Surface Hydrological Modeling and Applications

Overview

- Background
- Important datasets
- Concepts
- Analysis tools

Why Watershed Analysis with GIS?

- Watershed analysis is a spatial issue
- Used to analyze regional stressors

Regional stressors

1. Stream sedimentation
2. Habitat loss
3. Forest fragmentation
4. Acid mine drainage
5. Acid rain
6. Flooding
7. Invasive and non-native species

Impacts of human activities

Timber

Mining

Agriculture

Stream alterations

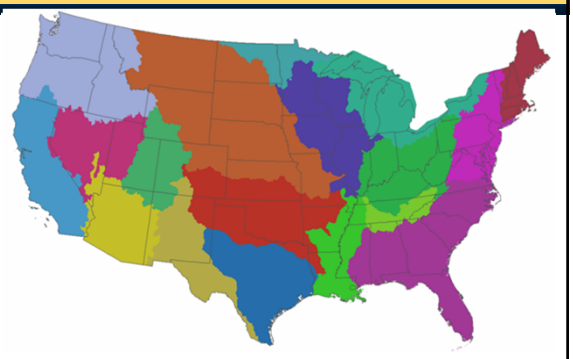
Watershed based frameworks

- Integrative approach
- Legislative roots in the 1972 Clean Water Act

  Goal to clean up and protect US water bodies from point and nonpoint sources

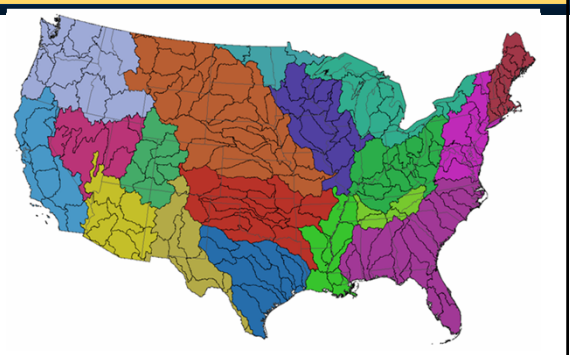
Designated uses – evaluated as part of the Clean Water Act

Watershed cataloging units



USGS Regions (2 digit)

Watershed cataloging units



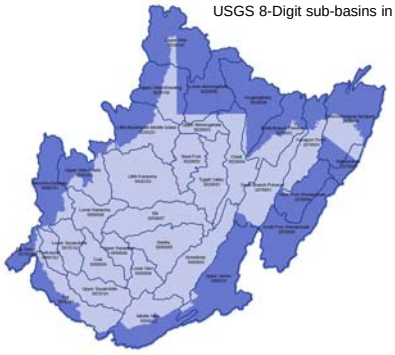
USGS Sub-regions (4 digit)

Watershed cataloging units

USGS Sub-basins (8 digit)

Statewide example

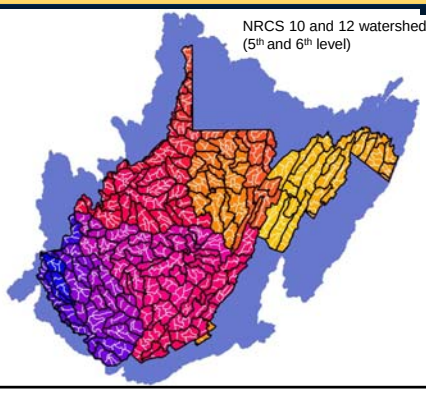
USGS 8-Digit sub-basins in WV



n=33

Statewide example

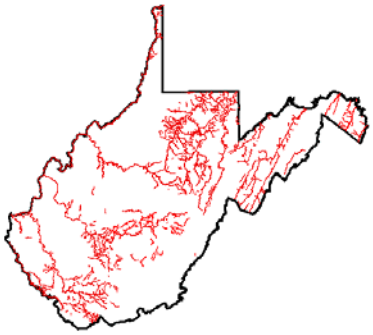
NRCS 10 and 12 watersheds in WV
(5th and 6th level)



n=342
n=745

Watersheds allow us to examine issues

- Streams not meeting designated uses



Cold water fishery

Warm water fishery

Safe for water contact recreation

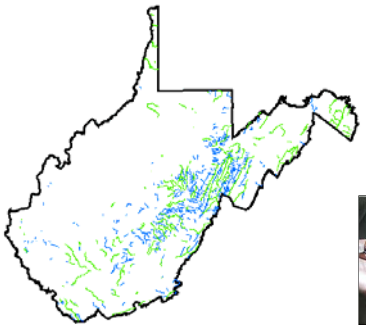
Public water use

Agricultural use

Industrial water use

Protect water resources

- High quality streams

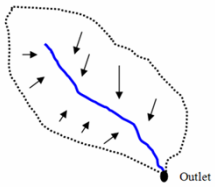


DNR Stocked streams

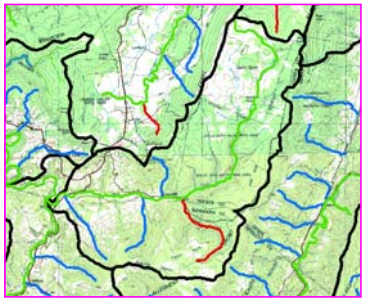
Tier 2.5 - Reproducing trout streams

Issues

- More local watersheds needed
- One to one relationship between land cover runoff and receiving stream segment
- Track runoff from land to stream



Example of scale differences



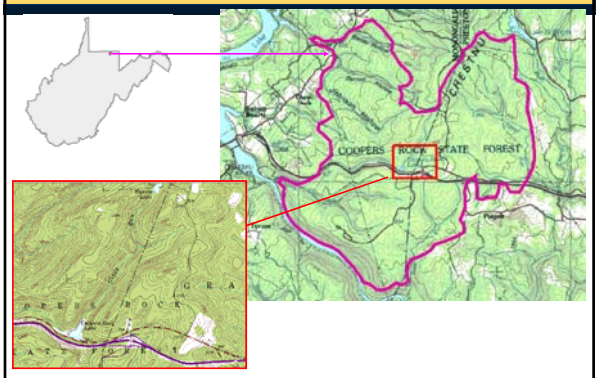
DNR Stocked streams

Tier 2.5 - Reproducing trout streams

Impaired streams

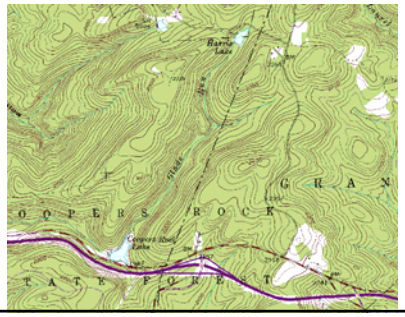
Watershed boundaries

Example study area

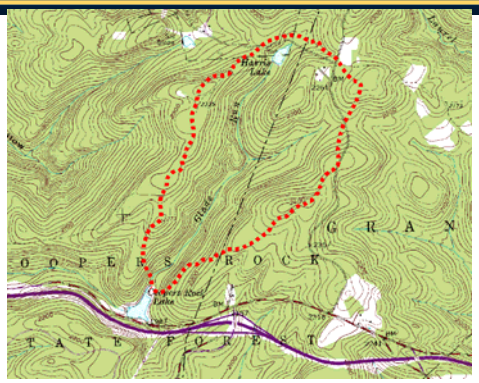


Previous method

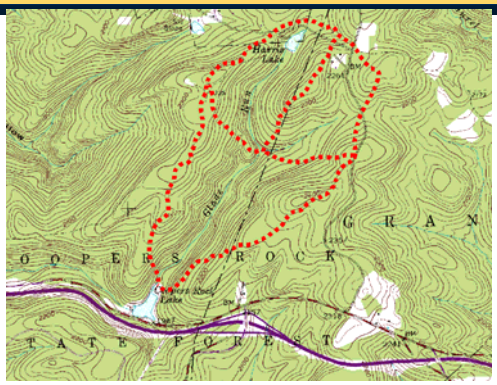
- Delineate watershed boundaries using the topography to guide us



Manual method



subwatersheds



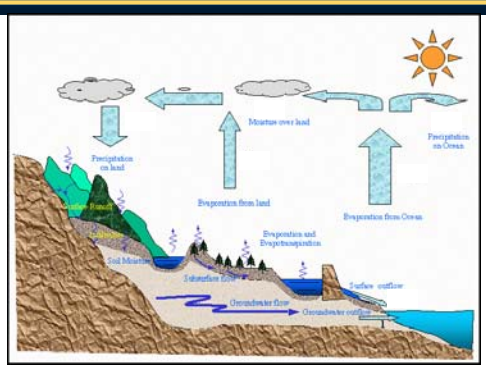
GIS and water resources

- Geographic information systems (GIS) is a valuable tool in water resources management

GIS in watershed management:

- **Elevation surface is key**
- **Delineate watersheds**
- **Track flow from a point**
- **Find intermittent stream paths**
- **Calculate drainage areas**

GIS use in the hydro cycle



Hydrology

- Water balance equation

$$R = P - ET - F - IG - S$$

where:

P	=	Precipitation
R	=	Runoff
ET	=	Evapotranspiration
F	=	Infiltration
IG	=	Groundwater
S	=	Depression Storage

- Inter-relationships between components
- Variation of components with time

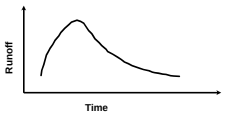
  consideration of soil condition, cover, antecedent conditions, land practices

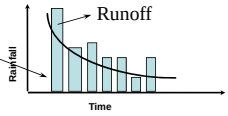
Surface hydrology

- Determine where the water came from and where it is going
- Describe the behavior of water as it moves over the surface of the earth
- Analysis starts with the creation of a hydrologically correct surface (no sinks or peaks interrupting drainage direction)
- Include the entire drainage

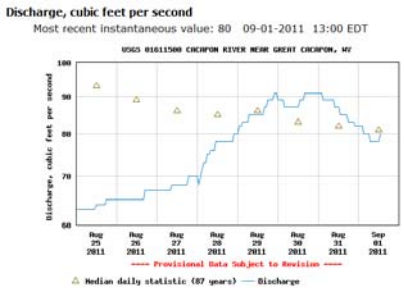
Surface hydrology

- Rainfall - runoff relationships
- Runoff - above curve
- Losses - below curve
  - interception
  - depression storage
  - evapotranspiration
  - infiltration

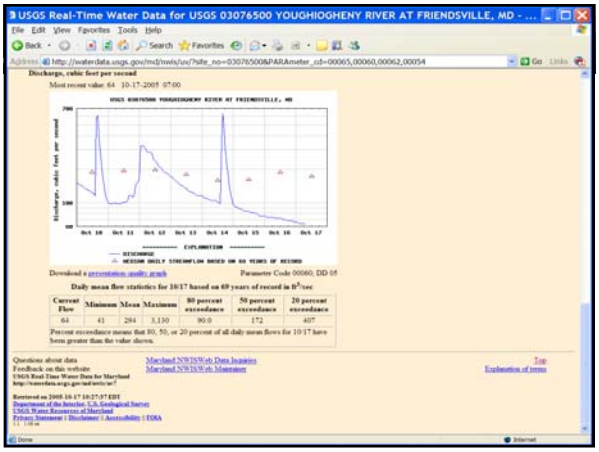




Runoff curve from gauge



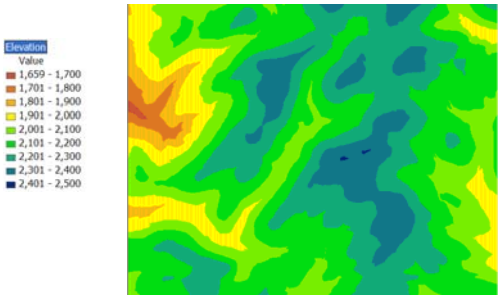
Source: http://waterdata.usgs.gov/nwis



GIS and surface hydrological modeling

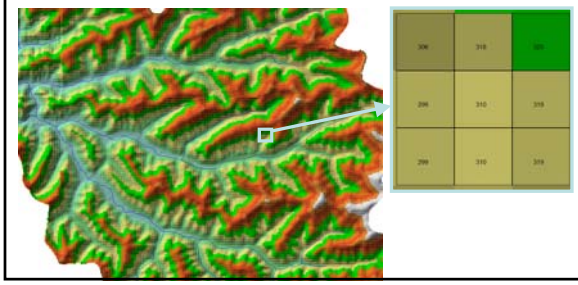
- Attempts to explain the hydrological cycle (best suited for surface runoff)
- Tools are available in GIS to measure, quantify and display surface runoff
- Watershed based (must consider the entire drainage to effectively model interactions)
- Begins with an elevation surface

Elevation surface

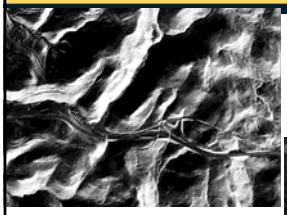


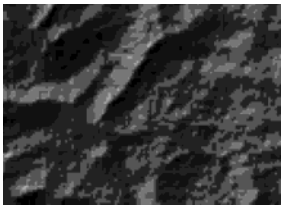
Elevation surface or grid

- The starting point for all hydrological modeling in GIS
- USGS Digital elevation model 30m or 10m elevation cells
- Each cell or grid represents a value for the elevation



10m to 30m DEM comparison





National 10m seamless DEMs

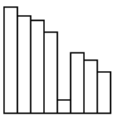
Helpful ArcGIS commands

If you have a *.dem file

To combine dems

Sinks

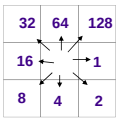
- Depressions in the DEM where water gets trapped
- A sink prohibits calculating future flow direction grid values.
- A sink occurs when all neighboring cells are higher than the processing cell.
- Sometimes they are natural features!



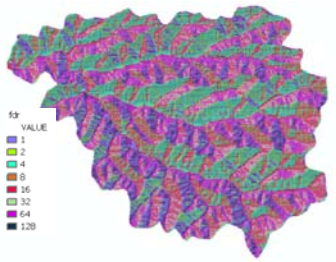
Profile view of a sink

Flow direction

- Created from an elevation surface
- Direction values are assigned
- Flow direction grids are used in many hydro GIS functions



Flow direction map



Flow direction

- Created from an elevation surface
- Direction values are assigned
- Flow direction grids are used in the other flow functions

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

=

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

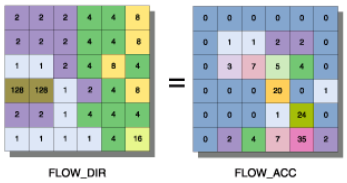
FLOW_DIR

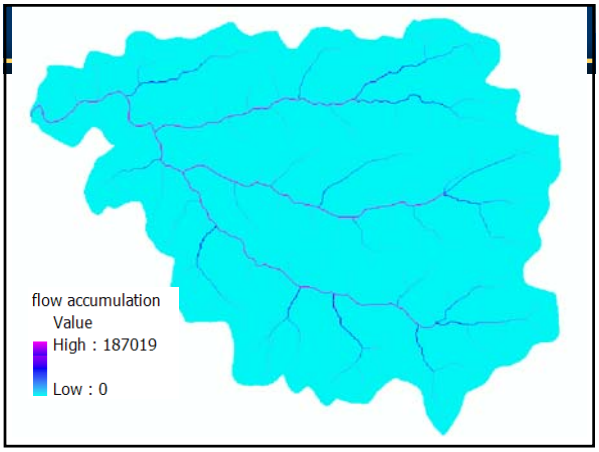
Flow accumulation

- Created from a flow direction grid
- Accumulates all uphill water into each cell
- Cells with high flow accumulation area are areas of concentrated flow
- Output cells with a flow accumulation of 0 may be used to identify ridges or watershed boundaries.

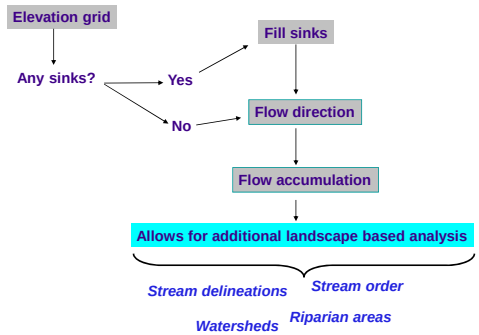
Flow accumulation

- The accumulated flow is based upon the number of cells flowing into each cell in the output grid. The current processing cell is not considered in this accumulation.



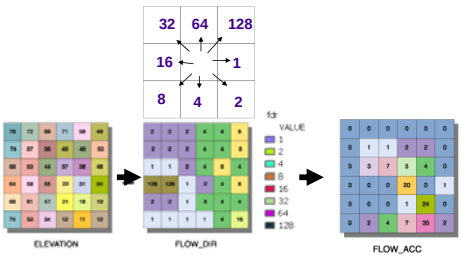


Summary of spatial techniques and tools available within a GIS

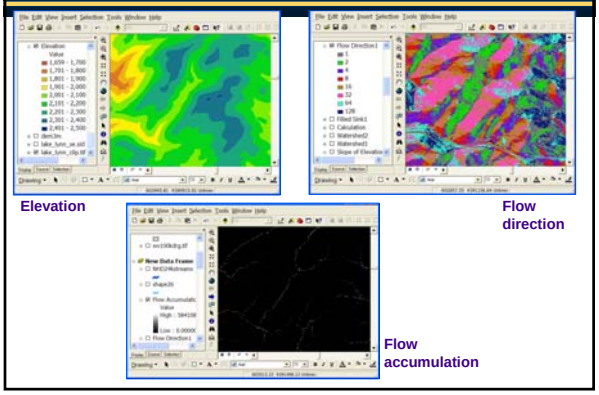


Automated watershed delineations

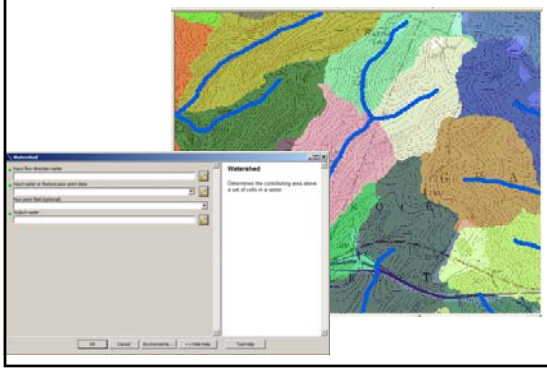
- Requires a flow direction grid and flow accumulation grid which are derived from elevation



GIS data needed for hydro work



Watershed delineation

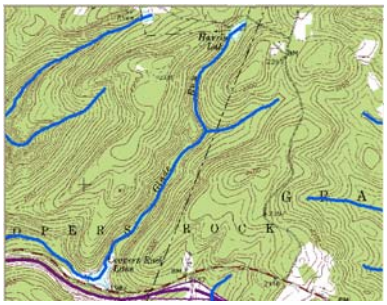


Find intermittent stream paths

Mapped streams from the 1:24,000 topomap

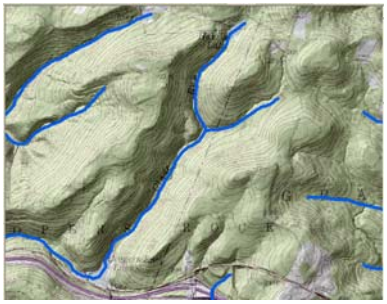
Find intermittent stream paths

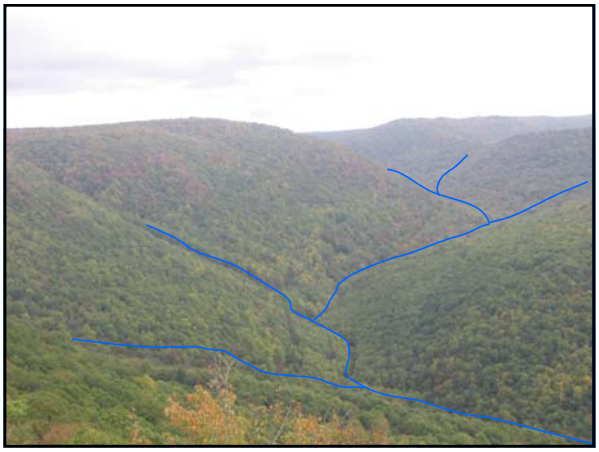
Mapped streams from the 1:24,000 topomap



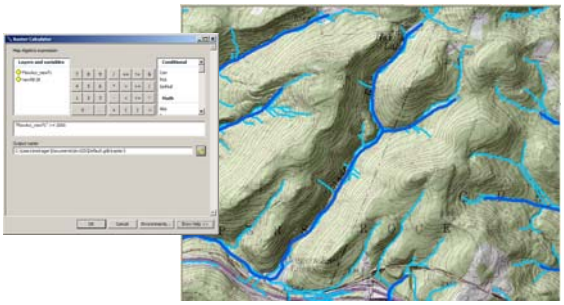
Find intermittent stream paths

Intermittent, debris slides, accumulators, path of easiest descent exist





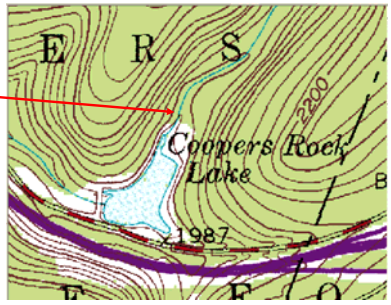
Find intermittent stream paths



Calculate drainage area

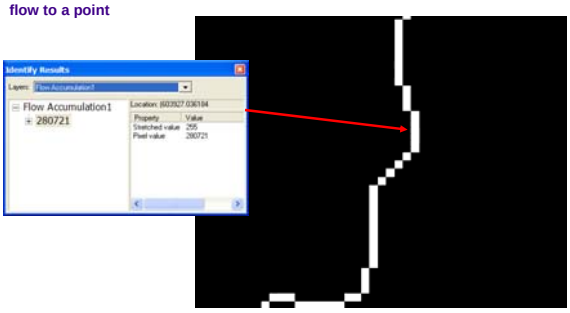
Flow accumulation grid = tells us the number of cells of a certain area that flow to a point

Drainage area?



Calculate drainage area

Flow accumulation grid = tells us the number of cells of a certain area that flow to a point



Calculate drainage area

So, if there are 280,721 cells that flow to that location…

and each cell is 3m by 3m in size (9sq meters)

Then

The total drainage area is (280,721) * (9) = 2,526,489 sq meters

Or

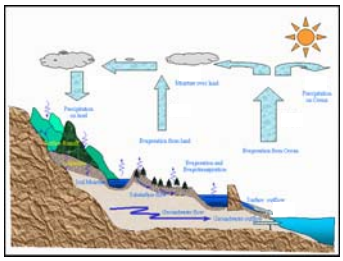
2,526,489 sq meters * 0.00024718 = 624 acres

Summary points

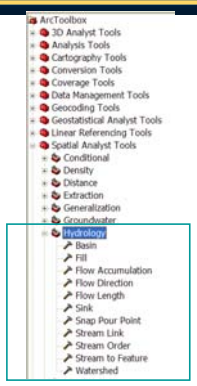
- Watersheds are the key unit of analysis for examining water quality issues
- Scale issues require us to delineate smaller watersheds for local issues
- GIS can aid in watershed management by
  - Using elevation grids
  - Delineate watersheds
  - Track flow from a point
  - Find intermittent stream paths
  - Calculate drainage areas

Limitations

- Static snapshot of data
- Older Elevation grids
- Only modeling surface interactions

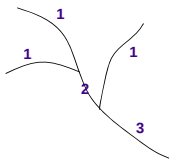


In ArcToolbox

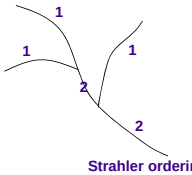


Stream order

- Assigns a numeric order to stream segments
- Classifies streams based on the number of tributaries
- Requires a flow direction grid and that streams be represented as rasters
- Uses either Shreve or Strahler ordering methods

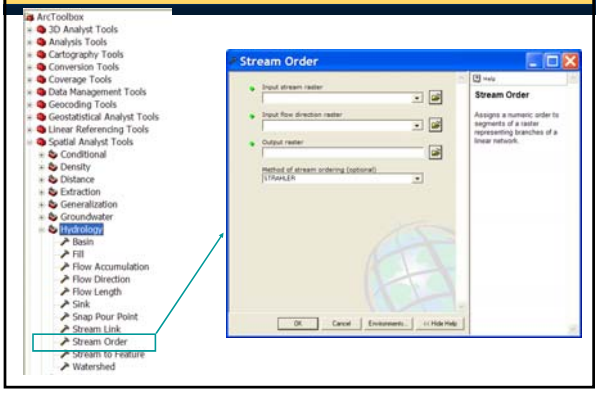


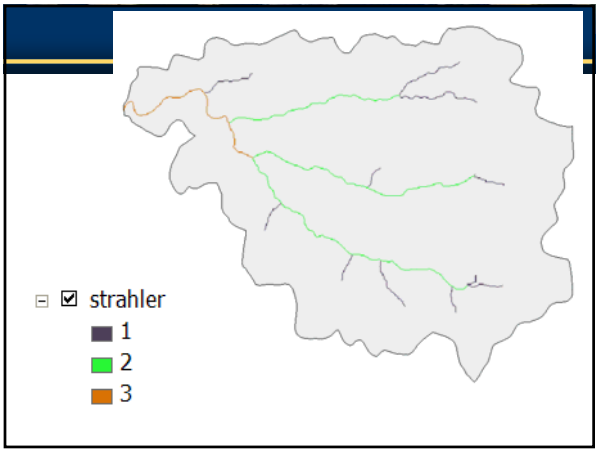
Shreve ordering



Strahler ordering

Stream order calculation

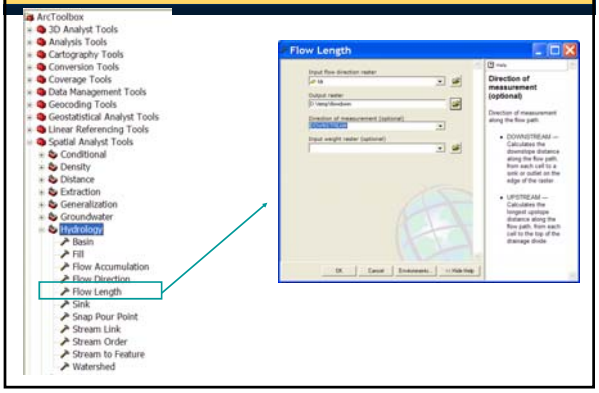




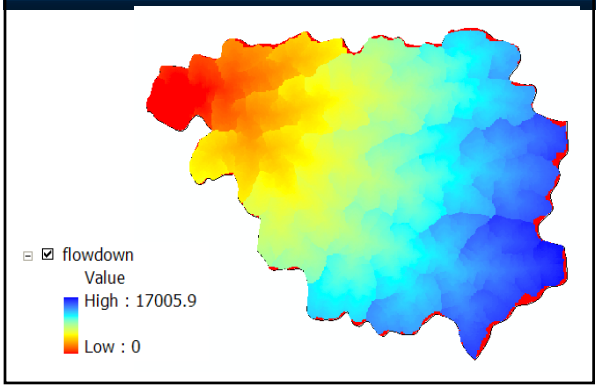
Flow length

- Created from a flow direction grid
- Calculates flow length
  - Upstream: from each cell to the top of the drainage divide
  - Downstream: for each cell to a sink or outlet

Flowlength calculation

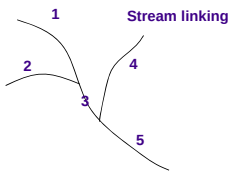


Flowlength down to outlet

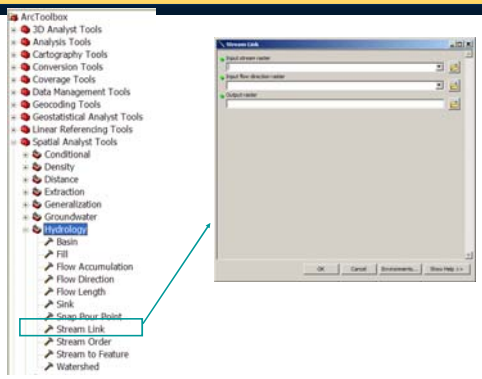


Stream link

- Assigns unique values to sections of the raster linear network
- All cells in a stream segment are assigned the same value
- Attribute information can be related to each unique segment or link

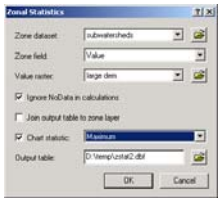


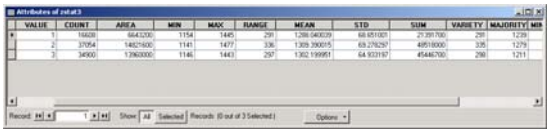
Stream link syntax



Zonal statistics

- As an example, if stream segments are unique (by using the stream link command) you could now find the min, max, mean, elevation for each stream
- Or for delineated watersheds that had a unique code, you could do the same





VALUE	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD	SUM	VARIETY	MAJORITY	MIN
1	16608	6643200	1154	1445	291	1286.040039	68.651001	21291700	291	1239	
2	37054	14821600	1141	1477	336	1309.390015	69.278297	48510000	335	1279	
3	34900	13960000	1146	1443	297	1302.199951	64.933197	45446700	298	1211	

Applications

Overview

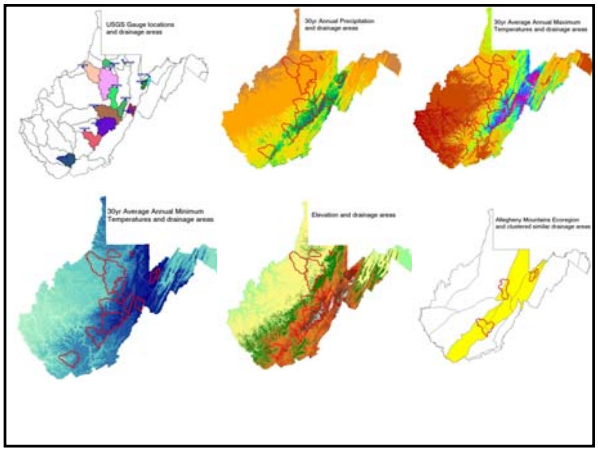
- Stream flow estimation
- Terrain analysis
  concave/convexity, moisture index, riparian buffers
- Stream order and stream flow length
- Finding potentially affected streams

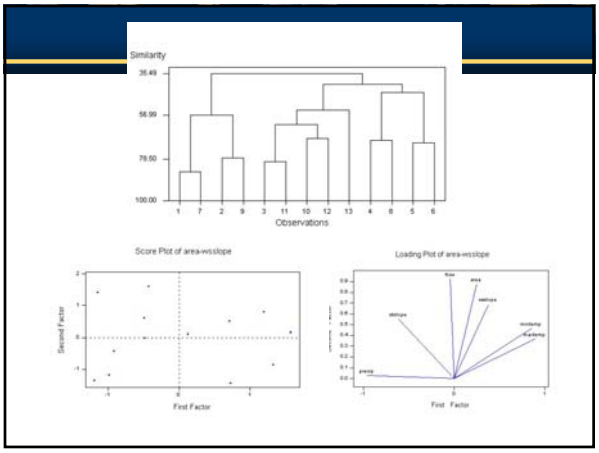
Stream flow modeling

- Why try to estimate it?
  Important for water quality modeling
  Permitting discharge sites
  Biological importance
  Recreation
  Flood forecasting
  Influenced by human factors

Literature based approaches

- Stream flow is a function of many different variables which differ across the country
- GIS is often used to compute these variables
- Variables are compared to recorded stream flow from gauges
- Linear, log linear, multivariate statistical approaches are used to interpret





Using drainage area to estimate stream flow

- More of a “back of the envelope” approach
- Uses ratio between drainage area and gauged flow to estimate flow
- Assumes stream flow is the same per unit area as a nearby gauge
- Best for sites near gauged locations (ratio .3 to 1.5) and on the same watershed

Flow accumulation for drainage area and flow estimation

- The values from the flow accumulation grid can be used to estimate drainage area
- The ratio of stream flow at a known gauge location with drainage area can be used to estimate flow upstream

Flow accumulation interpretation

# of cells * cell size^2 = drainage area in meters squared

Example:
If you have 5000 for an FAC value and a 20m Cell size, then your drainage area would be:
5000 * 400 = 2,000,000 meters squared

To convert meters squared to acres, multiply by 0.00024718
Or for the example above 494 acres

To convert meters squared to square miles, multiply by 0.000,000,3861
Or for the example above 0.772 square miles

Steps for ratio method

1. Find USGS gauge location downstream and in the same watershed
2. Summarize the recorded flow from gauge (USGS web site)
3. Find the FAC values at gauge and location of interest
4. Apply ratio of flow to drainage area at gauge to all upstream drainage areas in the FAC grid

USGS gauge data (http://waterdata.usgs.gov/

Example

- Big Creek gauge at mouth of the watershed has a drainage area of 187,003 FAC units and an average May flow of 56 cfs
- Using the ratio method below, we can find stream flow for the entire watershed's streams for May by dividing the FAC grid by 3339 to create a stream flow grid in cfs

USGS gauge FAC value		FAC values upstream
----------	=	----------
Flow value in cfs		Computed flow in cfs

187,003 / 56 = FAC values upstream / computed flow in cfs

Or

FAC values upstream / 3339 = computed flow in cfs

Assumptions / limitations

- lack of interception, evapotranspiration, baseflow from groundwater
- distribution of rainfall
- limited to natural systems (no dams or impoundments)

Watershed characteristics affecting runoff

Watershed configuration
- size
- shape
- orientation
- stream network

Topography

Geology
- soils, infiltration and erosion characteristics

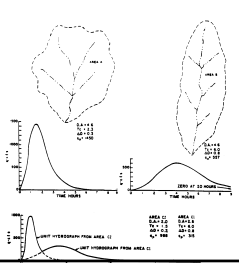
Surface culture
- agricultural practices
- residential land use practices

Structures
- hydrologic modification

Watershed characteristics affecting runoff

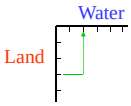
- Watershed shape

For a given area, watershed width affects the overland flow pattern
Effects can be seen in terms of the time of concentration of flow
The larger the width the longer the time of concentration



Possible Land-Water Transform Coefficients

Land-Water Connection	Transform Coefficient
Water yield	Runoff coefficient, C
Flood runoff	SCS Curve Number, CN
Groundwater	Recharge rate (mm/yr)
Water quality	Expected Mean Concentration (mg/l)
Sediment yield	Erosion rate (tons/ha-yr)



Terrain analysis - moisture index

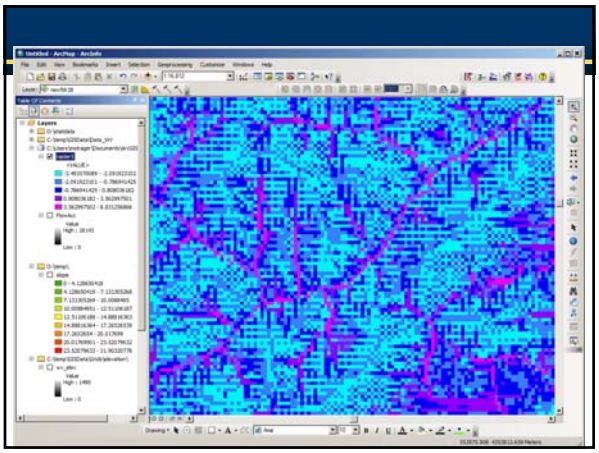
- Simply a function of two factors:
  - How much water is flowing into the area
  - How fast the water can flow out

Ln [(catchment area + 1) / (slope + 1)]

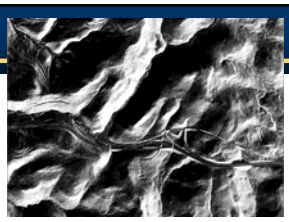
- NOTE: this is a relative moisture index, so the resulting numbers do not have units
  - Higher more positive numbers are wetter
  - Lower more negative numbers are drier

Calculating a moisture index

- Compute a flow accumulation grid
- Compute a slope grid
- Input into the raster calculator:

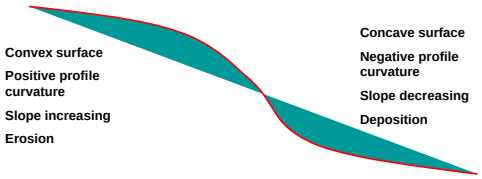


Curvature



Curvature

- Areas of convex profile curvature = areas of erosion
- Areas of concave profile curvature = areas of deposition

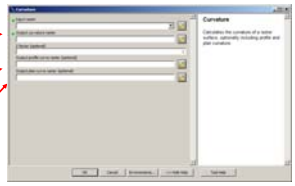


ArcMap Curvature tool

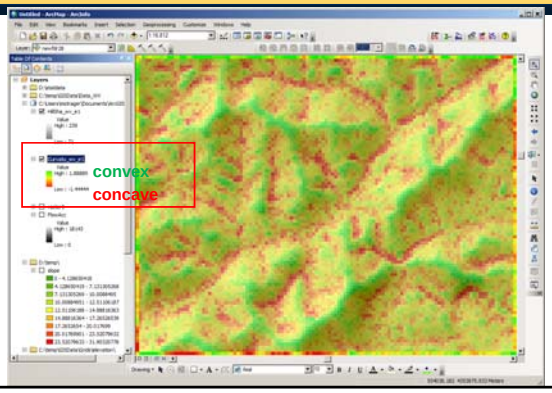
Output profile curve raster dataset.

This is the curvature of the surface in the direction of slope.

This is the curvature of the surface perpendicular to the slope direction.



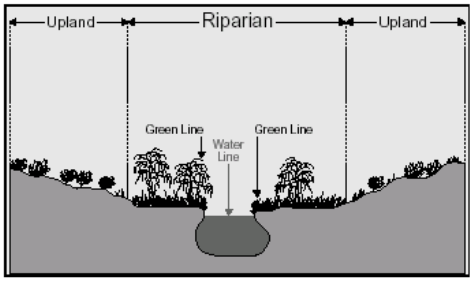
Curvature result



Riparian areas

- Riparian areas are next to streams, springs, rivers, ponds and lakes. Physical characteristics that influence riparian areas vary considerably and include
  - slope, aspect, topography, soil,
  - type of streambed material, water quality, elevation, size, and adjacent plant community

Riparian areas

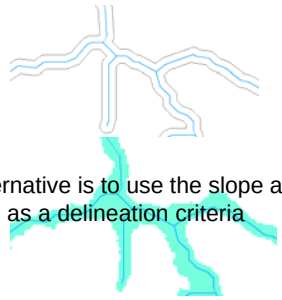


Why analyze riparian areas?

- When properly functioning with plenty of vegetation, it provides
  - reduced erosion
  - improved water quality
  - floodplain development
  - trapping of woody debris
  - flood water retention and ground-water recharge
  - habitat for fish
    - Clean, cool waters, stable channels, sustained water supply, bank overhangs for shelter, plants and animals for food, little or no silt to improve reproduction
  - increased use for wildlife

Riparian area delineation

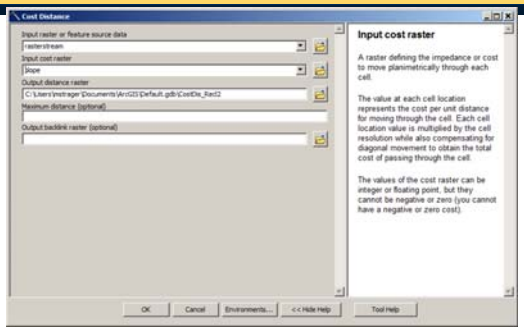
- Most riparian areas are defined by uniform buffer widths in GIS



- An alternative is to use the slope away from the stream as a delineation criteria

Variations in riparian areas

Riparian area delineation – cost weighted method



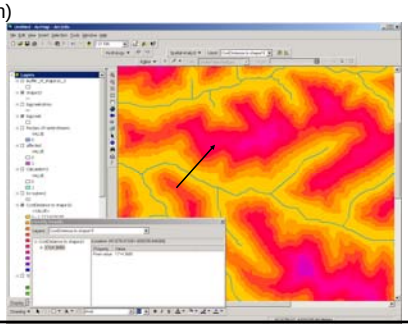
NOTE: be sure raster streams are 1 for streams and nodata for background

Cost weighted method steps

1. Set Processing extent in Geoprocessing-> Environment Settings-> Processing Extent
2. Start with a shapefile or raster grid of streams (1 for cells and nodata for background) to find riparian area
3. From an elevation grid, calculate the slope in either percent or degrees and use it as the "cost raster"
4. Leave the maximum distance blank and do not check creation of other grids

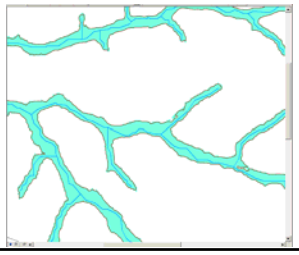
Cost weighted method steps

4. Query a cell value with the identify tool to use as the distance to define the riparian area (first slope break is one option)



Cost weighted method steps

5. Use the raster calculator to query the cost surface for this value, you may then convert to shapefile or define contours for the cost surface (defined riparian area), or find areas of natural cover

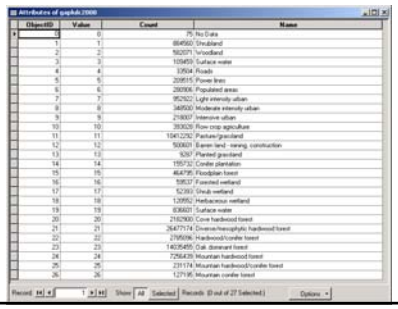


Determine the land cover in the riparian area

- Use a land use/cover grid to first select all forested, grassland or natural cover

Values: 1,2,3,11,13,14,15up are healthy riparian cover classes

Reclass to show problem areas



ObjectID	Value	Count	Name
1	1	884560	Shrubland
2	2	582071	Woodland
3	3	109459	Surface water
4	4	13504	Roads
5	5	209515	Power lines
6	6	28006	Populated areas
7	7	952922	Light intensity urban
8	8	349500	Moderate intensity urban
9	9	218007	Intensive urban
10	10	393029	Row crop agriculture
11	11	10412292	Pasture/grassland
12	12	503609	Barren land - mining, construction
13	13	9267	Planted grassland
14	14	195732	Conifer plantation
15	15	464795	Floodplain forest
16	16	59637	Forested wetland
17	17	52393	Shrub wetland
18	18	120952	Herbaceous wetland
19	19	836601	Surface water
20	20	2182900	Cove hardwood forest
21	21	3647174	Diverse mesophytic hardwood forest
22	22	2795896	Hardwood/conifer forest
23	23	14035455	Oak dominant forest
24	24	7264439	Mountain hardwood forest
25	25	231174	Mountain hardwood/conifer forest
26	26	127195	Mountain conifer forest

Record: 1 Show: All Selected Records: (0 out of 27 Selected) Options

Identifying potentially affected streams

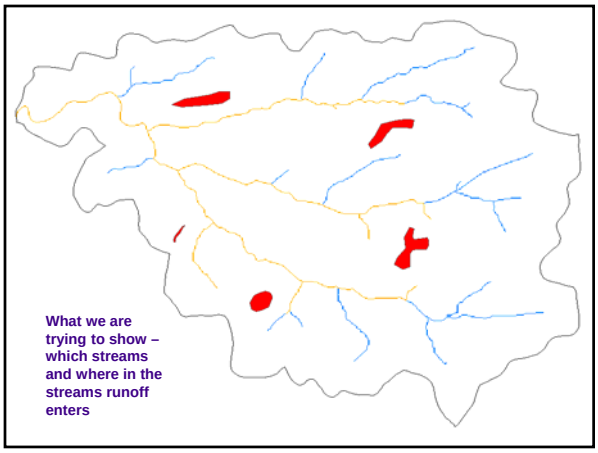
- Overland flow non point source pollution is the number one water quality problem in the majority of US waters (EPA, 2010)
- Almost 20% of the streams are impaired and not meeting designated uses
- Sources include mine drainage, leaking or overflowing sewage systems, illegal homeowner discharges, runoff from agriculture and urban areas

Identifying potentially affected streams

- Source of potential pollution can be mapped as points (discharge seeps), lines (mining headwalls), or polygons (nonpoint source pollution)
- The source is used as the weight grid in the flow accumulation function
- A network streamgrid shows the stream and the location where the potential pollution would enter the stream

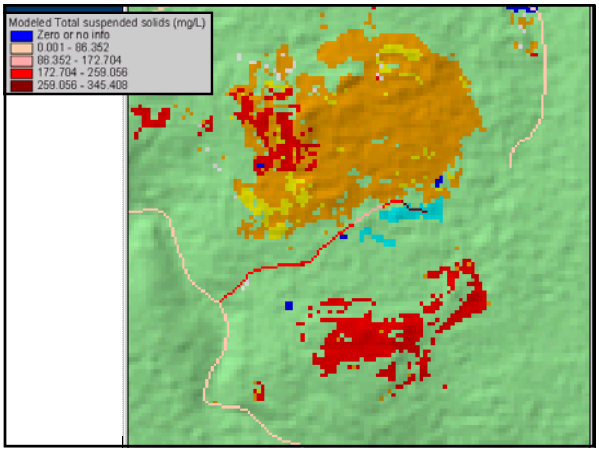
To find potentially affected streams

- Inputs
  - A flow direction grid
  - A raster or grid representation of the streams (derived from fac)
  - Mapped pollution sources converted to grids and reclassified to 1000
- Modeling process
  - Use the mapped pollution sources as a weight grid in the flow accumulation command



Potentially affected streams interpretation

- Can be used to direct water quality sampling efforts
- Very useful for large river systems and watersheds
- Can be used as a water quality prediction model
- Limitations: does not include any landscape alterations after DEM was created (diversion ditches, etc), detail of sources and resolution of DEM



Summary notes

- Best to perform hydro analysis at the watershed level not county
- Many of these global operations are very computer intensive, limit the size of the study area as much as possible