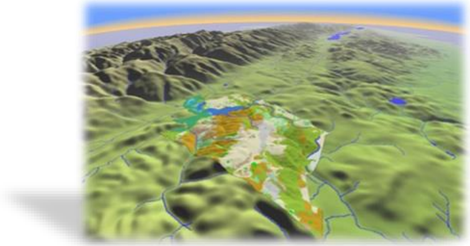
NICHOLAS SCHOOL OF THE
ENVIRONMENT AND EARTH SCIENCES
DUKE UNIVERSITY



ENVIRON 761:
Elevation, Terrain & Ecology
Part 1: Ecohydrology and GIS

Instructor: John Fay

Elevation

Highest Peaks in California

Rank	Mountain Peak	Elevation
1	Mt. Whitney	14,505 ' / 4421 m
2	Mt. Williamson	14,389 ' / 4386 m
3	White Mt. Peak	14,252 ' / 4344 m
4	North Palisade	14,248 ' / 4343 m
5	Mt. Shasta	14,179 ' / 4322 m
6	Mt. Humphreys	13,992 ' / 4265 m
7	Mt. Keith	13,982 ' / 4262 m
8	Mt. Darwin	13,837 ' / 4218 m
9	Mt. Kaweah	13,807 ' / 4209 m
??	Mt. Diablo	3,864' / 1178 m

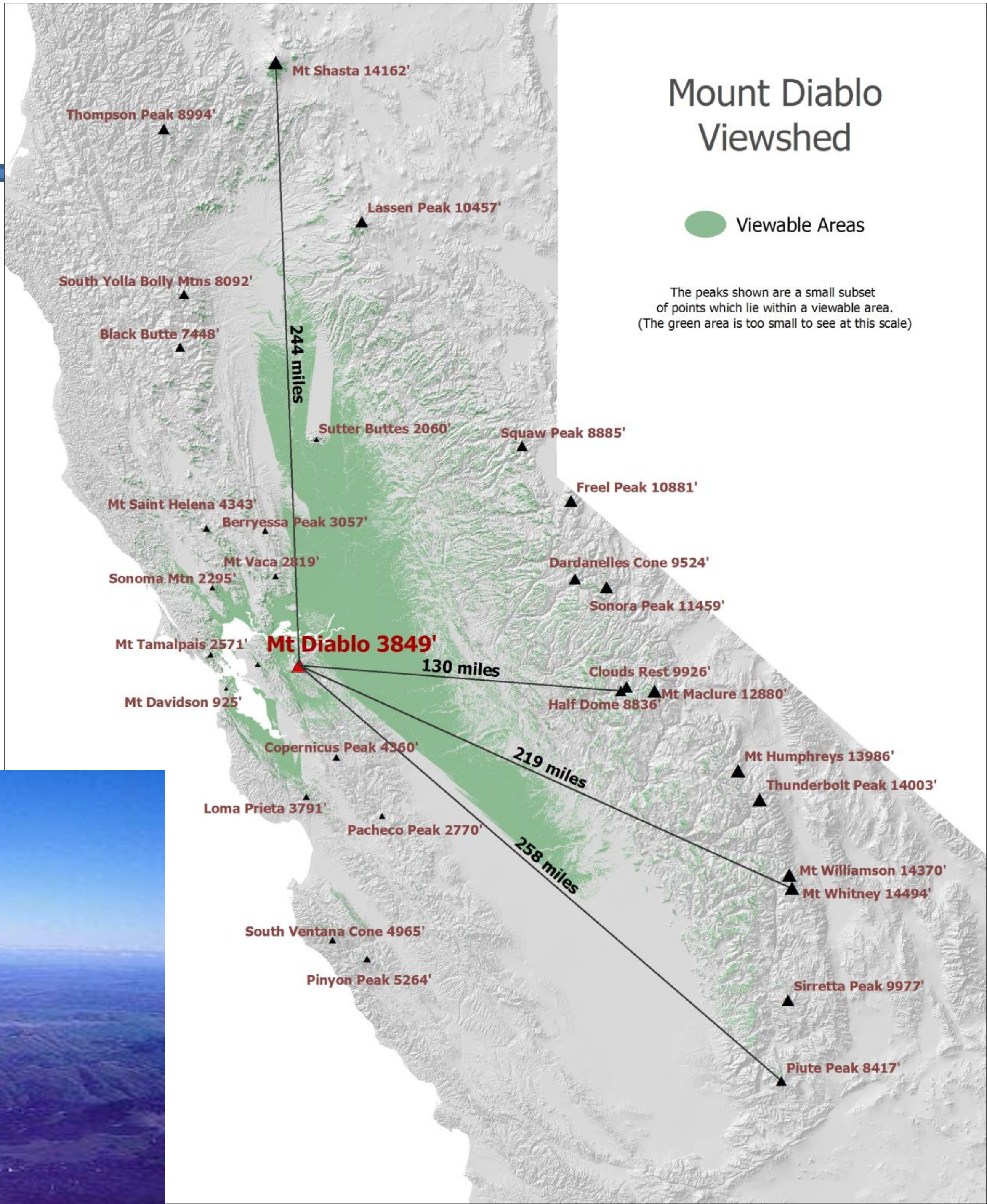
Elevation


Mt. Diablo
Williams
Yuba City
Wildwood
Grass Valley
Kings Beach
Carson City
Lake Tahoe
Alta Sierra
Olivehurst
Indian Hills
Johnson Lane
Nice
Lucerne
Ukiah
Lakeport
Clearlake Oaks
Kelseyville
Clearlake
Yerington
Schurz
North Auburn
Auburn
Lincoln
Kingsbury
South Lake Tahoe
Gardnerville
Gardnerville Ranchos
Cloverdale
Hidden Valley Lake
Pollock Pines
Roseville
Citrus Heights
Smith Valley
Healdsburg
Calistoga
Woodland
North Highlands
Folsom
Placerville
Sacramento
Arden-Arcade
Markleeville Peak
Windsor
Santa Rosa
St Helena
Rosemont
Parkway-South Sacramento
Vineyard
Garfield Hills HP
Hawthorne
Patterson, Mount
Sebastopol
Vacaville
Napa
Elk Grove
Ione
Jackson
Rohnert Park
Sonoma
Petaluma
Fairfield
Arnold
Hanging Valley Ridge
Vallejo
Lodi
Angels Camp
Novato
Pittsburg
Twain Harte
Martinez
Antioch
Stockton
Sonora
San Rafael
Concord
Brentwood
Jamestown
Phoenix Lake-Cedar Ridge
Berkeley
San Francisco
Oakland
Manteca
Tracy
Oakdale
Groveland-Big Oak Flat
June Lake
San Leandro
Salida
Riverbank
San Bruno
Ritter, Mount
Mammoth Lakes
Hayward
Pleasanton
Ceres
Waterford
San Mateo
Fremont
Modesto
Keyes
Patterson
Turlock
Mariposa
Redwood City
Palo Alto
Delhi
Bootjack
Mesa
Atwater
Oakhurst
West Bishop
Bishop
Wilkerson
Sunnyvale
San Jose
Newman
Planada
Campbell
Gustine
Merced
Yosemite Lakes
Humphreys, Mount
Big Pine
Los Gatos
Scotts Valley
Morgan Hill
Chowchilla
Shaver Lake
Madera Acres
Bonadelle Ranchos-Madera Ranchos
Auberry
Los Banos
Gilroy
Aptos
Dos Palos
Santa Cruz
Madera
Interlaken
Watsonville
Hollister
Firebaugh
Clovis
Independence
Castroville
Prunedale
Mendota
Kerman
Sanger
Marina
Salinas
Fresno
Whitney, Mount
Monterey
Fowler
Reedley
Orange Cove
Lone Pine
Carmel
Gonzales
Selma
Dinuba
Orosi
Woodlake

Elevation

… is not everything

Even at just 3864 ft., Mt. Diablo has the "second largest viewshed in the world"…



Mount Diablo Viewshed

🟩 Viewable Areas

The peaks shown are a small subset
of points which lie within a viewable area.
(The green area is too small to see at this scale)

Elevation vs. Terrain

Elevation:

- height [above sea level] at a given *point*

Terrain:

- the *surface features* of an area of land;
- elevation of a point *in the context of* the elevation of points around it

Looking at changes in elevation across an area (i.e. terrain) gives far more information about a landscape than mere elevation alone

Elevation, terrain & ecology: Overview

I. Ecohydrology & conservation
  - Surface terrain and the hydrologic cycle
  - GIS techniques for modeling surface flow using a DEM

II. Vegetation patterns across ecological gradients
  - Properties of a terrain that drive these gradients
  - GIS techniques to derive surface properties from a DEM

Ecohydrology

Catchment as a "superorganism"
(Lovelock 1995)

Hydrology ↔ Ecology

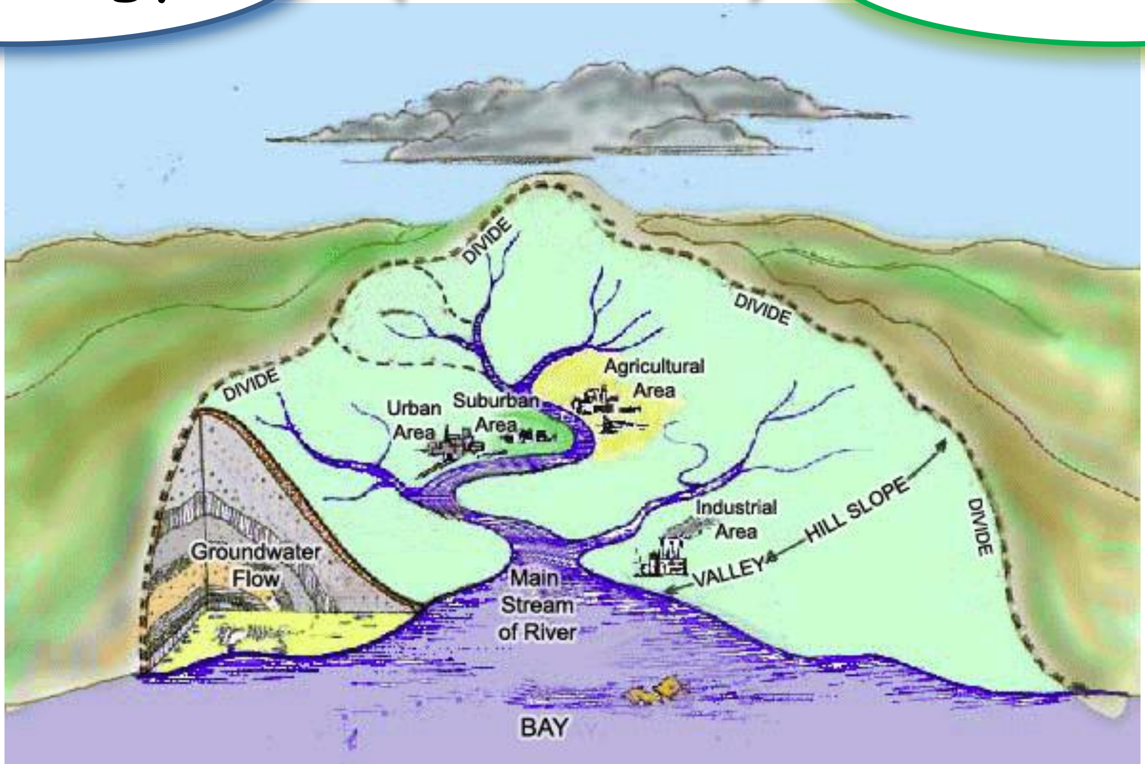


Image: Alice Ferguson Foundation

Ecohydrology: Principles

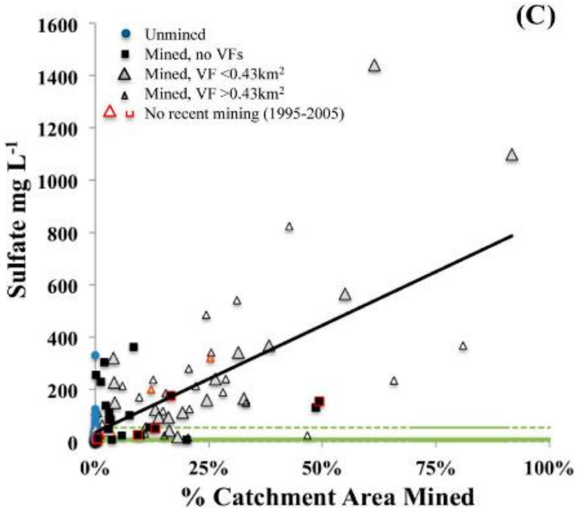
- Drainage systems should be considered as a template for quantifying the *threats* & *opportunities* [to conservation]

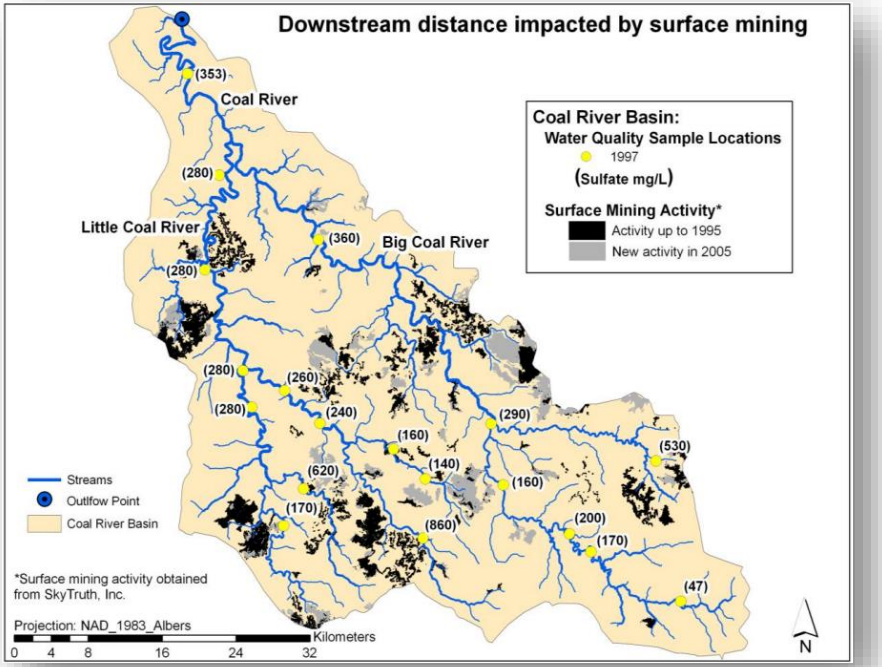
- Freshwater ecosystem robustness can be enhanced on the basis of understanding the evolutionary established resistance/resilience of the ecosystem
    - *Hydrology managed by tweaking ecological drivers*
    - *Ecology managed by tweaking hydrologic drivers*

(Zalewski 2002, Wagner & Zalewski 2009)

Ecohydrology: Case Study

Mountaintop mining in WV





Bernhardt et al. (2012)

What is a watershed?

aka: "catchment", "basin", "water divide"…

Simple:

The area of land where surface water converges into a single point.

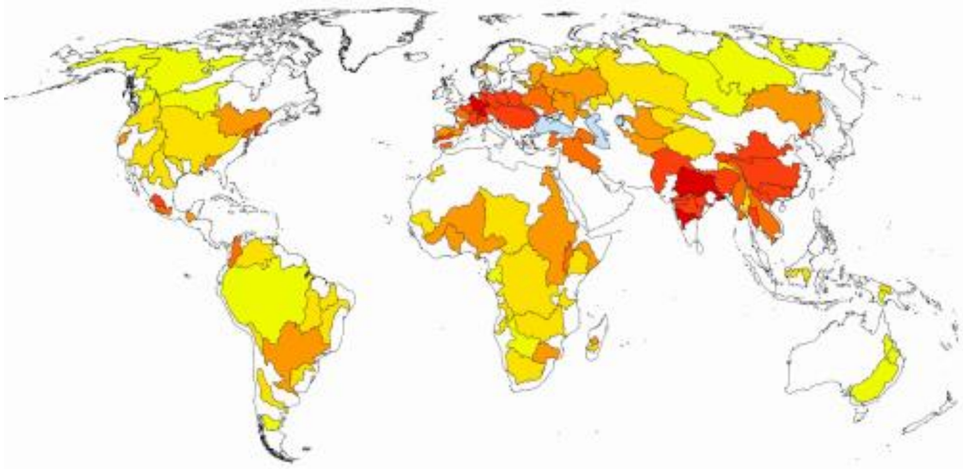
Holistic (and poetic):

"That area of land, a bounded hydrologic system, within which all living things are inextricably linked by their common water course and where, as humans settled, simple logic demanded they become part of a community"

-John Wesley Powell

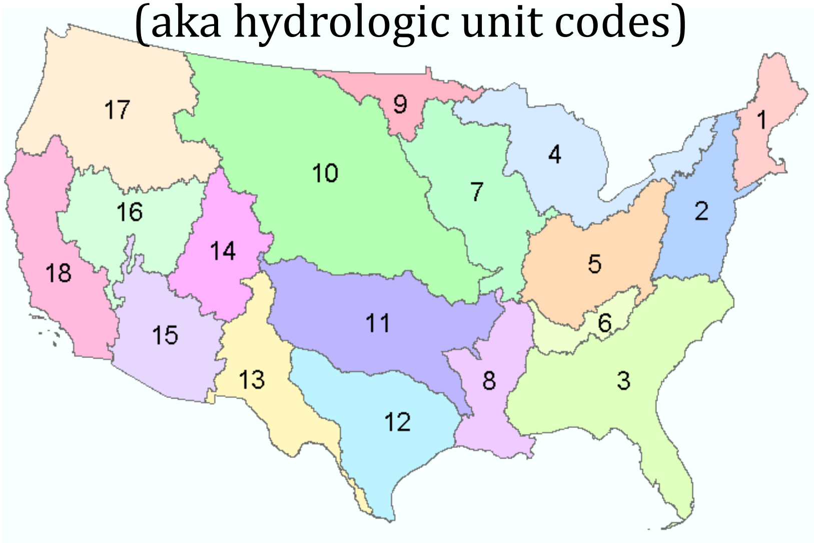
Watersheds of various scales

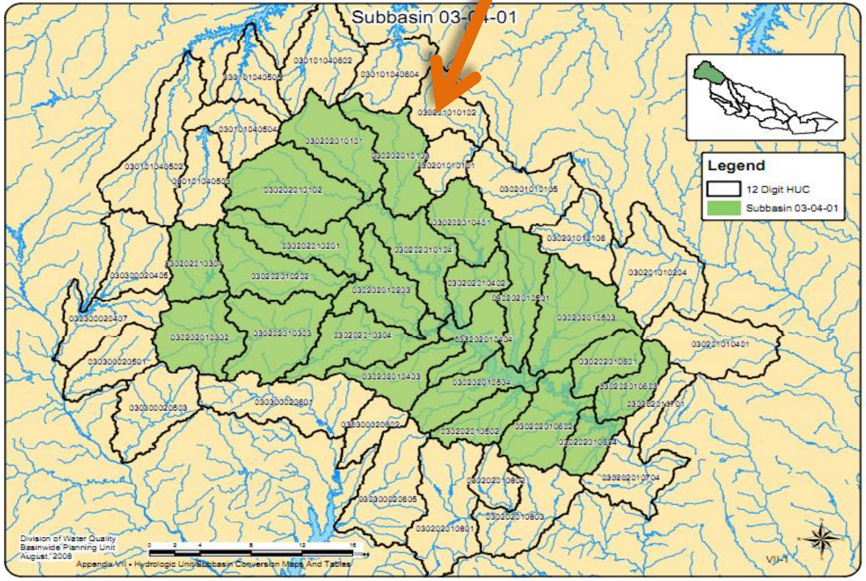
Population by global watersheds (wri.org)



8-digit HUC watersheds of NC

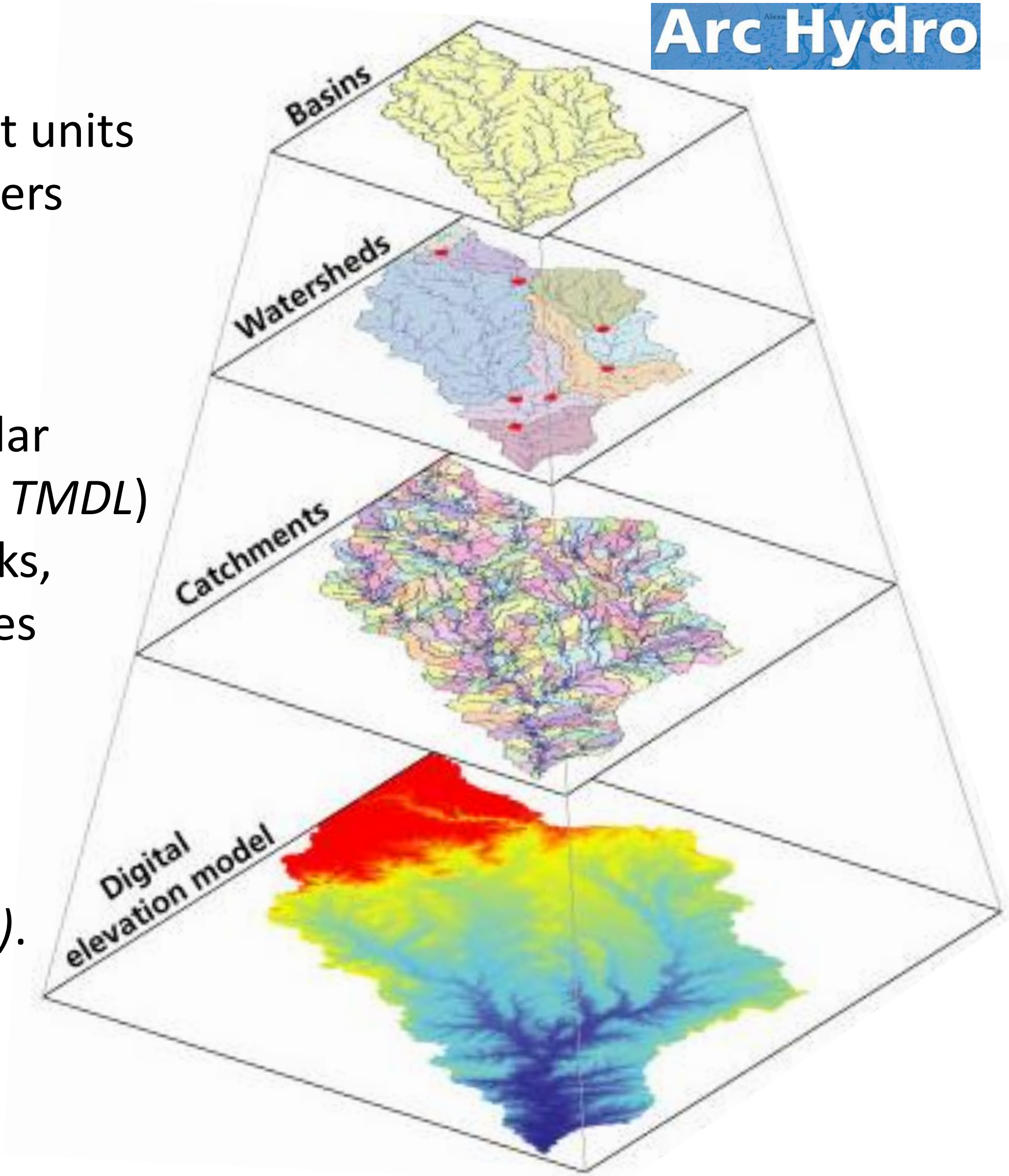
2-digit water resource regions
(aka hydrologic unit codes)





12-digit HUCs of Upper Neuse

Spatial scales of drainage systems



Arc Hydro

Basins:

- Administrative/water management units
- Normally named after principal rivers
- Popular data-packaging unit

Watersheds:

- Subdivisions selected for a particular hydrologic purpose (*e.g. Falls Lake TMDL*)
- Pour points are often river networks, segments, or receiving water bodies

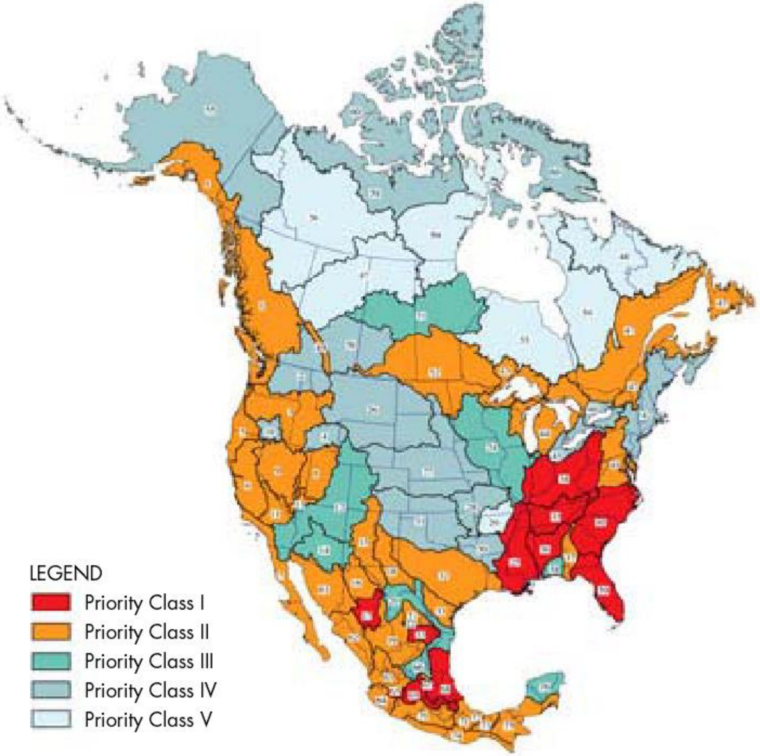
Catchments:

- Subdivisions often defined by a consistent set of physical rules. (*e.g., drainage area, stream nodes*).

Digital elevation model:

- Each cell is an operational unit

Watersheds: A useful ecoregional planning unit



WWF Priority Freshwater Ecoregions

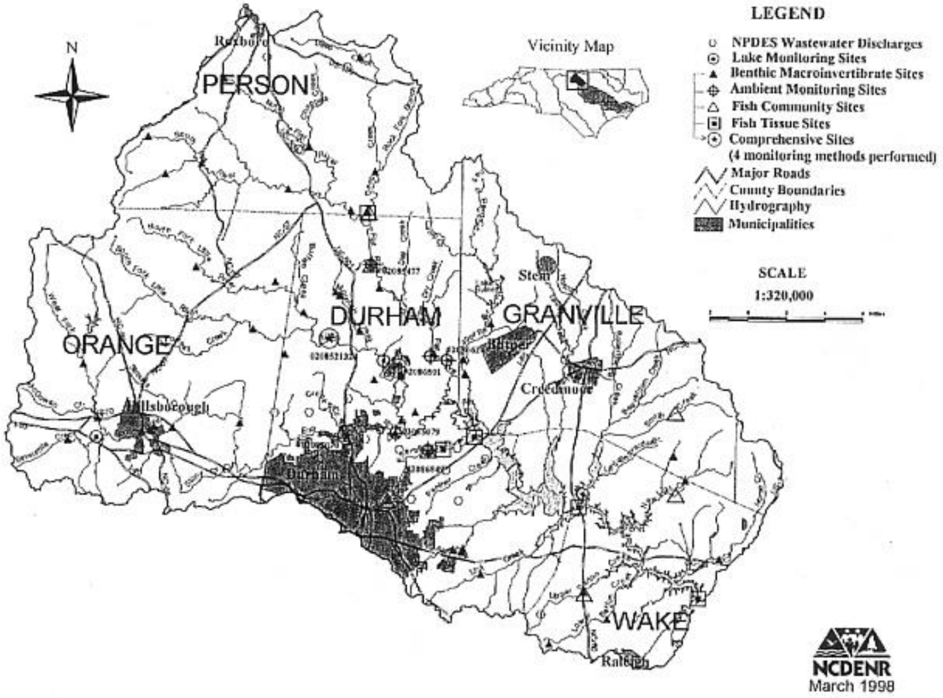


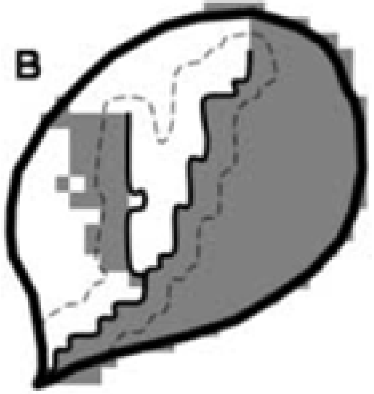
Figure 1.1 Water Quality Monitoring Stations in the Upper Neuse River Basin (Subbasin 01)

- Make sense ecologically (flow of resources)
- But, they often cross political & jurisdictional boundaries

Characterizing drainage areas

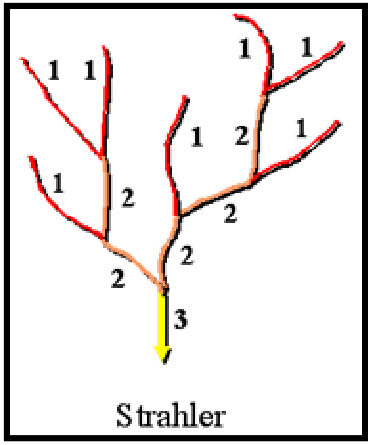
Upstream area & composition

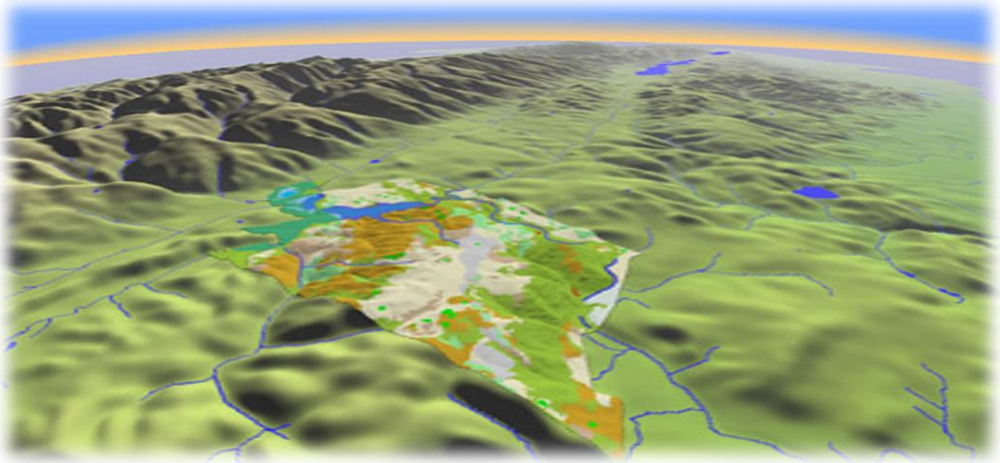
- Area & proportion of a contaminant
- Breakdown of catchment into cover types



Drainage patterns

- Stream channels/stream order
- Upstream accumulation





Determining drainage areas: The old way

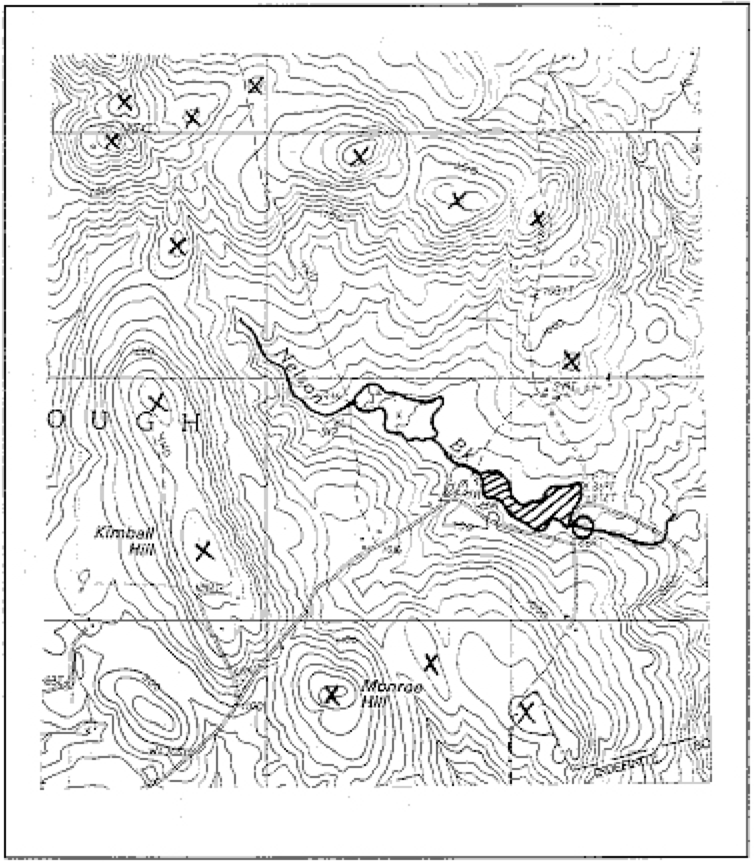


Figure E-4: Delineating a Watershed Boundary - Step 1

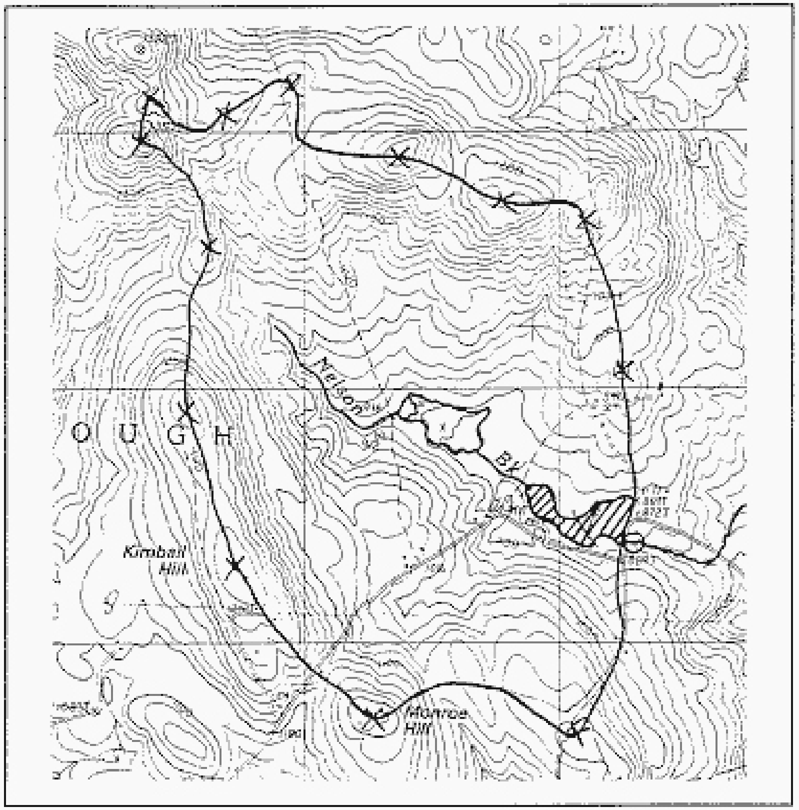
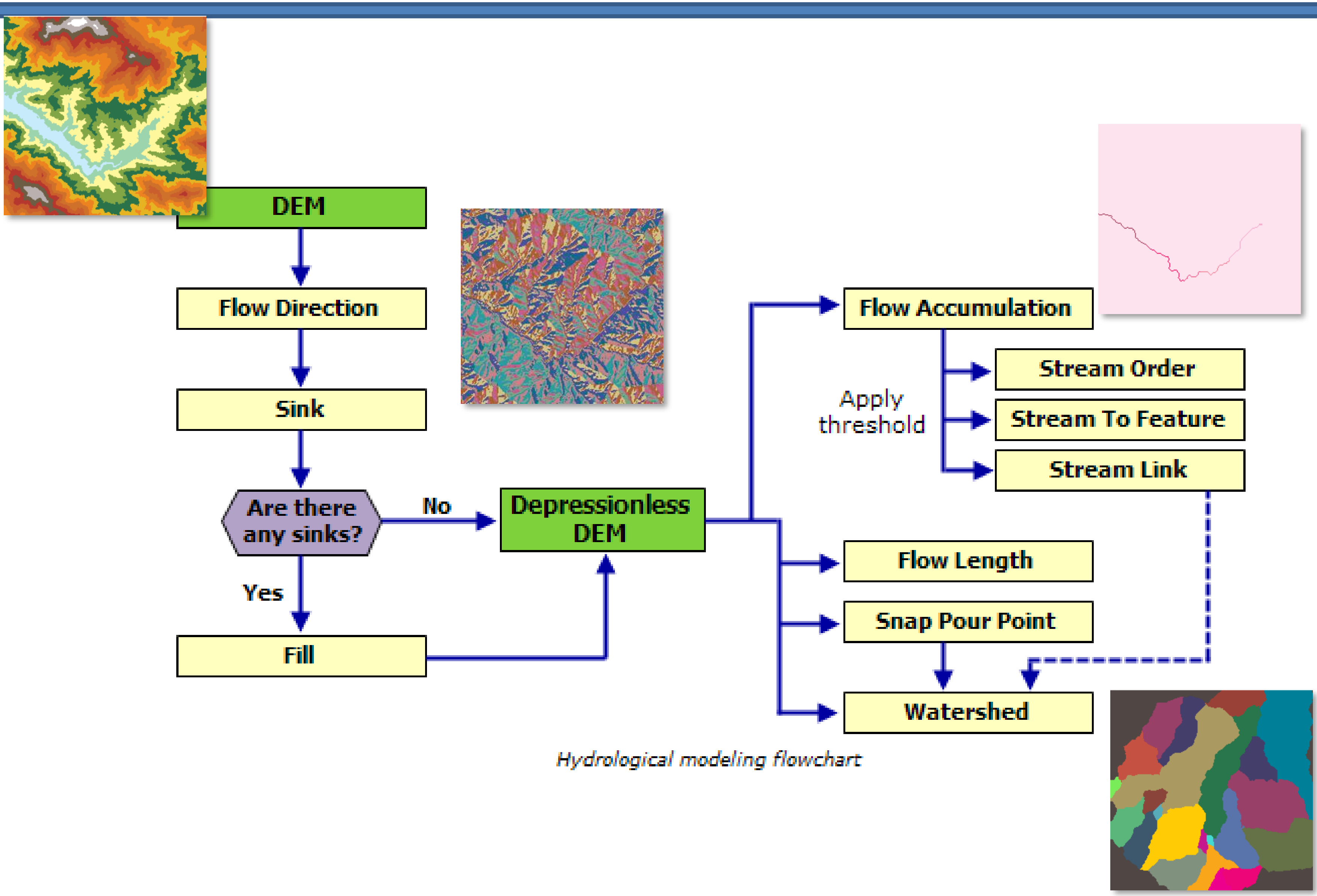


Figure E-5: Delineating a Watershed Boundary - Step 2

http://www.nh.nrcs.usda.gov/technical/WS_delineation.html

Determining drainage area: the new way



DEM

Flow Direction

Sink

Are there any sinks?

No

Yes

Fill

Depressionless DEM

Flow Accumulation

Apply threshold

Stream Order

Stream To Feature

Stream Link

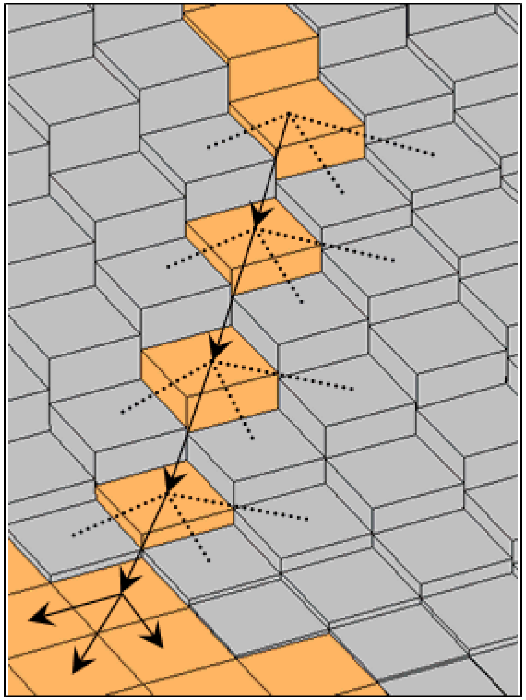
Flow Length

Snap Pour Point

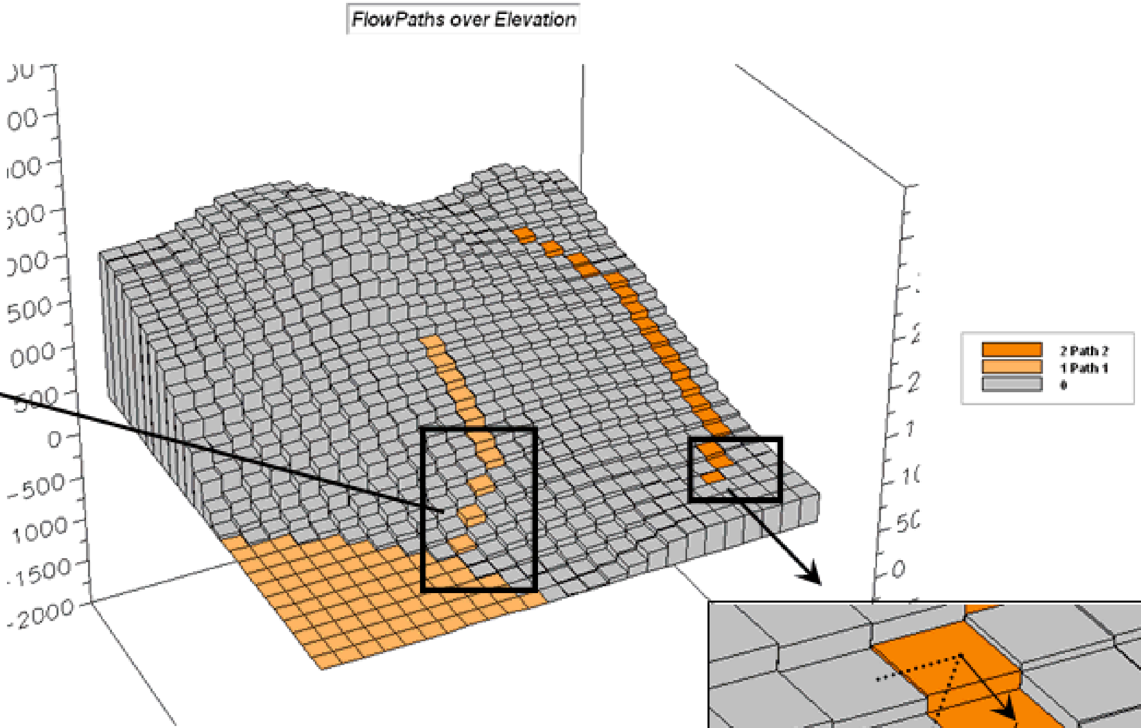
Watershed

Hydrological modeling flowchart

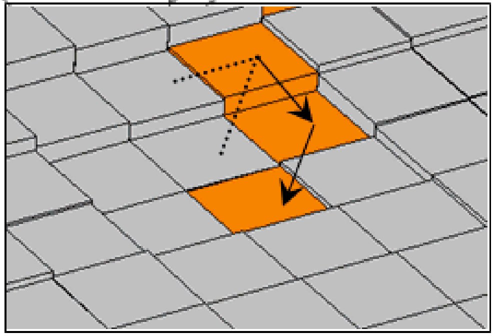
DEMs and Overland flow



Flat Areas



FlowPaths over Elevation



Depression Basin

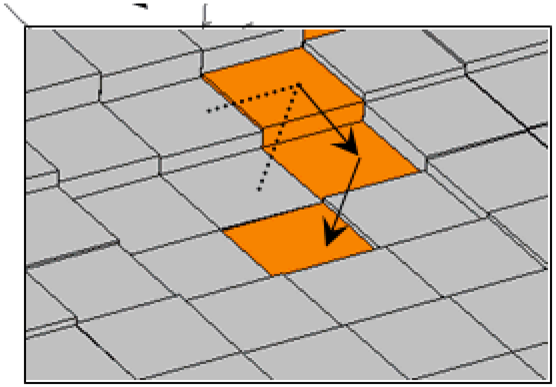
Overland flow moves downhill by the steepest path…

- *Spreads out across flat areas (cells of equal elevation)*
- *Stops in a depression (all surrounding cells greater)*

Tarboton (1997)

Sinks in a DEM

Sinks create havoc in calculating hydrologic flow

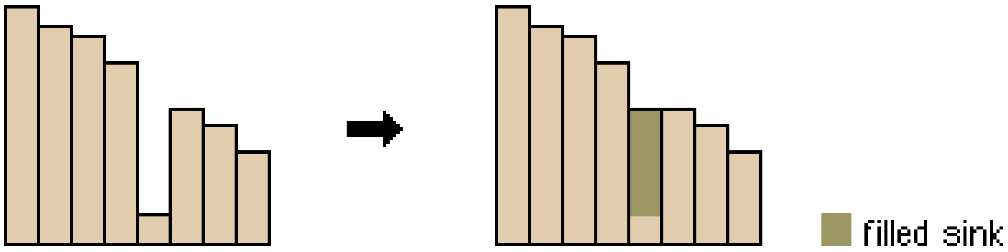


Depression Basin

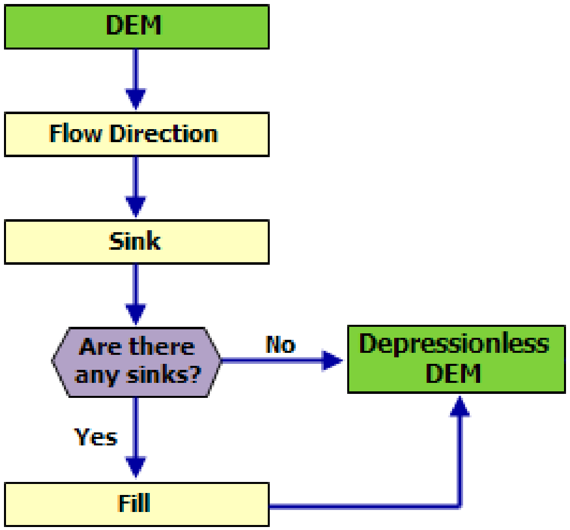
- Sinks are often errors due to the resolution of the data or rounding of elevations to the nearest integer value.
- 0.9 to 4.7% of the cells in a DEM are sinks. The mean adjustment of these sinks ranged from 2.6 to 4.8 m.
- This means that for a 1,000 by 1,000 cell grid (1 million cells), there may be 9,000 to 47,000 sinks to be filled.

Tarboton, et al (1991)

Creating a 'depressionless' DEM



Profile view of a sink before and after running Fill


DEM

Flow Direction

Sink

Are there any sinks?

No

Depressionless DEM

Yes

Fill

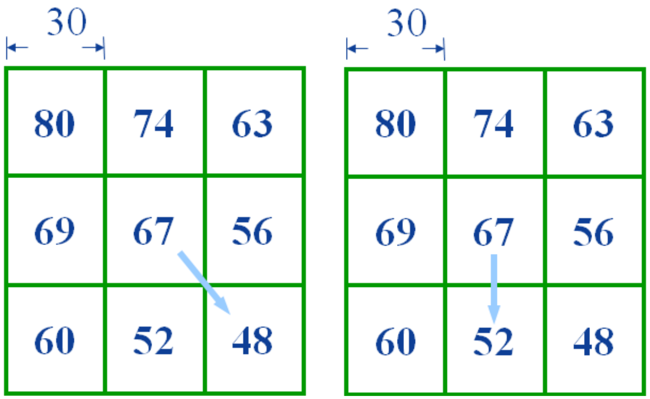
1. Identify sinks:
   - cells that are lower than all neighboring cells or
   - cells that flow into each other
2. Raise sinks to elevation of lowest neighbor
3. Repeat step 1 (in case raising sinks created new sinks)
4. Operation completes when no more sinks are found

Flow Direction

- Find neighboring cell with steepest drop…

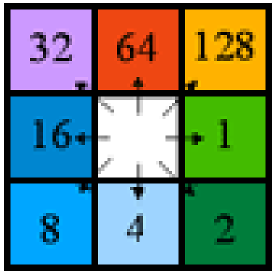
```
maximum_drop = change_in_z-value / distance * 100
```

- Assign a value representing that direction…



80	74	63
69	67	56
60	52	48

80	74	63
69	67	56
60	52	48

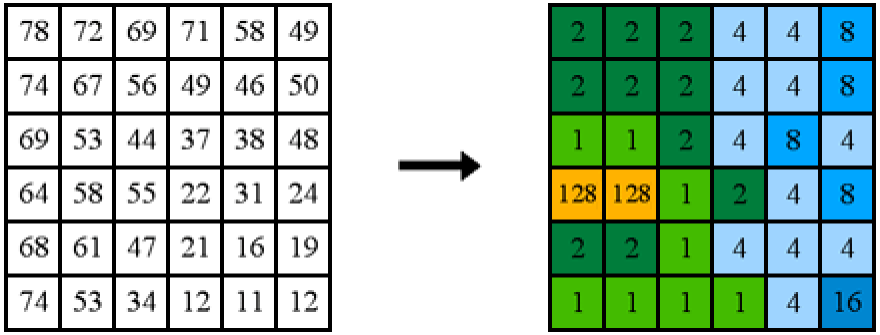


32	64	128
16		1
8	4	2

Direction coding

Any other value than these indicates an improperly filled DEM

Flow Direction



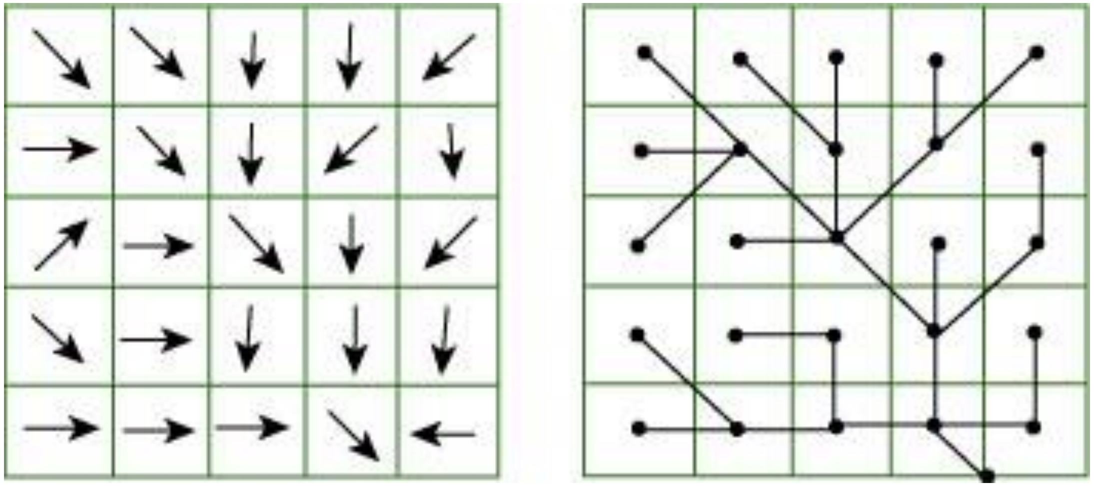
78	72	69	71	58	49
74	67	56	49	46	50
69	53	44	37	38	48
64	58	55	22	31	24
68	61	47	21	16	19
74	53	34	12	11	12

Elevation surface

2	2	2	4	4	8
2	2	2	4	4	8
1	1	2	4	8	4
128	128	1	2	4	8
2	2	1	4	4	4
1	1	1	1	4	16

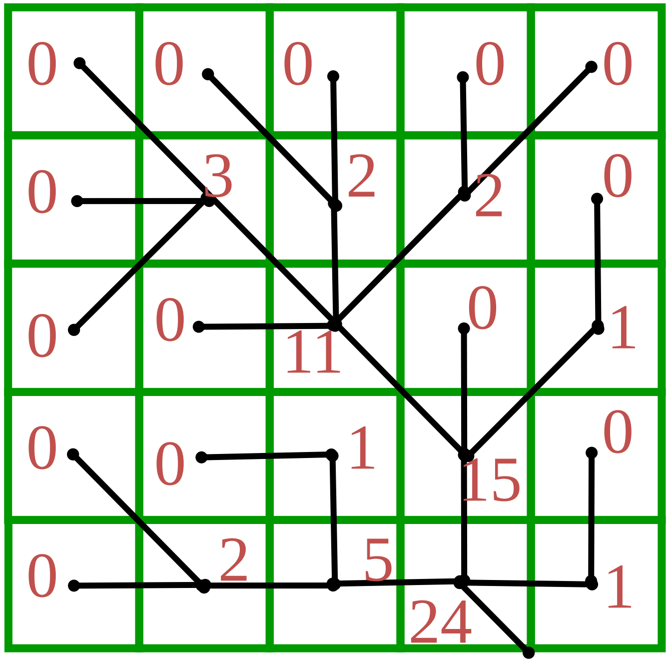
Flow direction

Once established, flow direction allows the creation of a hydrologic flow network



Flow Accumulation

- Calculates the total number of cells upstream of the given cell in the output raster. *(note: it doesn't count the cell itself!)*
- Determined via *network analysis* from the flow direction raster…

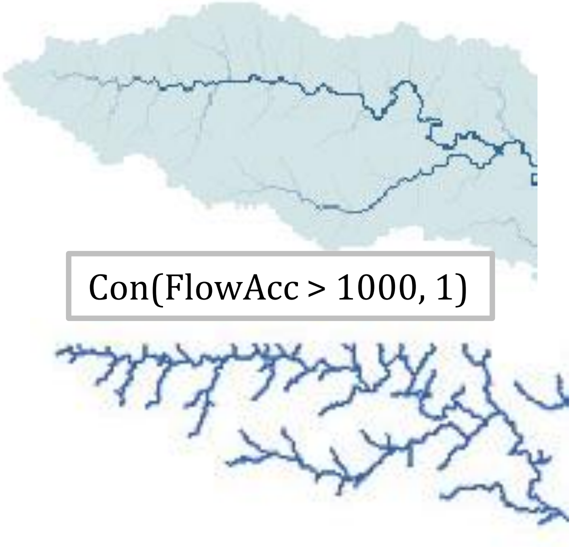


This cell has 3 others that drain into it

0	**0**	**0**	**0**	**0**
0	**3**	**2**	**2**	**0**
0	**0**	**11**	**0**	**1**
0	**0**	**1**	**15**	**0**
0	**2**	**5**	**24**	**1**

Identifying Stream Networks

- When surface runoff gets big enough, we call it a stream.
- "Big enough" can be interpreted as a *flow accumulation threshold*:

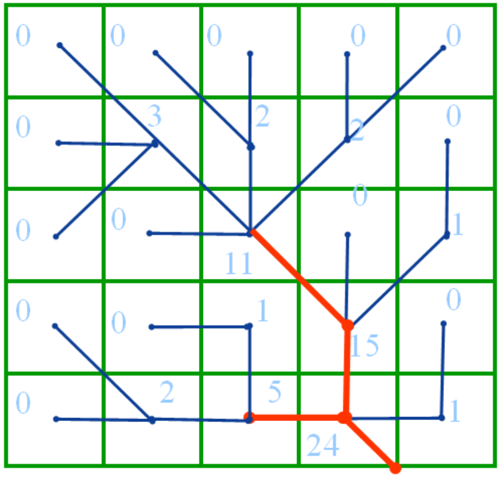


Con(FlowAcc > 1000, 1)

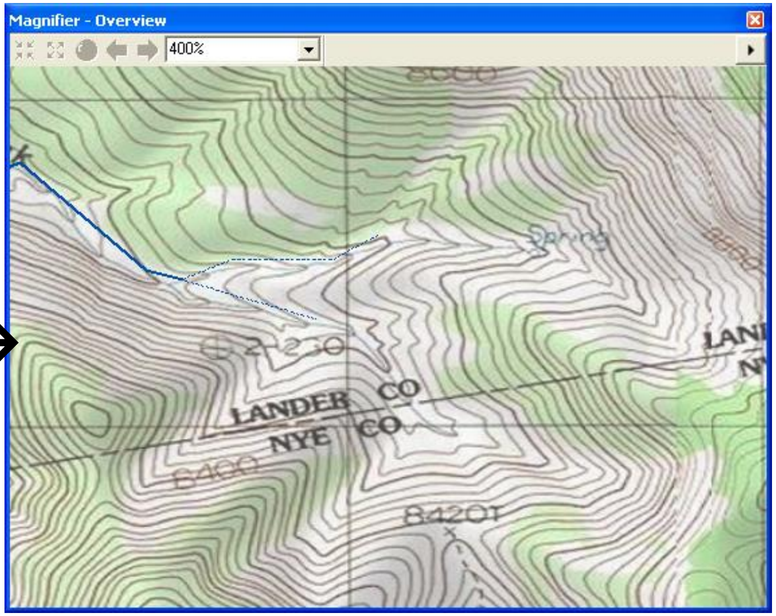
"All cells draining more than, say, 1000 upstream cells is likely to be a stream"

Flow Accumulation Thresholded Streams

- What threshold to use??
  No "correct" answer
  - Depends on DEM resolution
  - Depends on terrain

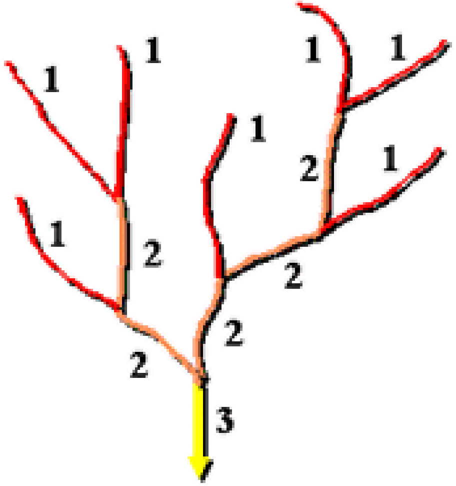


- Document & Validate your selection
  - Compare flow accum. streams to those on published maps →

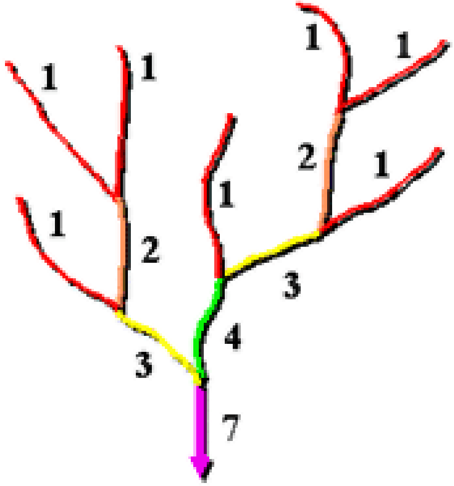


Stream Ordering

- Assigns a numeric order to streams
- Useful for classifying stream based on # tributaries
  - e.g., first order (smallest) streams dominated by overland flow and are more susceptible to non-point source



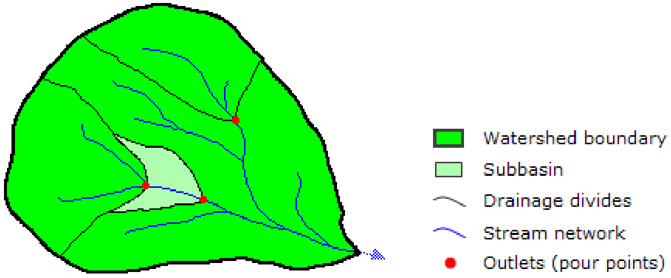
Strahler stream ordering method



Shreve stream ordering method

Delineating Watersheds

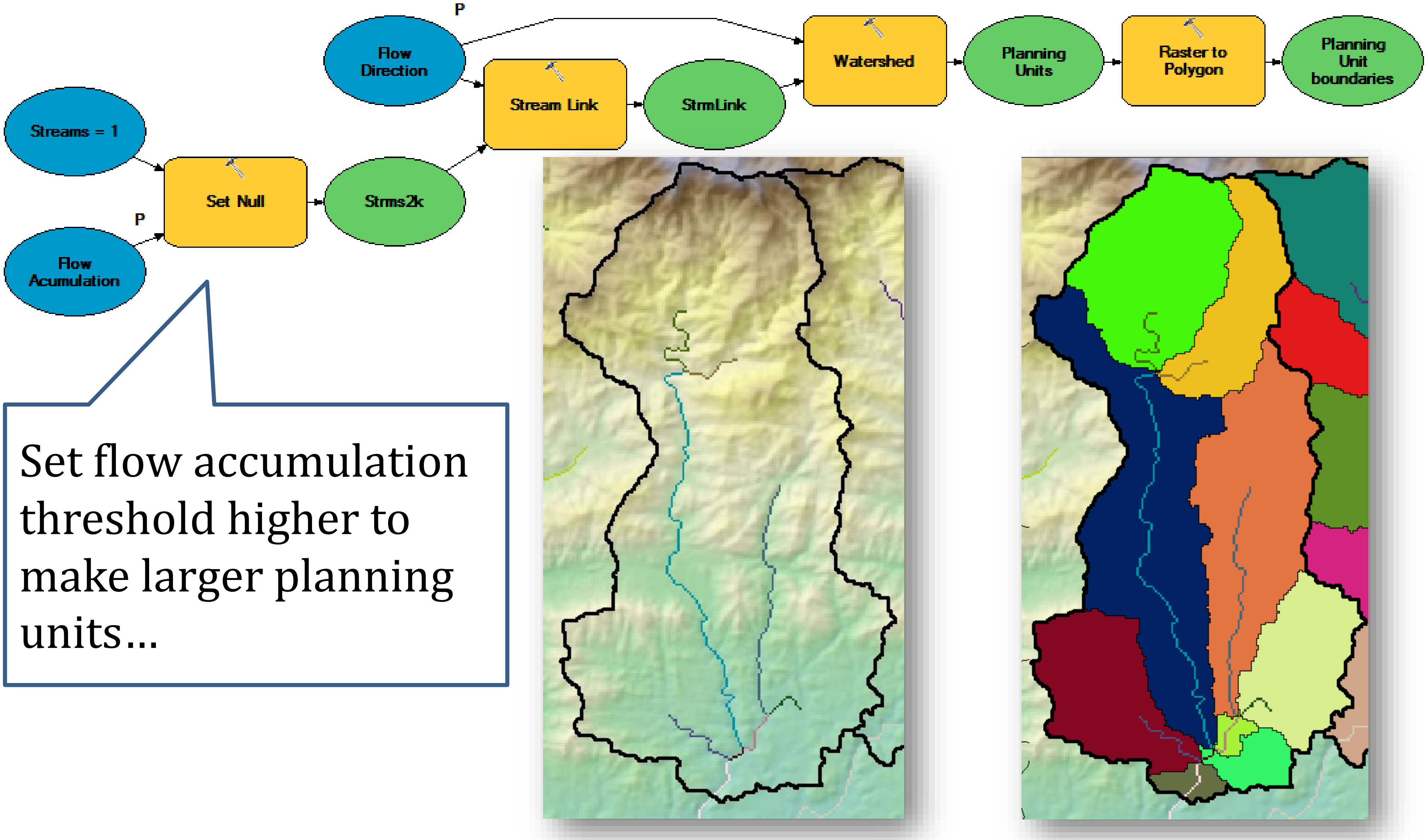
- Uses flow direction to identify cells upstream of a given pour point and assigns a unique value to those cells.



Watershed components

  - Does not nest watersheds; only goes to next pour point.
  - Pour points may need to be snapped to ensure that they fall on a stream cell, not near it.

Creating catchment-based planning units



Set flow accumulation threshold higher to make larger planning units…

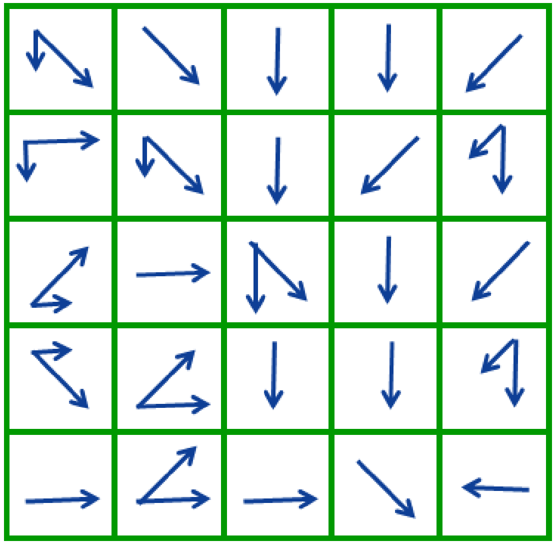
Alternative flow direction algorithms

"D8" - Eight directional flow direction

- All of a cells contents spill into the most downstream cell
- Simplifies things, but allows for a seamless hydro network

“MDF" – Multi Flow Direction (Qin et al., 2007)

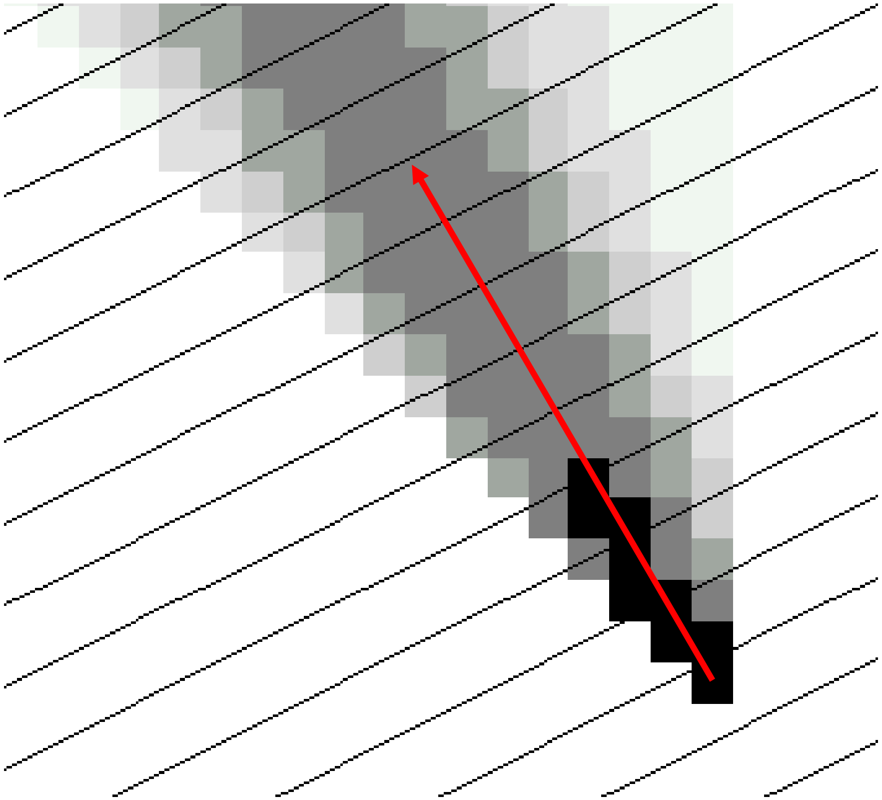
- Flow can go into multiple cells
- More realistic representation of surface flow, but modeling flow gets much more complicated
- Output is Cloud Raster Format; not easily analyzed in ArcGIS…



Alternative flow direction algorithms

"D∞" - Infinite directional flow direction (Tarboton 1997)

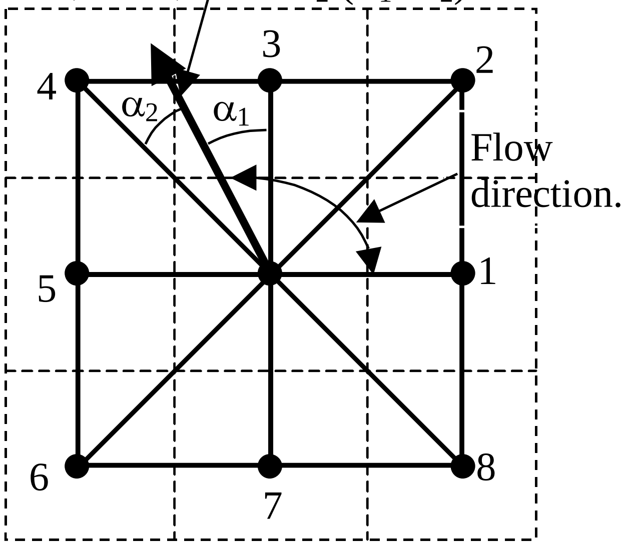
- Flow follow steepest descent, but not limited to 8 direction.
- Values are 0 -360° (where 0,360 are due east).



Proportion flowing to neighboring grid cell 4 is $\alpha_1/(\alpha_1+\alpha_2)$

Steepest direction downslope

Proportion flowing to neighboring grid cell 3 is $\alpha_2/(\alpha_1+\alpha_2)$



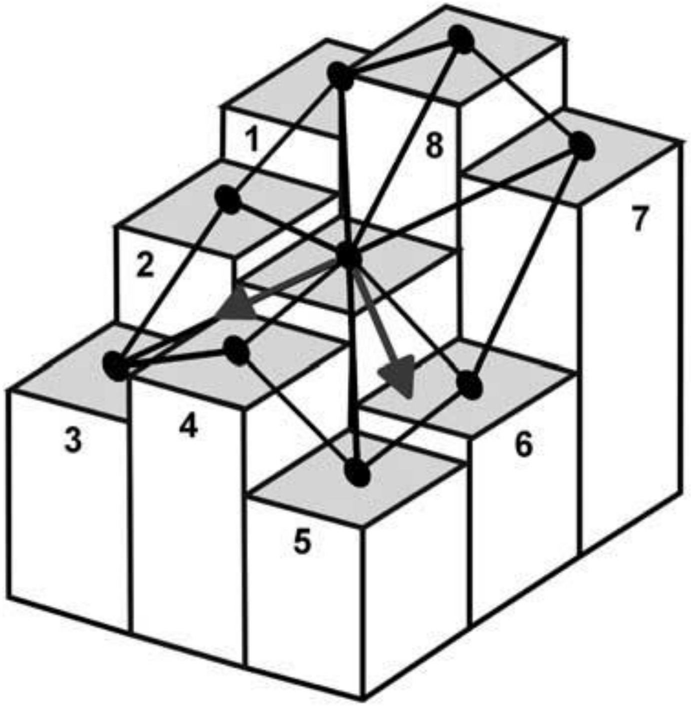
Flow direction.

The MD-∞ Algorithm

A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models

Jan Seibert[1] and Brian L. McGlynn[2]

WATER RESOURCES RESEARCH, VOL. 43



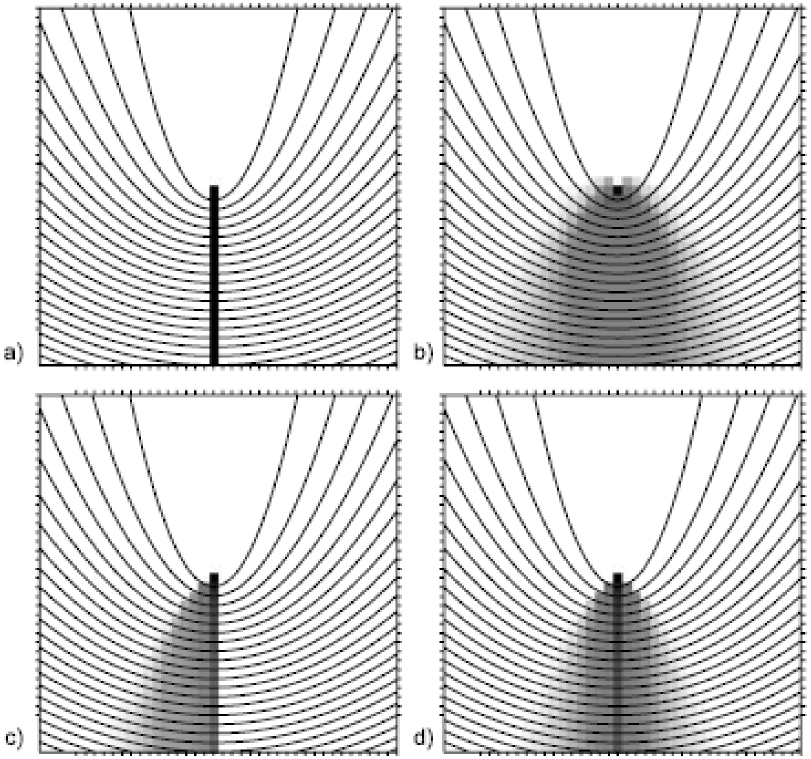
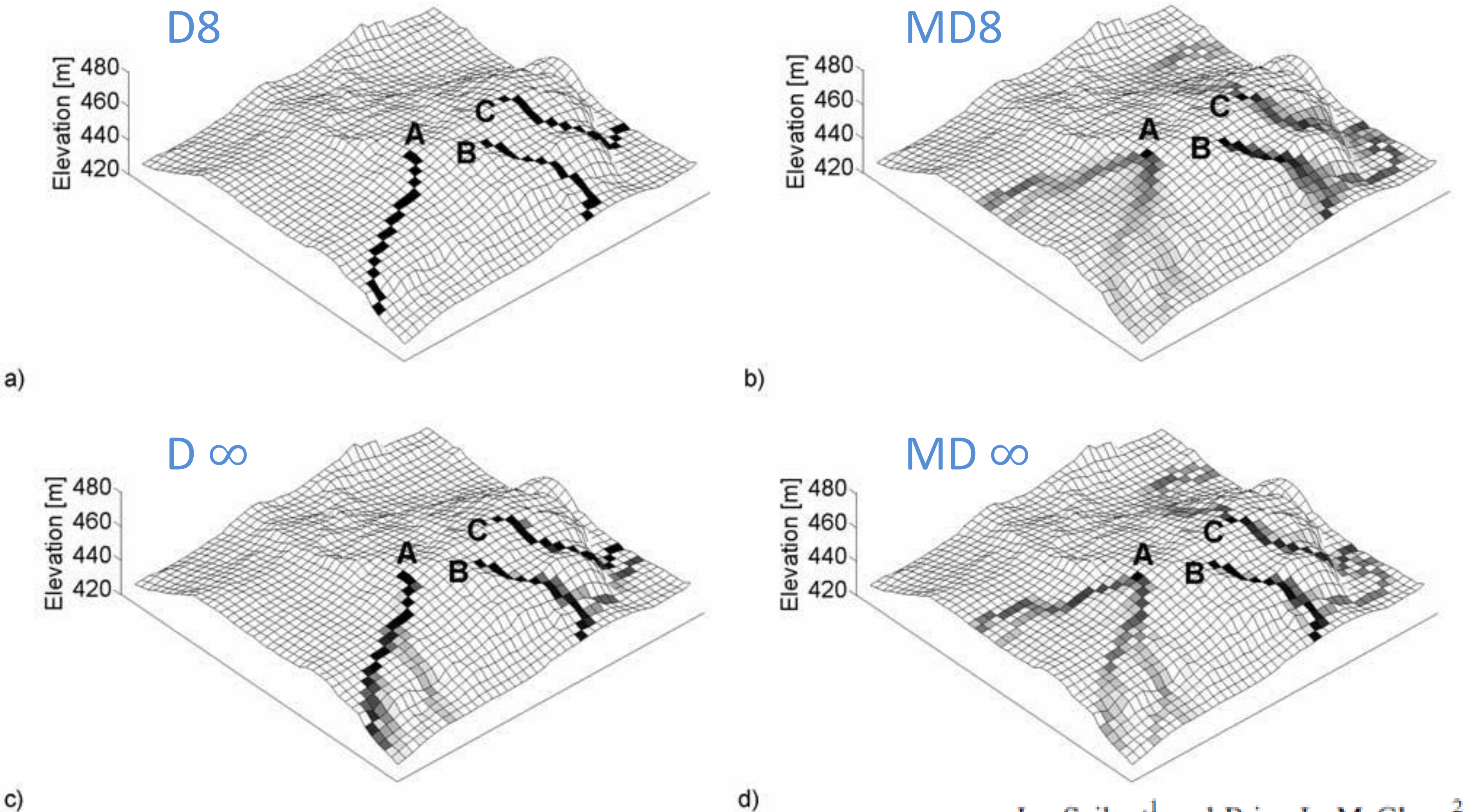


Figure 4. Downslope pattern of area distributed from one cell on a divergent hillslope (synthetic data) for the different algorithms: (a) D8, (b) MD8, (c) D∞, and (d) MD∞. The portions vary from 0 (white) to 1 (black).

Comparing Algorithms



D8

MD8

D ∞

MD ∞

Jan Seibert[1] and Brian L. McGlynn[2]

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D-8 vs. D-∞

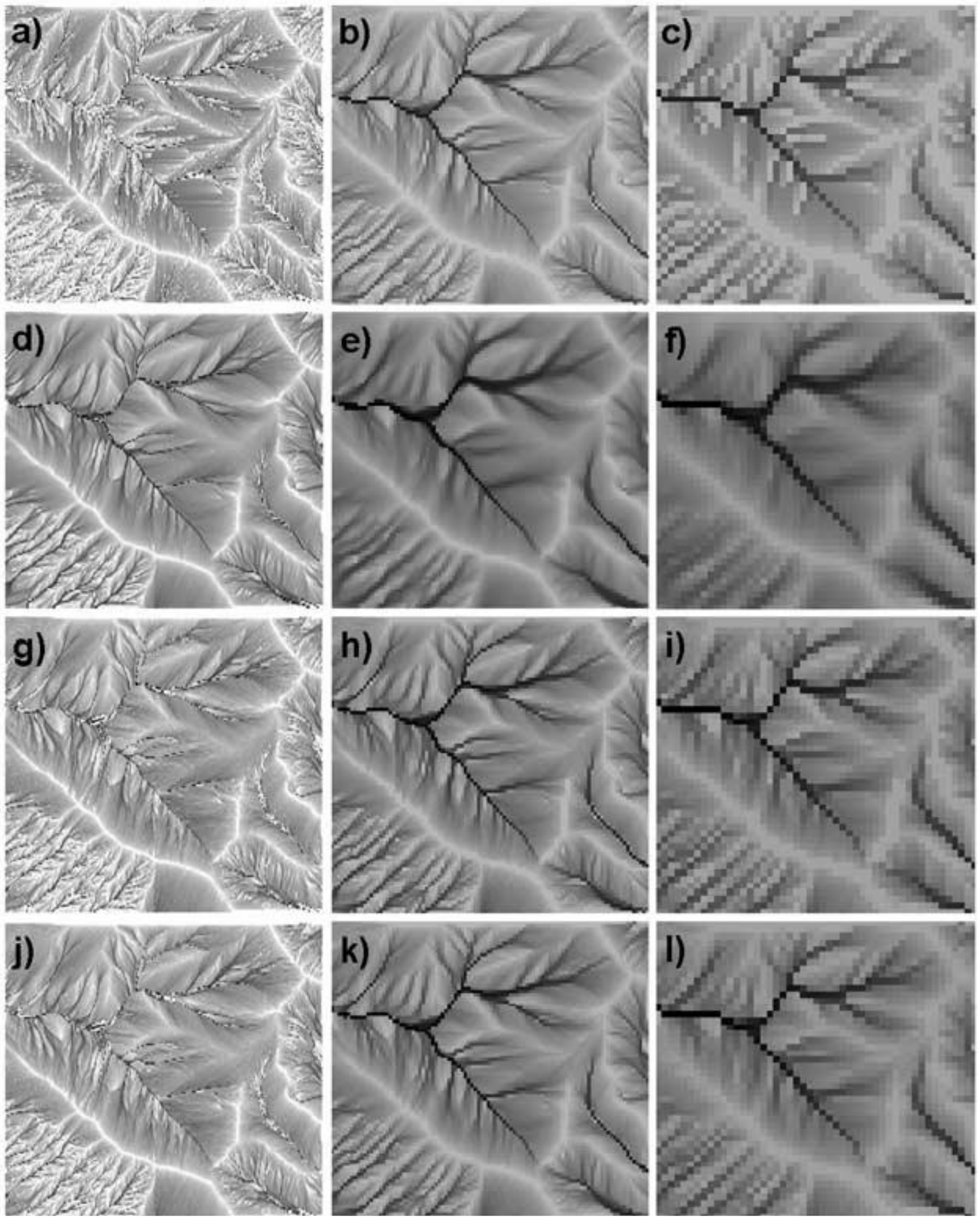
10 m 20 m 30 m

D8

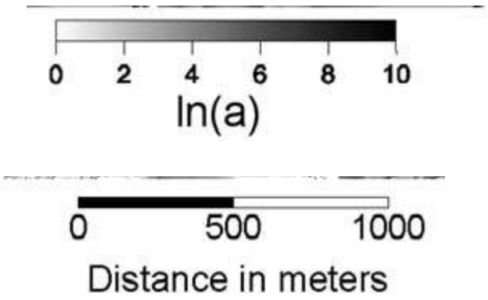
MD8

D-∞

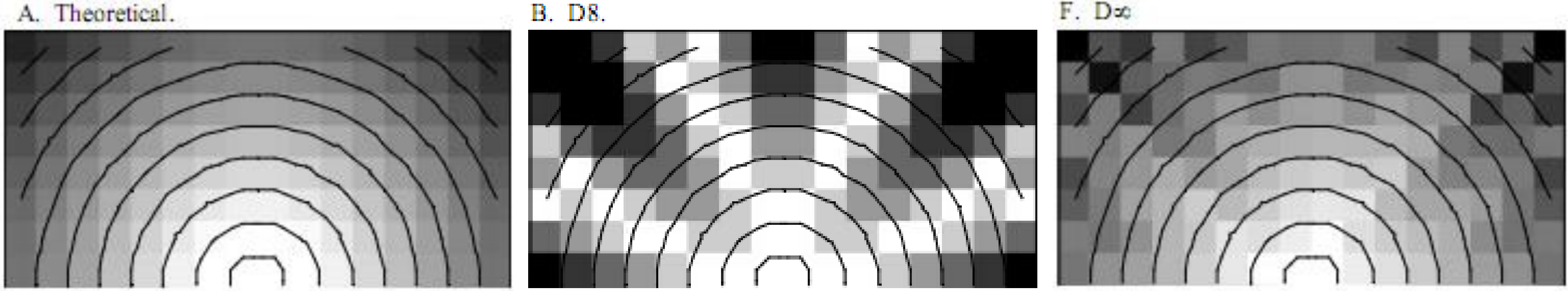
MD-∞



Flow accumulation



D-8 vs. D-∞: Flow Accumulation



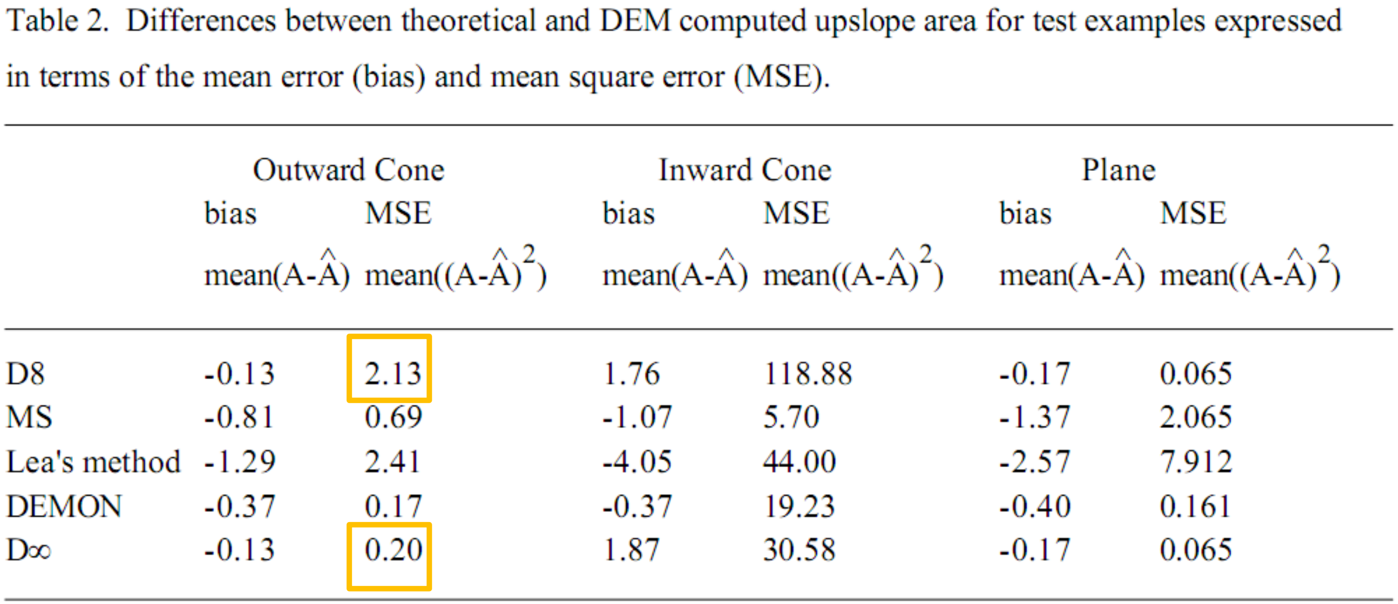
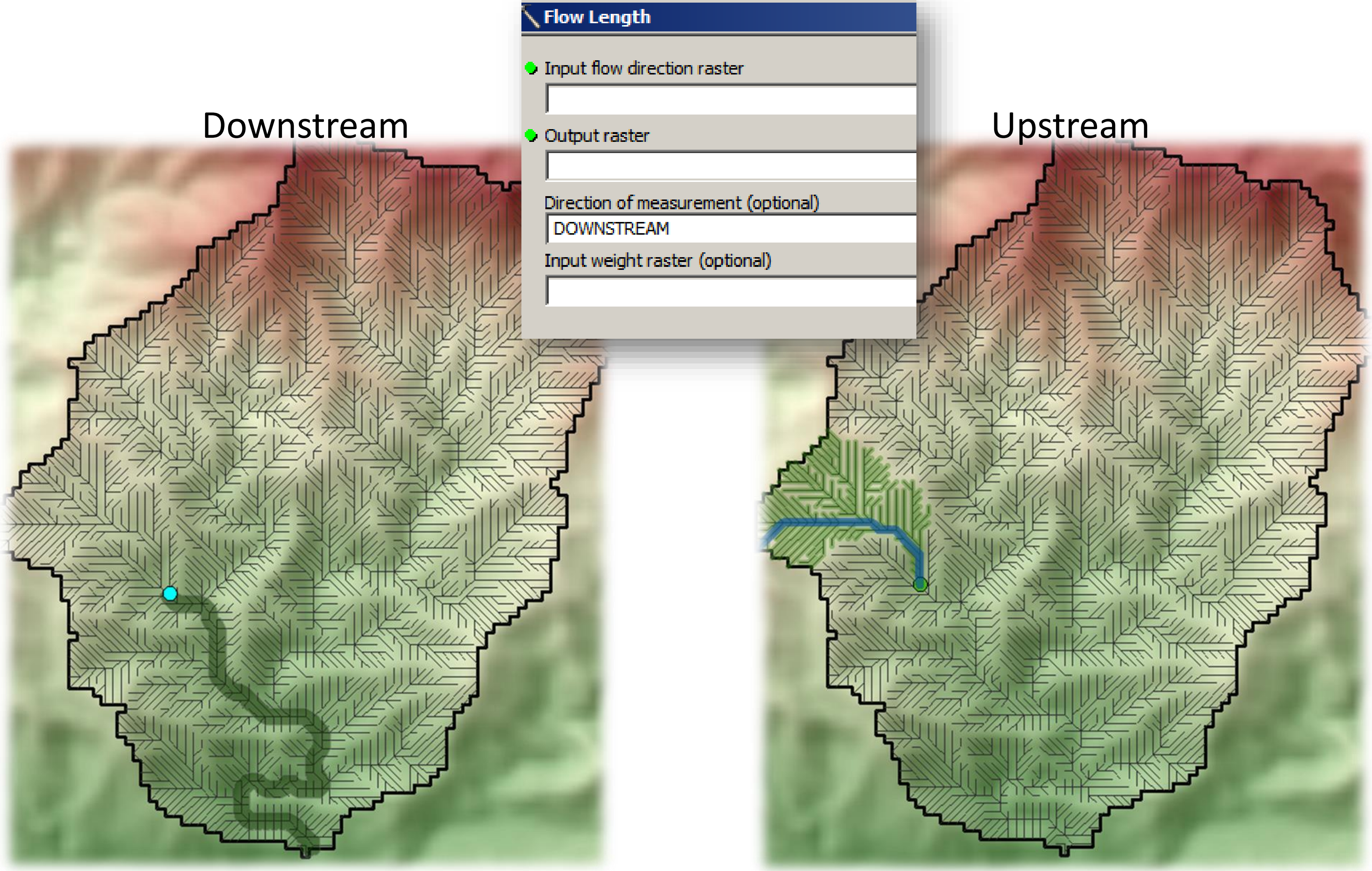


Table 2. Differences between theoretical and DEM computed upslope area for test examples expressed in terms of the mean error (bias) and mean square error (MSE).

	Outward Cone		Inward Cone		Plane	
	bias	MSE	bias	MSE	bias	MSE
	$\mathrm{mean}(A-\hat{A})$	$\mathrm{mean}((A-\hat{A})^2)$	$\mathrm{mean}(A-\hat{A})$	$\mathrm{mean}((A-\hat{A})^2)$	$\mathrm{mean}(A-\hat{A})$	$\mathrm{mean}((A-\hat{A})^2)$
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 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

http://www.neng.usu.edu/cee/faculty/dtarb/dinf.pdf

Flow Length



Downstream

Upstream

Flow Length

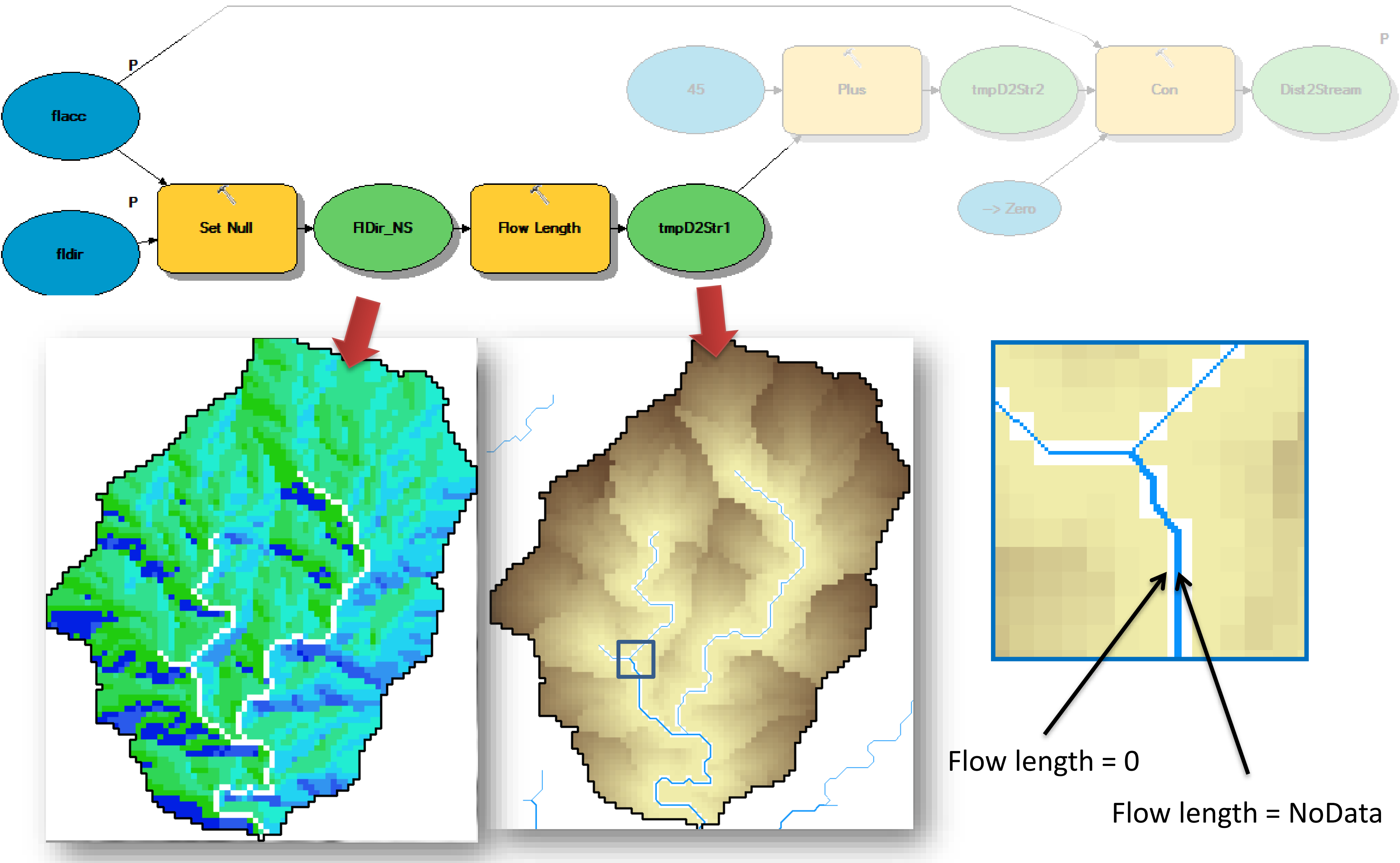
● Input flow direction raster

● Output raster

Direction of measurement (optional): DOWNSTREAM

Input weight raster (optional)

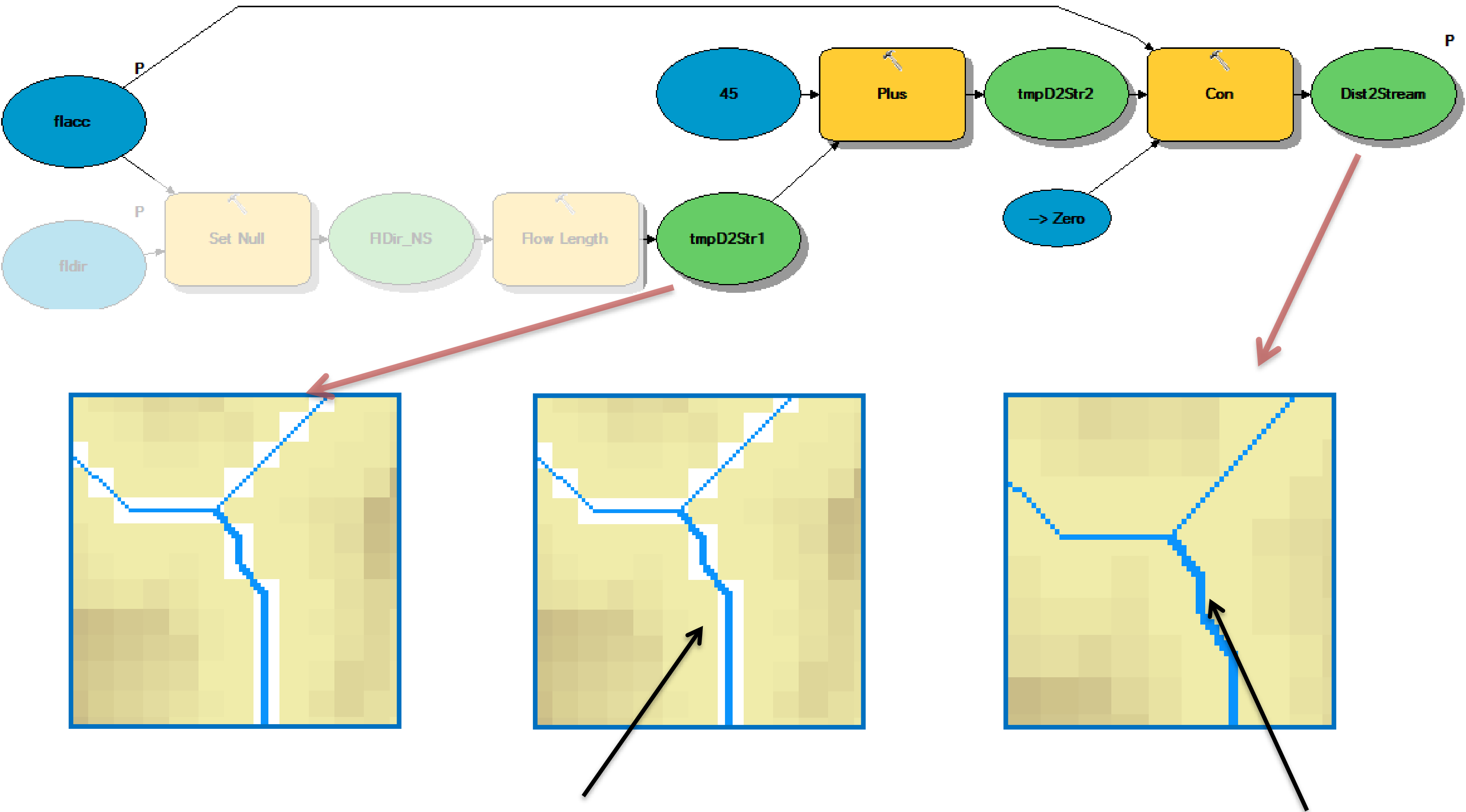
Flow Length (downstream)



Flow length = 0

Flow length = NoData

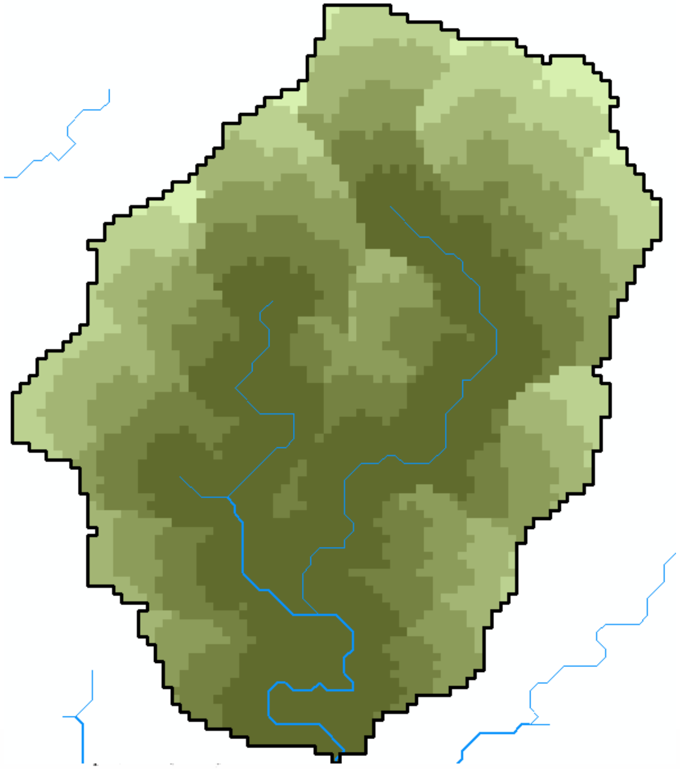
Flow Length (downstream)

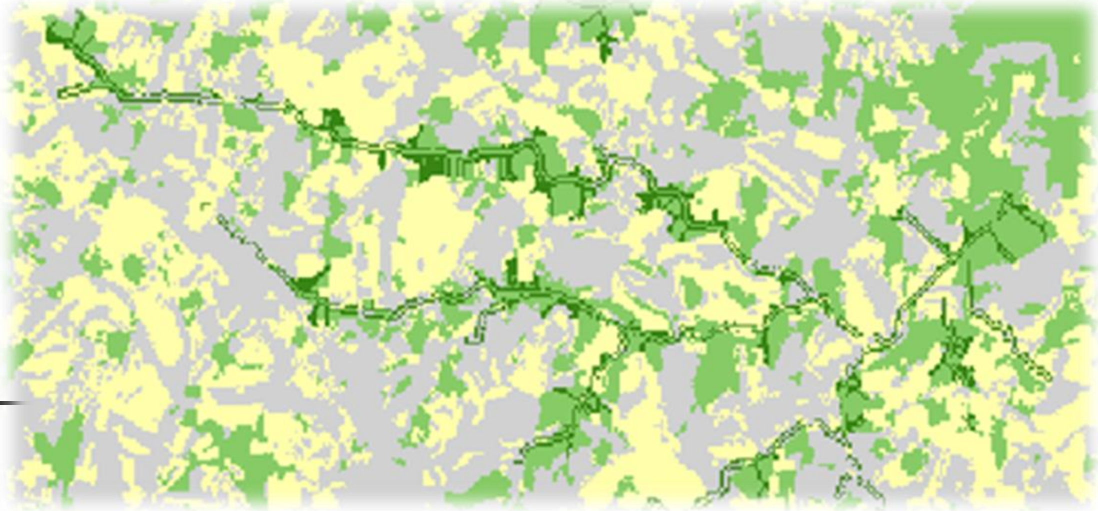


Flow length = 45
(1/2 cell length)

Flow length = 0

Riparian Areas





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RESEARCH ARTICLE

Improved methods for quantifying potential nutrient interception by riparian buffers

Matthew E. Baker · Donald E. Weller ·
Thomas E. Jordan

Other topics

- Weighted flow accumulation
- Weighted flow length
- Stream burning

- NHD+ dataset:
  http://www.horizon-systems.com/nhdplus/
- ArcHydro:
  http://resources.arcgis.com/en/communities/hydro/01vn0000000s000000.htm
- Whitebox:
  http://www.uoguelph.ca/~hydrogeo/Whitebox/

Ecohydrology: Summary

- Ecohydrology: couples hydrology + ecology
  - Catchment a useful ecological unit

- DEMs & Ecohydrology:
  - DEMs are all you need to roughly approximate:
    1. Drainage area
    2. Accumulated flow (and materials)
    3. Stream courses & stream order