GIS in Hydrology and Water Management

Leibniz Universität Hannover

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Surface-Water Hydrology

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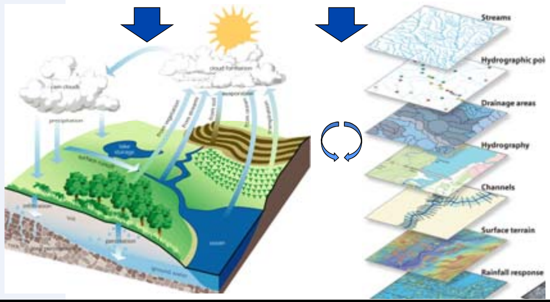
Introduction

- All are spatial in character / availability of digital data -> using GIS tools (organize, analyze, etc) for hydrologic models

Hydrology and water management	**GIS**
Hydrologic cycle	GIS 'reality'



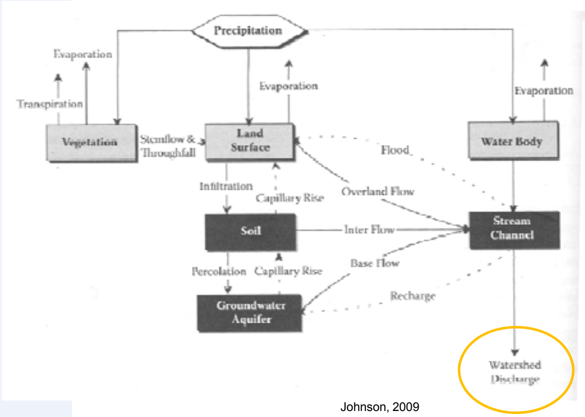
3

Introduction

- Hydrologic models attempt to represent various components of the watershed-runoff process (hydrologic-cycle):
  - Precipitation – fall on the watershed's vegetation, land surface and water bodies
  - Precipitation returns to atmosphere (evaporation, transpiration)
  - Surface – pond or infiltrate, dependent on soil type, ground cover, land surface properties
  - Land surface restrict infiltration -> increase runoff -> (excess will) flow to stream
  - Infiltrated water stored temporarily in upper layers of soil -> rise back to surface/move horizontally as interflow (-> flow to stream)/percolate vertically to groundwater aquifers (-> some returns to stream as base flow)
  - Stream-channel network collects and routes the overland flow, interflow, and base flow to the watershed

4

Introduction



Johnson, 2009

5

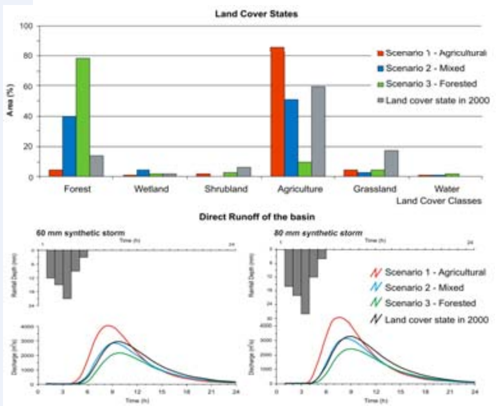
Introduction

- Surface-Water hydrologic data:
  - Terrain: DEMs / slope and aspect / watersheds and sub-catchments / drainage networks
  - Hydrology: Stream paths and network topology / channel data (shape and roughness) / lakes and wetlands / ditches and canals
  - Soils: permeability / layer depths / soil textural percentages / soil water content
  - Land use: types / cover / population / forecast
  - Satellite and aerial imagery: land use and land cover / vegetation / surface temp.
  - Precipitation and climate
  - …

6

Introduction

- Effect of different land cover scenarios



7

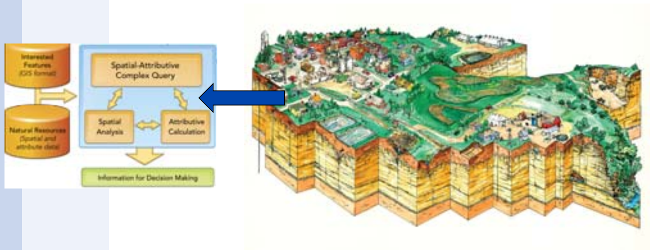
Introduction

- The goal in surface-water analysis is finding stream discharge at all locations for given precipitation, e.g., watershed discharge.
- GIS is used to summarize the terrain and hydrologic characteristics of the watershed for input to a model.
- There exist statistical methods to do this (USGS regression equations, i.e., NFF, StreamStats, …).
- There exist physical modeling (rainfall-runoff models) to do this (HEC-HMS, TR-20,…).
- ArcGIS uses mainly hydrologic modeling of HEC-HMS (embedded in Arctoolbox hydrologic analysis).

8

Introduction

- Processing of DEMs to derive landscape features that are pertinent to hydrology modeling: stream paths and drainage divides (spatial).
- Non-spatial attributes are also required (land use types, temperature, etc.).



9

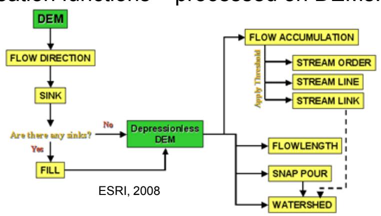
Introduction

- Partial list of supportive GIS operations:
  - Data development: DEMs / slope and aspect / flow direction / pit filling and sinks / area and flow accumulation / stream paths and drainage networks / watersheds and sub-catchments
  - Data management: database of spatial data (attributes related to specific locations and depths) / archives / visualization of input data (error checking and consistency) / statistical interpolations (watershed extent)
  - Modeling: watershed model boundary conditions / soil moisture using map algebra on grid cells / time-area hydrographs / routing channel flows through stream network / interactive model simulations / …

10

Processing of DEMs in ArcGIS

- DEM can determine reliably specific landscape features using numerical algorithms: slope, aspect, flow length, contributing areas, drainage divides, and channel network.
- Resolution and quality are measures that should be taken into account during analysis and processing, i.e., pre-processing and quality control.
- ArcGIS includes hydrology toolset that provide with various watershed delineation functions – processed on DEMs.



ESRI, 2008

11

Processing of DEMs in ArcGIS

- Basin: creating a raster delineating all drainage basins
- Fill: fills sinks in a surface raster to remove small imperfections in the data
- Flow accumulation: creates a raster of accumulated flow to each cell
- Flow direction: direction from each cell to its steepest down slope neighbor
- Flow length: calculates distance along a flow path
- Sink: creates a raster identifying all sinks or areas of internal drainage
- Watershed: determines the contributing area above a set of cells in a raster
- …

12

Watershed Analysis

- The total land area that drains to a common point.
- Also called *river basin*, *drainage basin*, or *catchment (area).*
- The watershed is *delineated* by finding the watershed *divide*, or *ridge*, that separates the watershed from its neighbors.

TABLE 3.1 World's Largest Drainage Basins

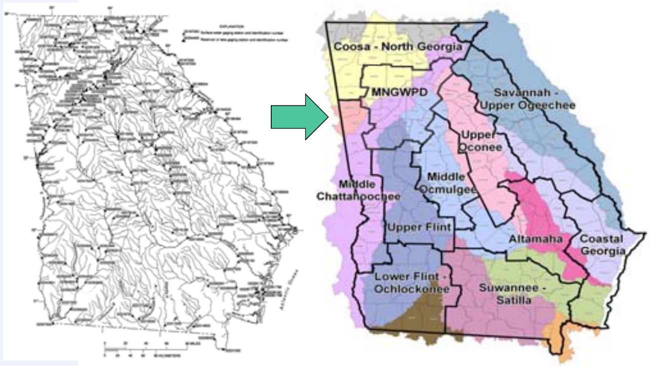
River Basin	Drainage Area (1000 mi²)	Drainage Area (1000 km²)	Average Discharge cfs*	Average Discharge cms*
Amazon, South America	2380	6160	6,183,750	175,100
Zaire (Congo), Africa	1480	3830	1,413,430	40,000
Mississippi, United States	1260	3260	649,820	18,400
Parana-La Plata, South America	1090	2820	526,500	14,910
Yenisei, Russia	1000	2590	627,560	17,770
Lena, Russia	970	2510	568,900	16,110
Yangtze (Chang Jiang), China	750	1940	1,008,480	28,560
Ganges-Brahmaputra, India	570	1480	1,087,990	30,810
Orinoco, South America	380	980	1,232,510	34,900
Mekong, Vietnam	310	800	526,500	14,910

*cubic feet per second and cubic meters per second.

The world of figures (1973)

13

Watershed Analysis



Delineation of water planning regions

14

Watershed Analysis

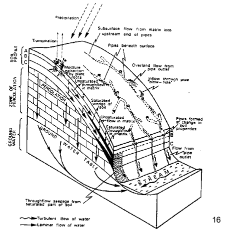
- John Wesley Powell:
  "that area of land, a bounded hydrologic system, within which all living things are inextricably linked by their common water course and where, as humans settled, simple logic demanded that they become part of a community."

Latoriţa River drainage basin, Romania

15

Watershed Analysis

- Following four 'simple' rules:
  - Ridges are indicated by the highest elevation contour line
  - Surface water generally flows at right angles (perpendicular) across contour lines
  - Drainages are indicated by flow lines (also called streamlines) that point downstream, e.g., flow direction
  - (commonly used) Hydrologic functions assume that water can flow in from many cells but out through one cell only

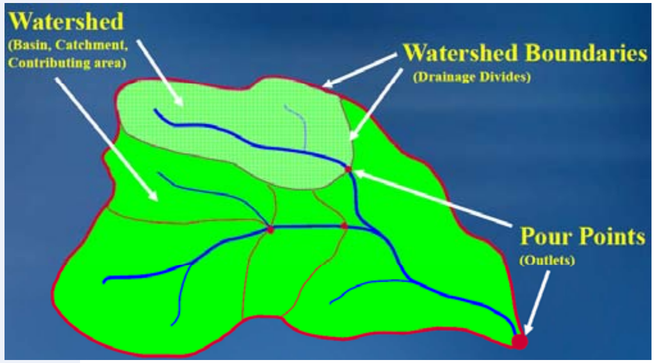


16

Watershed Analysis

- Drainage system = the area upon which water falls and the network through which it travels to an *outlet*.
- (This flow is a subset of what is commonly referred to as the hydrologic cycle)
- A *watershed* (*drainage basin*) is an area that drains water to a common outlet.
- The area (scale dependent) is normally defined as the total area flowing to a given outlet, or *pour point*, which is usually the lowest point along the boundary of the *drainage basin*.
- Boundary between two basins is referred to as a *drainage divide* or *watershed boundary*.
- Intersection of two stream channels is referred to as a *node* or *junction*. The sections of a stream channel connecting two successive junctions or a junction and the outlet are referred to as *stream links*.

Watershed Analysis



ESRI, 2008

Watershed Analysis (1) – Depressionless DEM

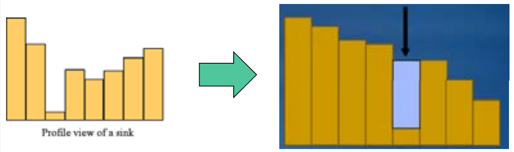
- Errors in DEMs are usually classified as either *sinks* or *peaks*.
- Sink (*depression* or *pit*) is an area surrounded by higher elevation values -> an area of internal drainage.
- Peak (*spike*) is an area surrounded by cells of lower value. These are more commonly natural features (e.g., mountains) and are less detrimental to the calculation of flow direction.
- Sinks should be removed before attempting to derive any surface information and analysis (since they prevent down slope flow routing of water); hence continuous flow path is defined from every cell to the edge of the data set or to the watershed outlet.
- ‘Real’ sinks (features) can be lakes, depressions, glacial landscapes (should be preliminary identified).
- Methods: global fill \ internal basins \ selective fill (depth, area)

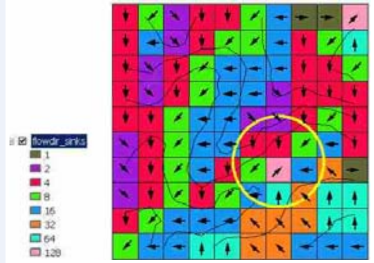
Watershed Analysis (1) – Depressionless DEM

Watershed Analysis (1) – Depressionless DEM

- DEM free of sinks (depressionless DEM) is required to processing of flow direction.
- Understanding the morphology of the area is important to know what features may truly be sinks on the surface of the earth - and which are merely errors in the data.
- ‘Sink function’ analyses a (direction) raster that is created by the ‘Flow Direction function’.
- Sinks can be filled using the ‘Fill function’ (input surface, fill limit, output raster). When a sink is filled, it is filled to its pour point, the minimum elevation along its watershed boundary (the lowest pour-point on the edge of the pit).
- Depressionless DEM is an iterative process, since when a sink is filled, the boundaries of the filled area may create new sinks, which then need to be filled.

Watershed Analysis (1) – Depressionless DEM





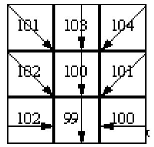
Surface with “sinks“ were flow direction produces an un-drained depression (ambiguous flow-direction) .

Watershed Analysis (2) – Flow Direction

- Key element to deriving surface hydrologic characteristics.
- Output is a raster showing the direction of flow out of each cell.
- Several approaches exist: some partition flow to only one cell, some divide it up based on the proportion of flow into each cell (usually 3 or less neighboring cells).
- Vary depending on whether single or multiple flow paths allowed.
- Single flow direction algorithms: D8 (O’callghan and Mark, 1984), Rho4/Rho8 (Fairfield and Leymarie, 1991), Aspect-driven (Lea, 1992).
- Multiple flow direction algorithms: FD8 (Quinn et al., 1991), dinf (Tarboton, 1997), and more.

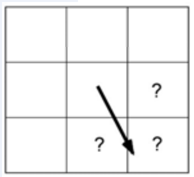
Watershed Analysis (2) – Flow Direction

- ArcGIS uses 8 valid output directions, which relate to 8 adjacent cells into which single flow could travel (commonly referred to as the D8 flow model, Jensen and Domingue (1988)).
- If maximum descent to several cells is the same, the neighborhood is enlarged until the steepest descent is located.
- Output cell is coded with the value representing that direction.
- In case all neighbors are higher than the cell, the cell is declared as *sink,* thus has an undefined flow direction. (sinks should be filled to obtain accurate representation of flow direction across a surface).



Watershed Analysis (2) – Flow Direction

- Direction is binary coded (1 – 128).
- Flow direction is determined by the direction of steepest descent (maximum drop) from each cell:
  drop = (change in z-value / distance)
  (for cell size of one, the distance between diagonal cells is 1.414. e.g., res = 50m -> diag = 70.7m).



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

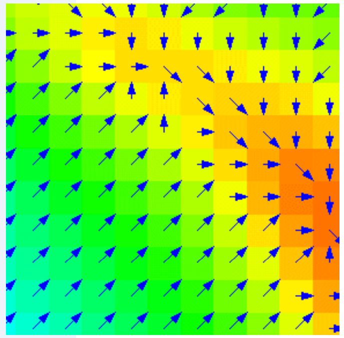
Flow Direction

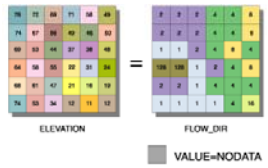
32	64	128
16		1
8	4	2

Direction Coding

25

Watershed Analysis (2) – Flow Direction





26

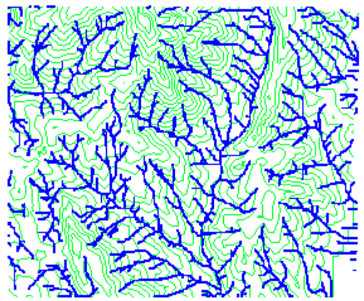
Watershed Analysis (3) – Flow Accumilation

- Calculates accumulated flow as the accumulated weight of all cells flowing into each down slope cell in the output raster, e.g., counting the number of contributing cells to each cell in the grid.
- If no weight raster is provided (for example, a raster representing average rainfall during a given storm) a weight of one is applied to each cell, and the value of cells in the output raster will be the number of cells that flow into each cell.
- Cells with a high flow accumulation are areas of concentrated flow and may be used to identify stream channels/network.
- Cells with a low flow accumulation are areas near watershed boundaries and where overland flow dominates.
- Cells with a flow accumulation of zero are local topographic highs and may be used to identify ridges.

27

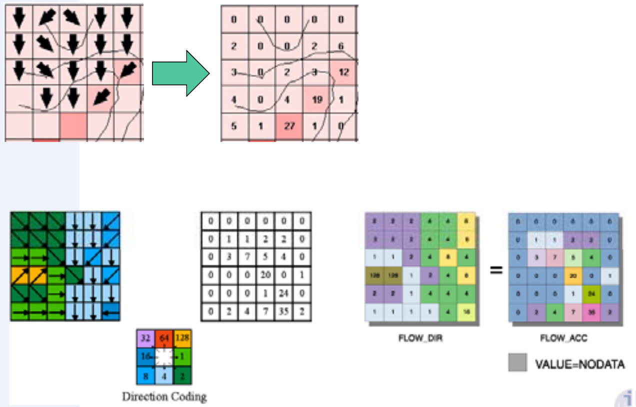
Watershed Analysis (3) – Flow Accumilation

- Flow accumulation grid superimposed on a contour map. Only the cells whose flow accumulation is greater than 50 (cells) are displayed, clearly defining the stream channels present in this portion of the elevation grid.



28

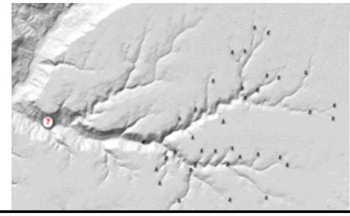
Watershed Analysis (3) – Flow Accumilation



29

Watershed Analysis (4) – Stream Ordering

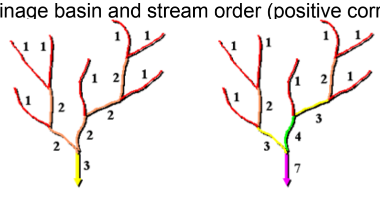
- Assigns a numeric order to links in a stream network.
- Identifying and classifying types of streams based on their number of tributaries.
- For example, first-order streams are dominated by overland flow of water; they have no upstream concentrated flow. Because of this, they are most susceptible to nonpoint source pollution problems and can derive more benefit from wide riparian buffers than other areas of the watershed.



30

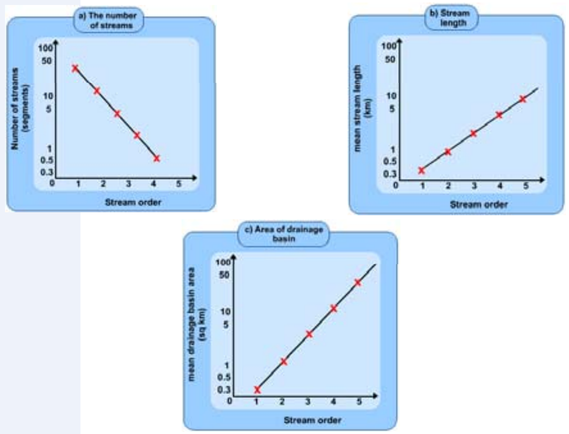
Watershed Analysis (4) – Stream Ordering

- Two methods can be used: Strahler (1957) and Shreve (1966).
- Drainage basin is named after the highest order stream found within it, for example, a fourth order drainage basin.
- Relationships:
  - stream order and the number of stream in a drainage basin (negative correlation).
  - stream length and stream order (positive correlation).
  - area of drainage basin and stream order (positive correlation).



31

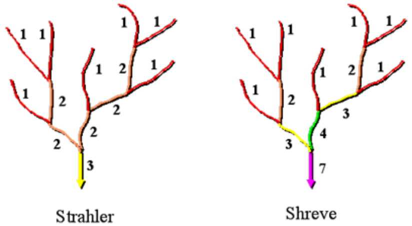
Watershed Analysis (4) – Stream Ordering



32

Watershed Analysis (4) – Stream Odering

- Strahler (1957) method is the most common stream ordering method. Still, because this method only increases in order at intersections of the same order, it does not account for all links and can be sensitive to the addition or removal of links.
- In Shreve (1966), because the orders are additive, the numbers are sometimes referred to as magnitudes (number of upstream links) instead of orders.



33

Watershed Analysis (5) – Watershed Delineation

- Delineate the contributing area to a cell or group of cells.
- Requires a flow direction grid and a set of pour-points (outlet locations) – scale dependent.
- Pour-points may be:
  - selected interactively (with a mouse, use of snapping).
  - selected automatically at the downstream end of each link in the drainage network created using an area threshold (Jenson and Domingue (1988); Maidment and Mizgalewicz (1993)).
  - identified using existing point features.
- Assigning pour-points to the cell of highest flow accumulation within a neighborhood prevents accidental creation of small watersheds on channel side slopes.
- Once outlet locations are specified, watershed and sub-basin delineation can be performed.

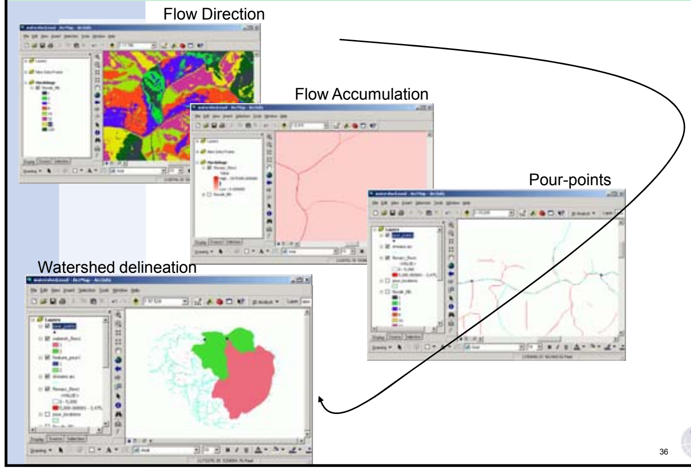
34

Watershed Analysis (5) – Watershed Delineation

- Flow direction from each grid cell is traced until either an outlet cell or the edge of the grid is encountered (similar process to flow accumulation).
- If an outlet cell is found then the grid cell is assigned the ID of the basin for that outlet point. If the edge of the flow direction grid is found then the cell is assigned a "no data" value, meaning that it does not contribute flow to any of the defined outlets.
- The process of assigning basin IDs to grid cells can be optimized by first assigning the basin IDs to all stream cells upstream from the outlet points. Then, whenever a traced grid cell flow path encounters a stream cell it can be assigned the same basin id as the stream cell encountered.

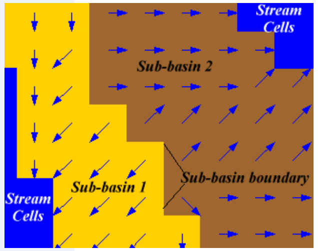
35

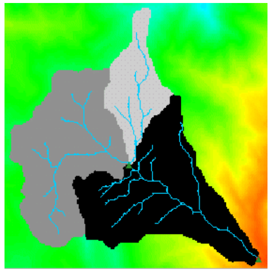
Watershed Analysis (5) – Watershed Delineation



36

Watershed Analysis (5) – Watershed Delineation





37

Watershed Analysis (5) – Watershed Delineation

38