

Combined with roughness estimate to determine rating curve and depth from discharge



Slide from David Maidment

The challenge of increasing Digital Elevation Model (DEM) resolution demands a parallelization approach

e.g. 50,000 km^2 Watershed

1980's DMA 90 m

10^2 cells/km^2

27 MB

1990's USGS DEM 30

10^3 cells/km^2

240 MB

2000's NED 10 m

10^4 cells/km^2

2 GB

2010's LIDAR ~1 m

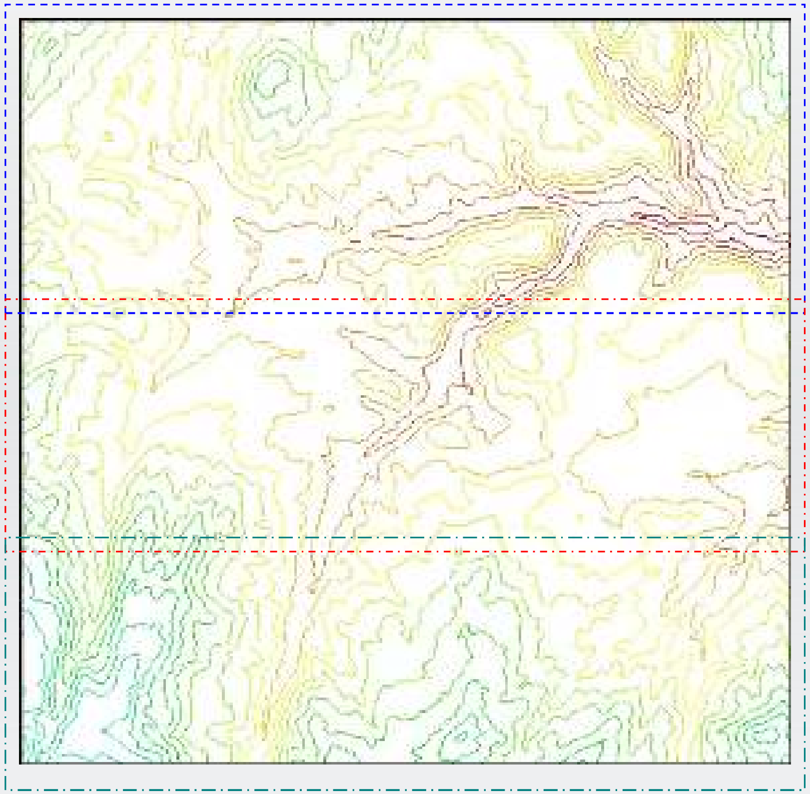
10^6 cells/km^2

200 GB

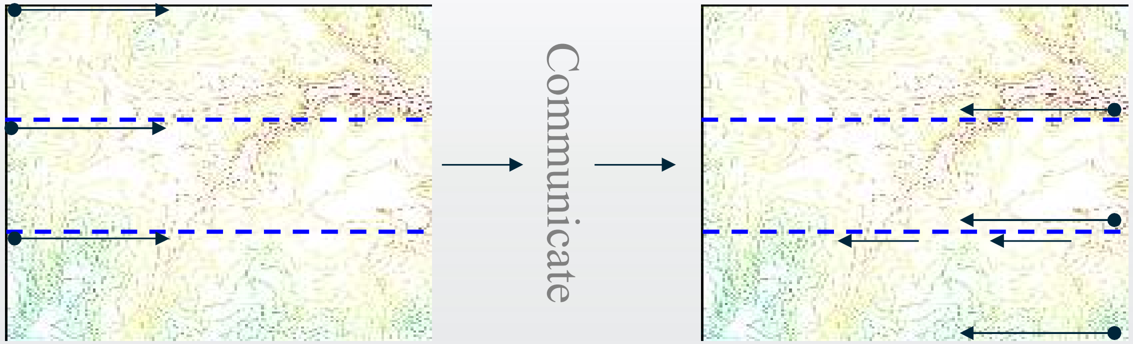
A factor 10,000 increase in 30 years

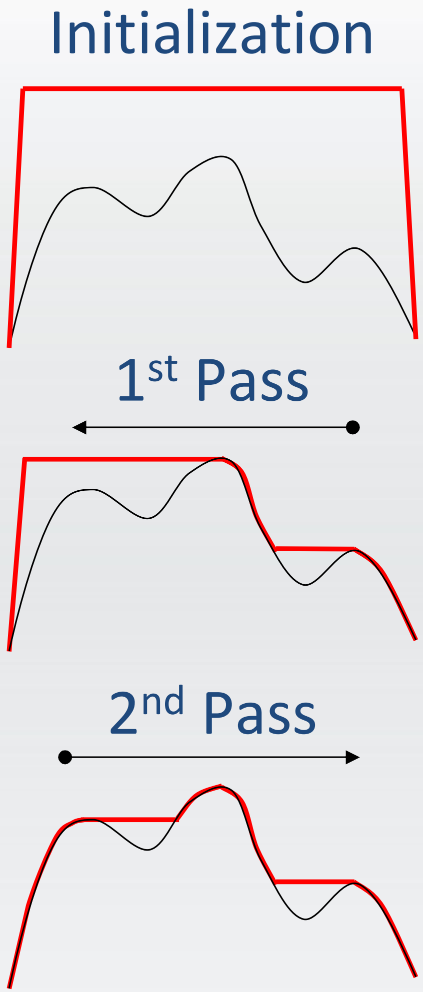
TauDEM Parallel Programming Approach

- MPI, distributed memory paradigm
- Row oriented slices
- Each process includes one buffer row on either side
- Each process does not change buffer row
- Improved runtime efficiency
- Capability to run larger problems



Parallel Pit Filling based on Planchon and Darboux approach






```
Initialize( Z,F)
Do
    for all grid cells i
        if Z(i) > n
            F(i) ← Z(i)
        Else
            F(i) ← n
            i on stack for next pass
    endfor
    Send( topRow, rank-1 )
    Send( bottomRow, rank+1 )
    Recv( rowBelow, rank+1 )
    Recv( rowAbove, rank-1 )
Until F is not modified
```

Z denotes the original elevation.
F denotes the pit filled elevation.
n denotes lowest neighboring elevation
i denotes the cell being evaluated

Iterate only over stack of changeable cells

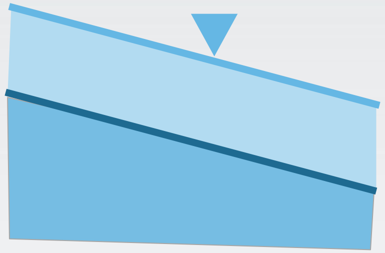
Planchon, O. and F. Darboux, (2001), http://dx.doi.org/10.1016/S0341-8162(01)00164-3.

Continental-Scale HAND layer evaluated on ROGER supercomputer at NCSA using TauDEM

Catchments and Flowlines

Digital Elevation Model

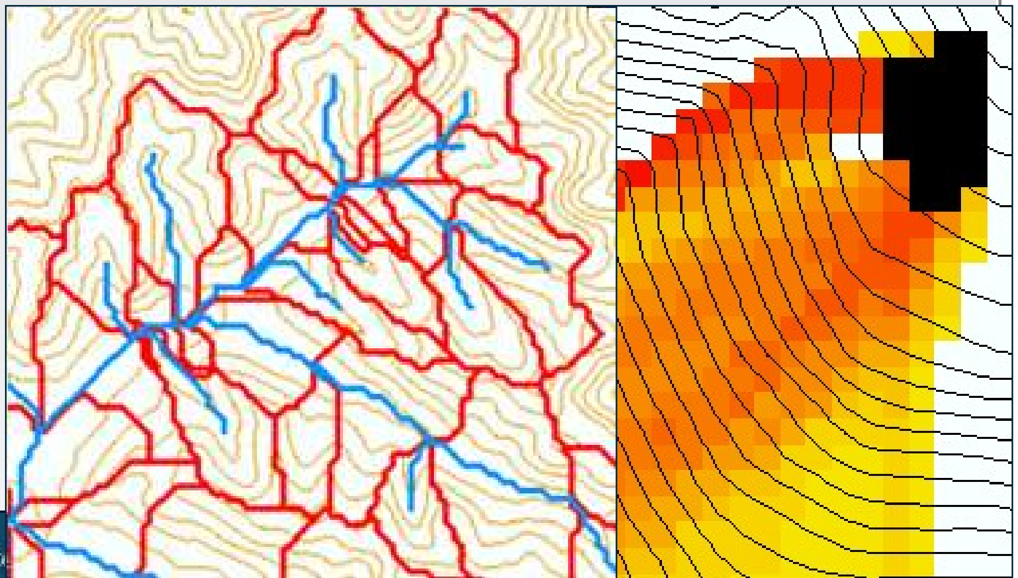
Height Above Nearest Drainage (HAND)
(relative elevation of land surface cell above cell in stream to which it flows)

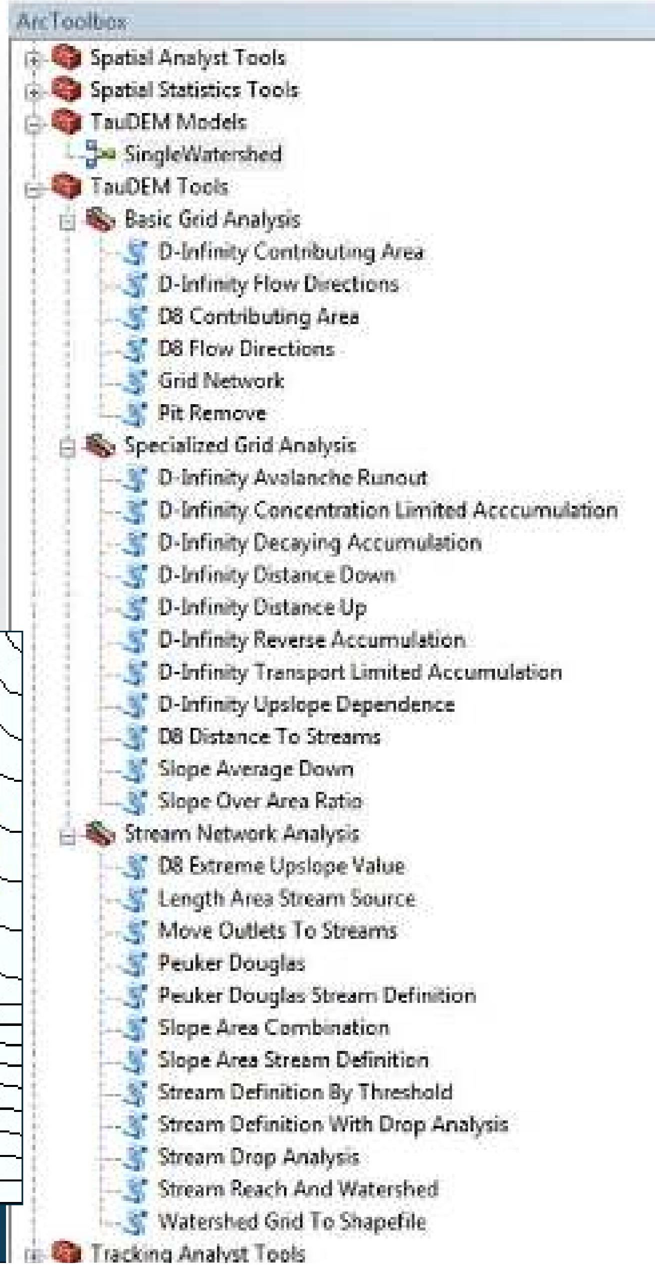


Slide from David Maidment

TauDEM

- Dinfinity and D8 flow direction models
- Includes multiple hydrological proximity measures such as distance to stream which measured vertically gives height above the nearest drainage (HAND)
- Uses parallel algorithms for processing large datasets
- Includes Toolbox for ArcGIS
- Open source platform independent C++ command line executables for each function
- Deployed as an ArcGIS Toolbox with python scripts that drive command line executables





http://hydrology.usu.edu/taudem/

TauDEM Programming

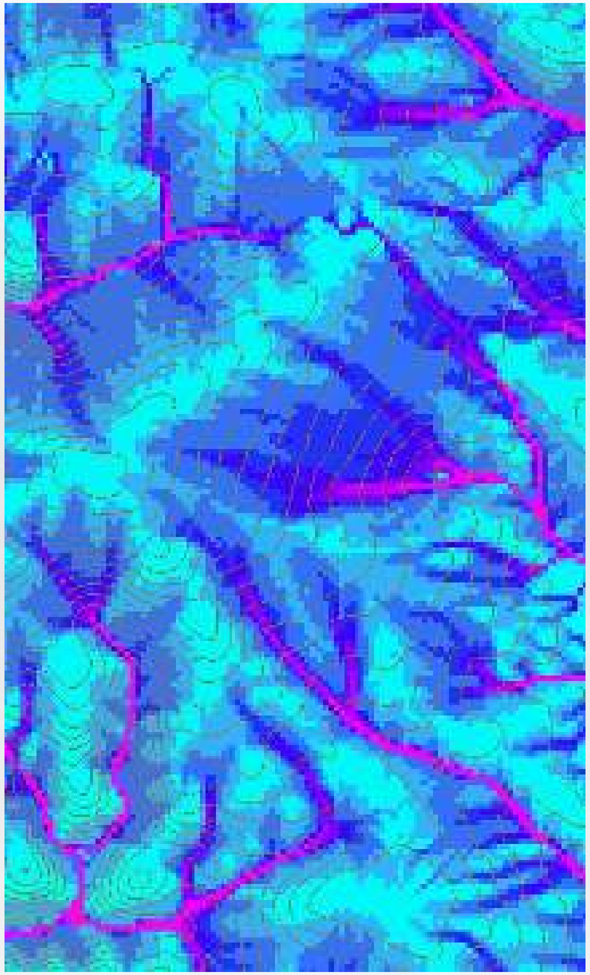
- C++ Command Line Executables that use MPI
- Use GDAL/OGR library to read and write datasets in open standard formats for exchange with other programs
- ArcGIS Python Script Tools
- Python validation code to provide file name defaults
- Shared as ArcGIS Toolbox

Any computer

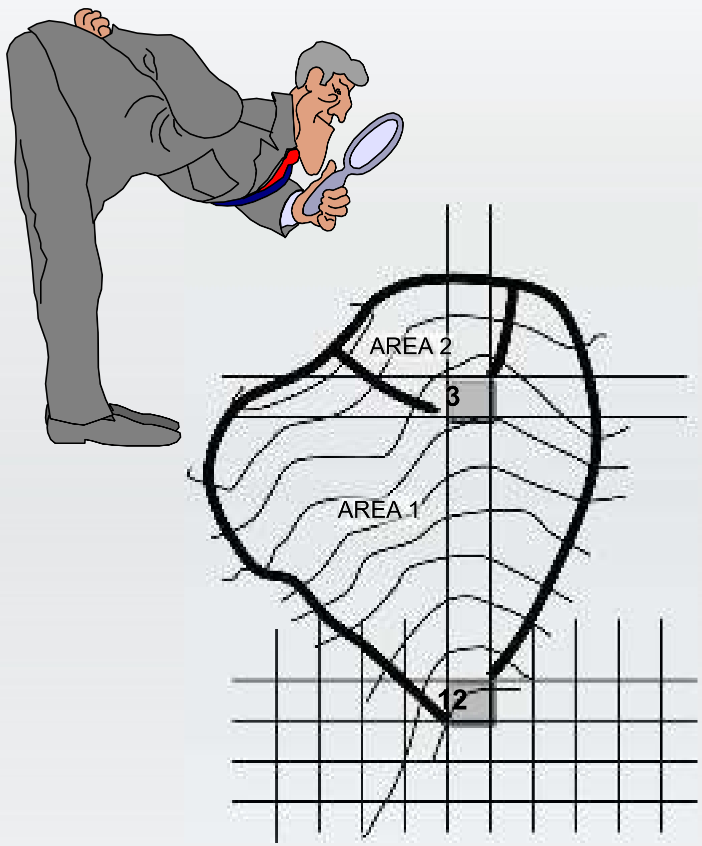
Requires ArcGIS

Conclusions

- Starting from a simple grid DEM, a rich set of data structures and information useful for hydrologic analysis can be derived
- Empirical geomorphology "laws" offer approaches objective selection of channel network delineation threshold
- Terrain surface derivatives enhanced by use of D∞ model.
- Flow algebra a general "recipe" for terrain flow related modeling.
- The height above nearest drainage approach provides a way to rapidly approximate real time flood inundation and approximate reach scale hydraulic properties
- Future challenges and opportunities remain as to how to leverage increasingly high resolution DEMs and emerging cloud and high-performance computing capabilities



Questions



Some References

- 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, http://doi.org/10.1029/96WR03137.
- Tarboton, D. G. and D. P. Ames, (2001), "Advances in the mapping of flow networks from digital elevation data," World Water and Environmental Resources Congress, Orlando, Florida, May 20-24, ASCE, http://dx.doi.org/10.1061/40569(2001)166.
- Tesfa, T. K., D. G. Tarboton, D. W. Watson, K. A. T. Schreuders, M. E. Baker and R. M. Wallace, (2011), "Extraction of hydrological proximity measures from DEMs using parallel processing," Environmental Modelling & Software, 26(12): 1696-1709, http://dx.doi.org/10.1016/j.envsoft.2011.07.018.
- Zheng, X., D. G. Tarboton, D. R. Maidment, Y. Y. Liu and P. Passalacqua, (2018), "River Channel Geometry and Rating Curve Estimation Using Height above the Nearest Drainage," JAWRA Journal of the American Water Resources Association, 54(4): 785-806, http://doi.org/10.1111/1752-1688.12661

Others at: https://hydrology.usu.edu/dtarb/tarpubs.htm

Thank You !