Governing Rules of Water Movement

- Like all physical processes, the flow of water always occurs across some form of **energy gradient** from high to low…
  - e.g., a topographic (slope) gradient from high to low elevation
  - Or a **concentration gradient, pressure gradient**, etc.
- All other things being equal, in a fluvial landscape that **has some relief**, water movement near the surface is going to follow the **topographic gradient downhill**
- Thus, by **modeling terrain** using a continuous surface, we can learn some useful things about the **movement of water** through a landscape

Watershed (a.k.a. Drainage Basin, Catchment)

- A geomorphically distinct **landscape unit** defined by topographic boundaries, or drainage 'divides' that acts as a spatially discrete hydrological system

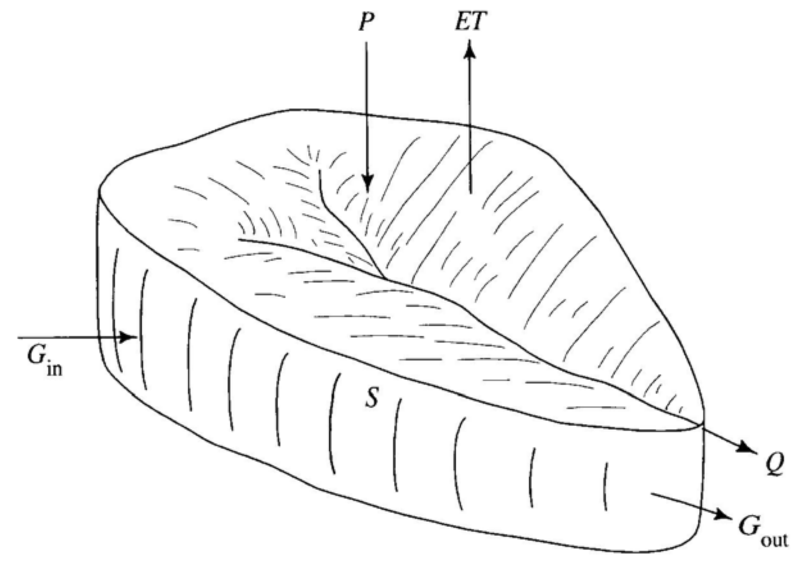


FIGURE 2-3
Schematic diagram of a watershed, showing the components of the regional water balance: P = precipitation, ET = evapotranspiration, Q = stream outflow, G_{in} = ground-water inflow, G_{out} = ground-water outflow.

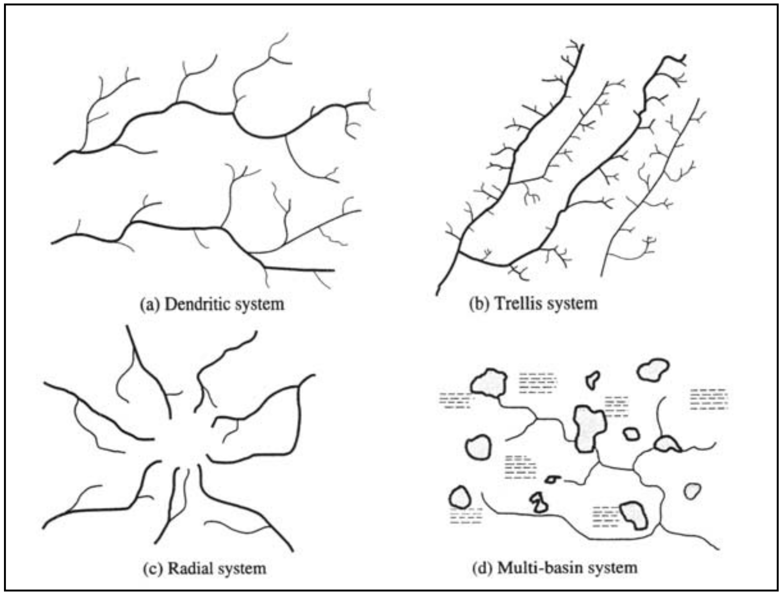
Davis' (1899) Notion of a Watershed

- Davis provided the very useful metaphor of **the river as a leaf**, such that:
  - "one may **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" (Chorley, 1969, p.78).

Drainage basin properties

- basins consist of **networks** of interconnected & hierarchically organized channels (rills to rivers)
  - each with smaller **sub-catchments** separated by divides or 'interfluves'
- fluvial action alters the landscape & continually **maintains & expands** basin network…
  - headward erosion, stream piracy, channel incision/degradation &/or aggradation
- network patterns reflect geology, climate, topography, time… most common type is '**dendritic**'

Drainage network patterns



- Wind, ice and water act on land surfaces to create **several types of drainage patterns**
  - Particular design is a function of several factors
    - e.g. climate, geology, time, topography, sediment transport

- **Dendritic** - numerous small tributaries joining at right angles into higher-order streams
- **Trellis** - long main streams intercepted by numerous shorter right-angle tributaries (Appalachians, Foothills of Rockies)
- **Multi-basin** - low gradient swampy areas with numerous depressions and normally have only a few tributaries (permafrost, glaciated, plains, valleys)
- **Radial** – occur in foothill or mountain areas

Stream order (Horton 1945, Strahler 1954)

- **hierarchy of channels** from 1st order tributaries to nth order main channel
  - e.g., Mississippi R. at New Orleans is 14th order
- **Strahler's rules**:
  - junction of 2 streams of order 'x' form next downstream order 'x +1'
  - junction of 2 streams of different orders x & y, where y > x, creates order equal to higher order stream (y)

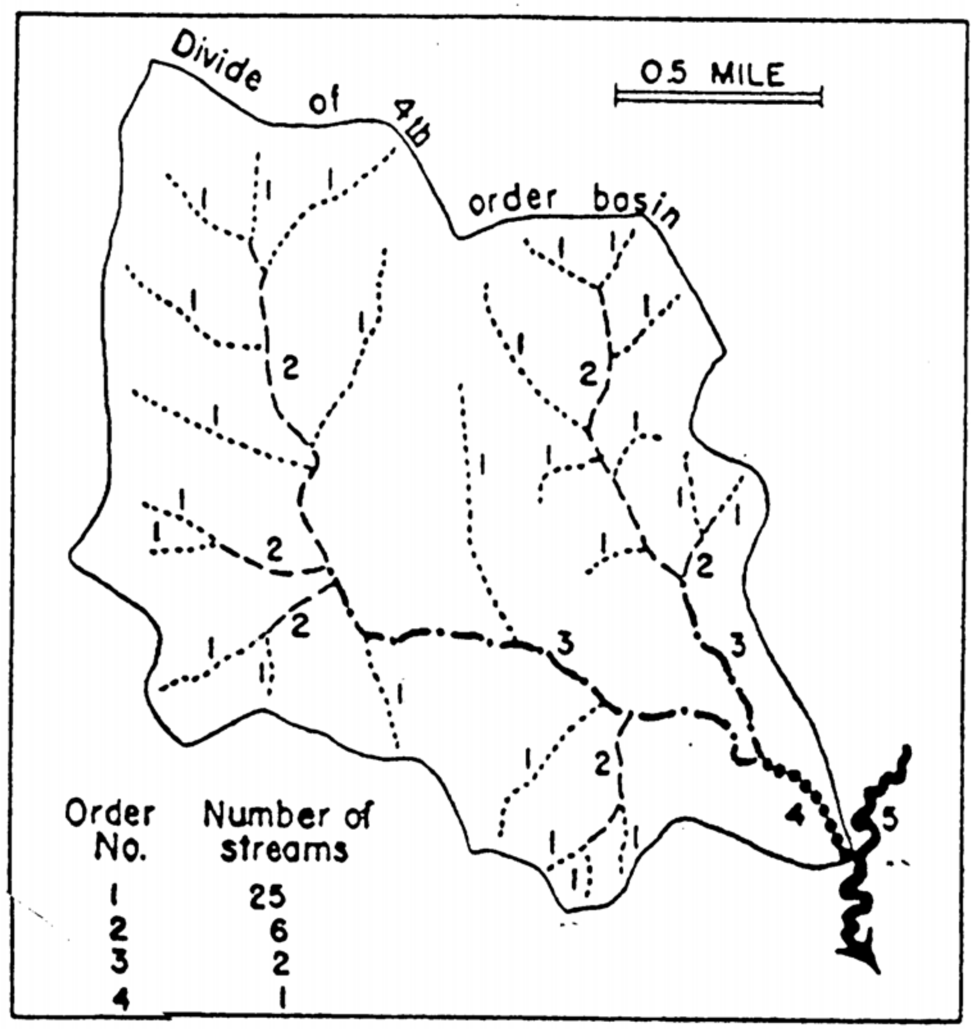


FIG. 2 – Method of designating stream orders (Strahler, 1954a, p. 344)

Stream Order/Magnitude Methods

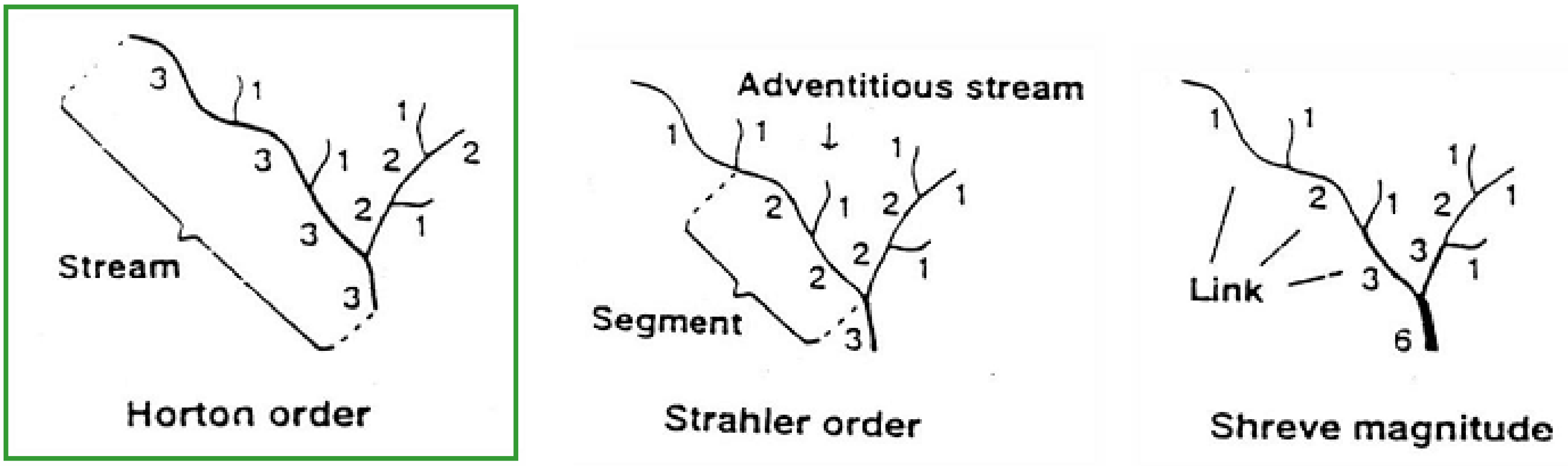


Figure 5: Stream Ordering Methods (Jones, 1997, p.176)

- **Horton** sub-divided the stream network on a **stream-ordering** basis, where the drainage network was broken into component parts, or reaches, and these reaches were assigned a stream-order, **descriptive of their size** (Chorley et al., 1984, p.317)

Stream Order/Magnitude Methods

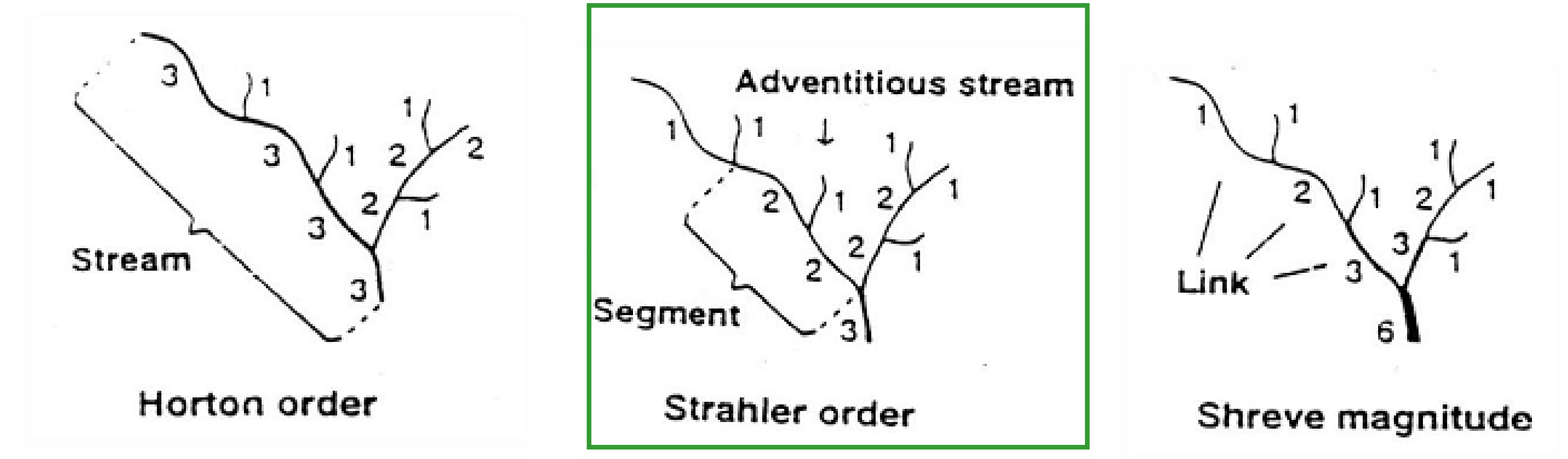


Figure 5: Stream Ordering Methods (Jones, 1997, p.176)

- In 1964, **Strahler improved** Horton's stream-ordering approach. Horton's assignment of order values **underestimated** the importance and number of **lower-order tributaries**. Strahler's scheme corrected this, and assigned values more impartially, rather than extending the higher-order stream further up the divide as Horton did (Jones, 1997, p.176).

Stream Order/Magnitude Methods

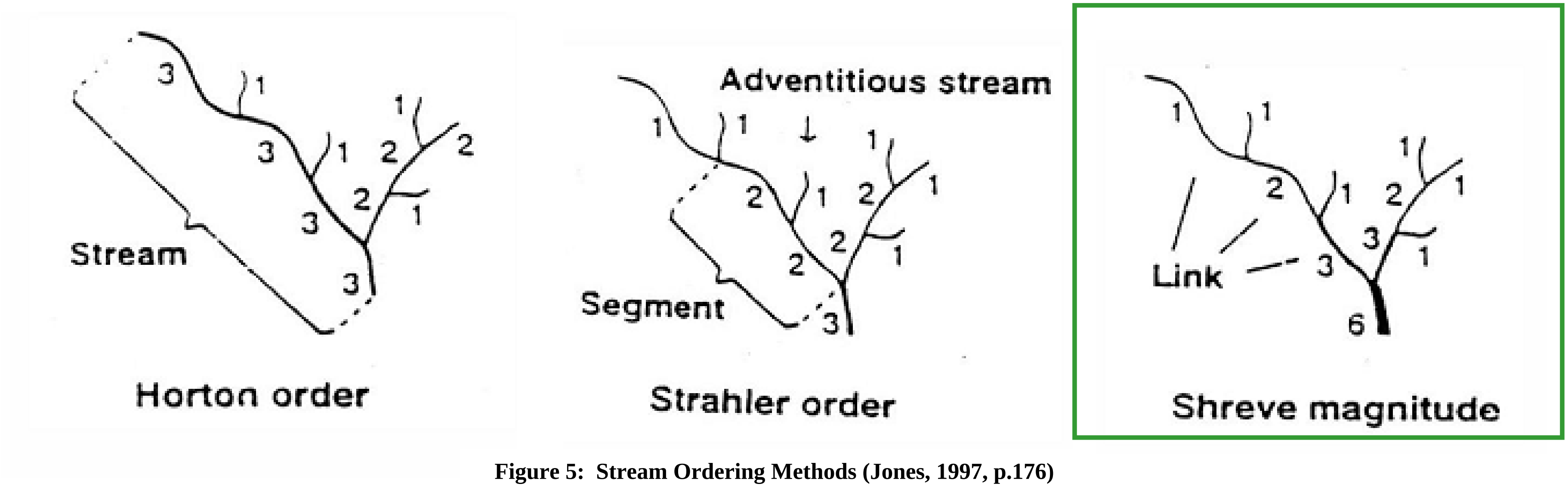


Figure 5: Stream Ordering Methods (Jones, 1997, p.176)

- **Shreve further improved** stream ordering in 1966 by introducing the concept of **stream magnitude**: Values assigned to a reach represented the **sum of contributing reaches**. This scheme better preserves the sense of the contribution of a given reach's drainage (Jones, 1997, p.176).

Relief

- **maximum elevation difference** in a watershed
- normalized by **channel length** to allow comparison between basins of different size
  - **relief ratio**, S = H / L where H is elevation change in basin along length main channel (L)
  - describes travel distance relative to elevation change… relevance?
- must also consider **basin area** (A)
  - **relative relief**, $R = H / (A^{0.5})$
  - indicates overall slope of the watershed & controls delivery time… how so?
- changes in **lowest elevation** (base level) in a basin have far-reaching effects on drainage basin function… how?

Drainage network arrangement

- basin hydrological response largely a function of '**effectiveness**' of the drainage network
  - how could you define effectiveness?
- length, slope (relief) & shape of main channel, stream order, vegetation cover, land use…
- **drainage density**: average Length (L) per unit area (A)
  - $D_d = (\Sigma L) / A$
  - how would D_d control 'effectiveness' of water delivery in a basin?
- **bifurcation ratio**,
  - R_b… (# streams order x) / (# streams order x+1)

Shape

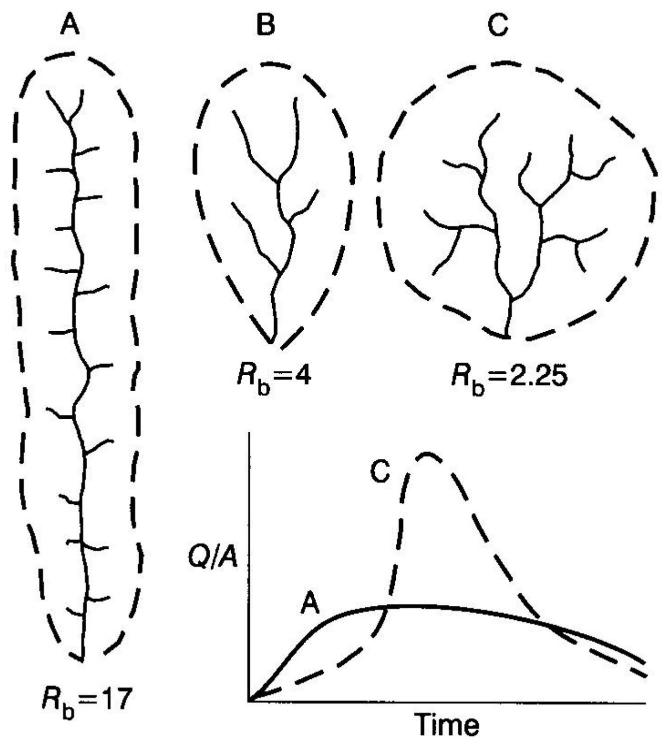
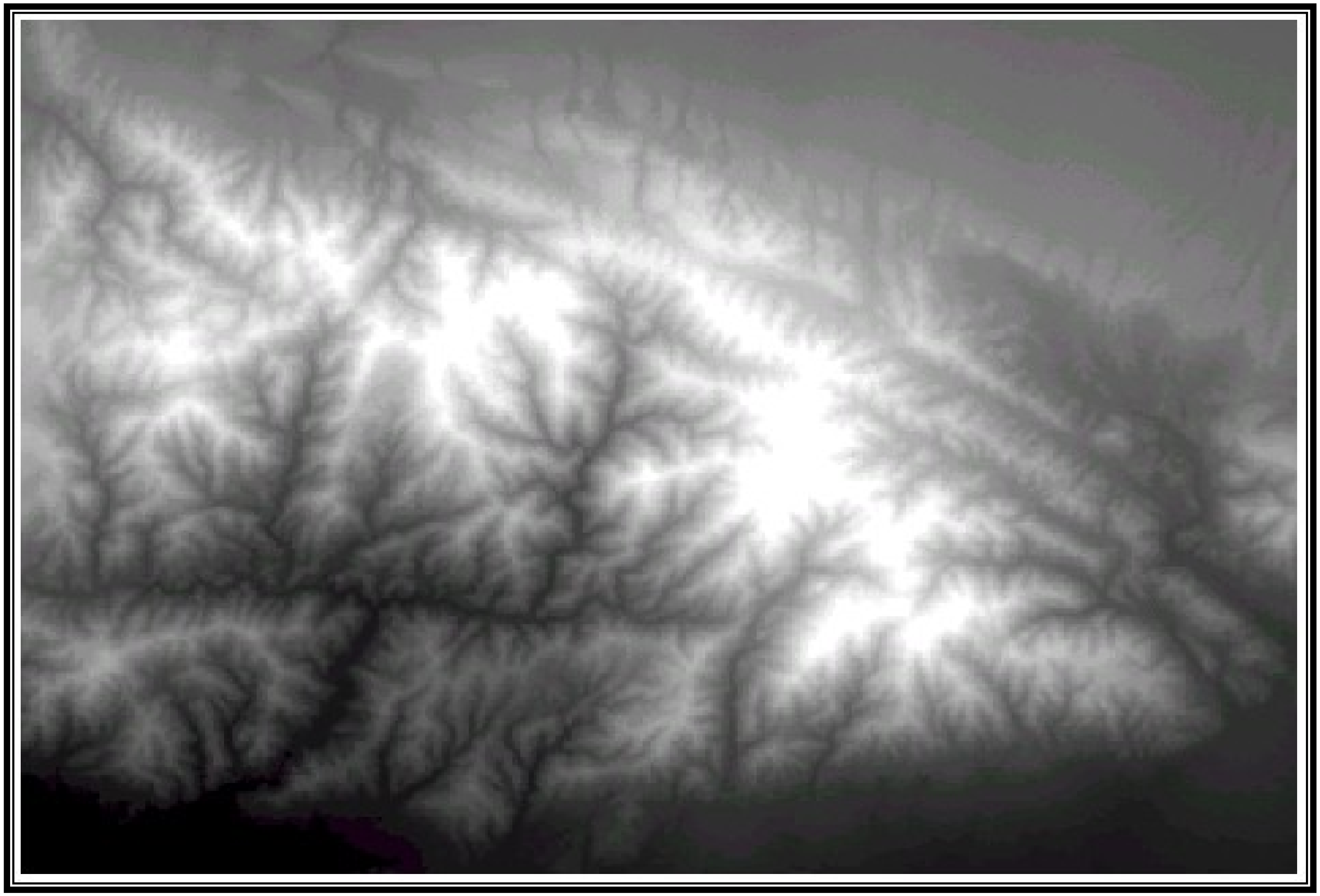


Figure 7.24 Relations between catchment shape, bifurcation ratio (R_b) and the shape of the flood hydrograph (from an original diagram by Strahler, 1964).

Digital Elevation Models

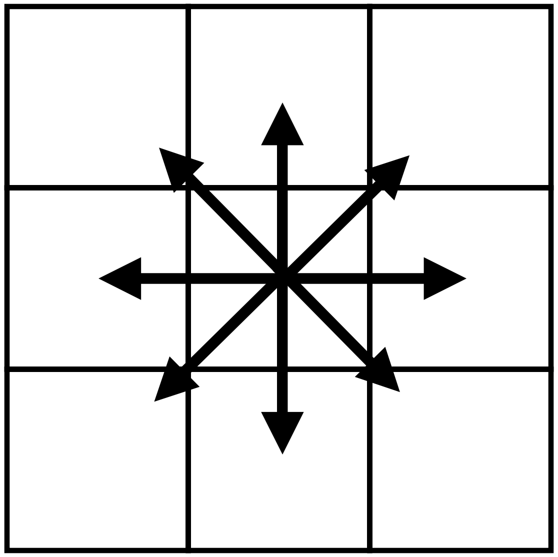
Raster Grid



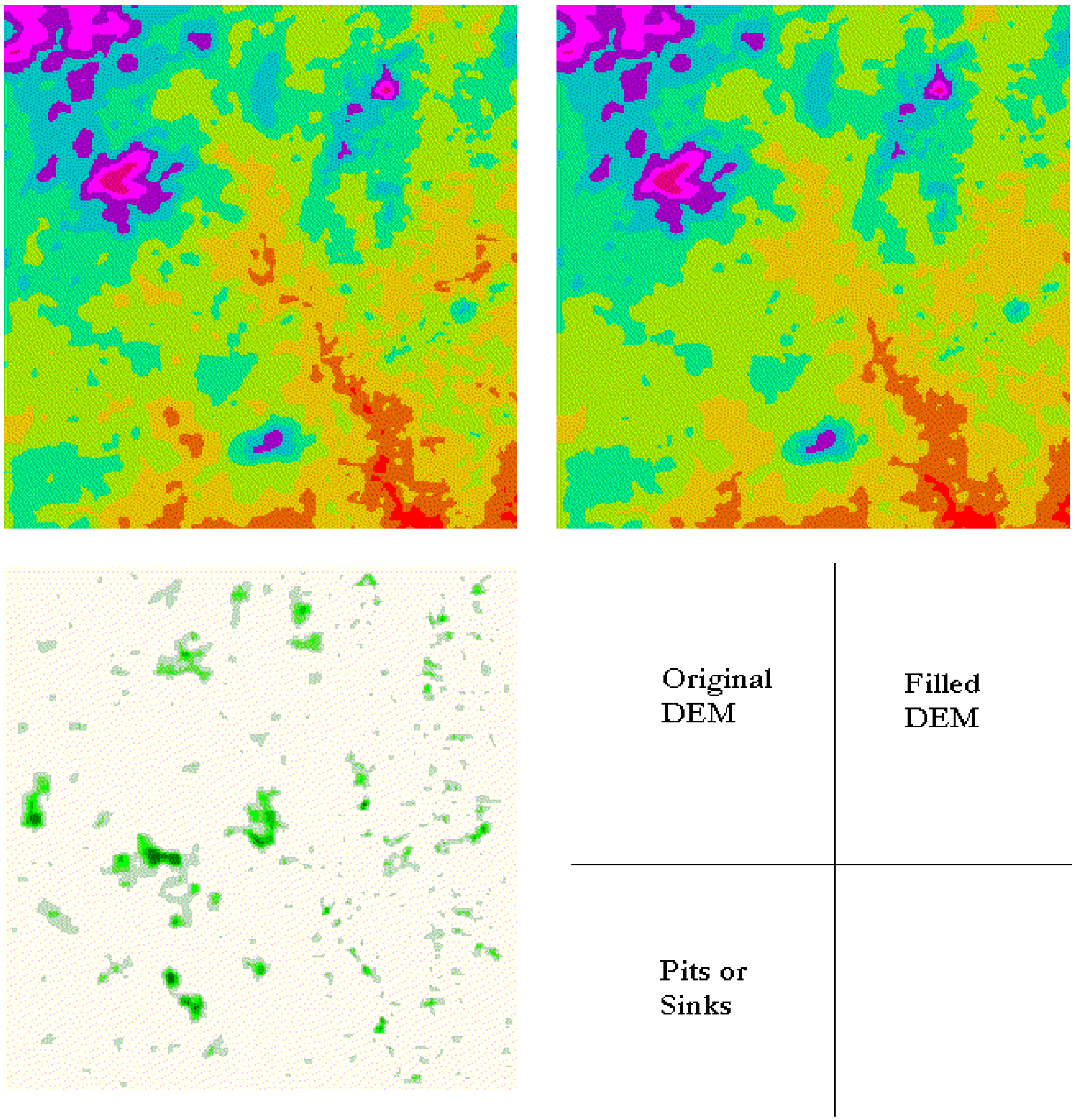
D8 Analysis Sequence

- Assume we now have a raster DEM and we want to use it **find a watershed and drainage network** through D8 analysis
- We can follow this **sequence of analysis** steps, each of which involves a neighborhood analysis operation:
  - Fill Sinks
  - Slope
  - Aspect
  - Flow Direction
  - Flow Accumulation
  - StreamLink & StreamOrder
  - Watershed

D8 Analysis



Fill Sinks



- We need a DEM that does not have any **depressions or pits** in it for D8 drainage network analysis
- The first step is to **remove all pits** from our DEM using a **pit-filling algorithm**
- This **illustration** shows a DEM of **Morgan Creek**, west of Chapel Hill

Slope and Aspect

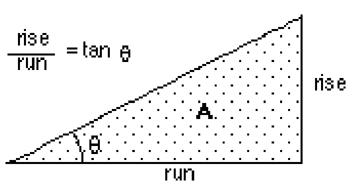
- These are **measurements of terrain attributes**, usually calculated from a digital elevation model
- **Slope and aspect** are calculated for each cell in the grid, by comparing a cell's elevation to that of its neighbors
  - Usually **eight neighbors** are used and the result is expressed as an angle, but the exact method varies
  - It is important to know exactly what method is used when calculating slope, and exactly how slope is defined, because **different methods** can give **different results**

Slope and Aspect

- We can **calculate** these topographic attributes directly from the grid-elevation values using a second-order finite difference scheme applied over a 3x3 neighborhood

From ArcView 3.2 Help

Degree of slope = θ



Degree of slope = 30
Percent of slope = 58

Slope

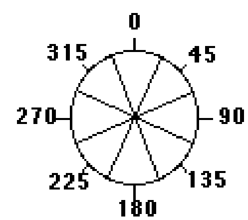
The actual algorithm that is used to calculate slope is:

```
rise_run = SQRT(SQR(dz/dx)+SQR(dz/dy))
degree_slope = ATAN(rise_run) * 57.29578
```

where the deltas are calculated using a 3x3 roving window,

```
a b c
d e f
g h I
```

```
(dz/dx) = ((a + 2d + g) - (c + 2f + i)) / (8 * x_mesh_spacing)
(dz/dy) = ((a + 2b + c) - (g + 2h + i)) / (8 * y_mesh_spacing)
```



Aspect

1	1	1	1	1	1
1	3	3	2	1	
1	1	3	2	2	2
1	2	2	2	2	2
1	1	1	2	2	2
1	1	1	1	1	2

INGRID1

=

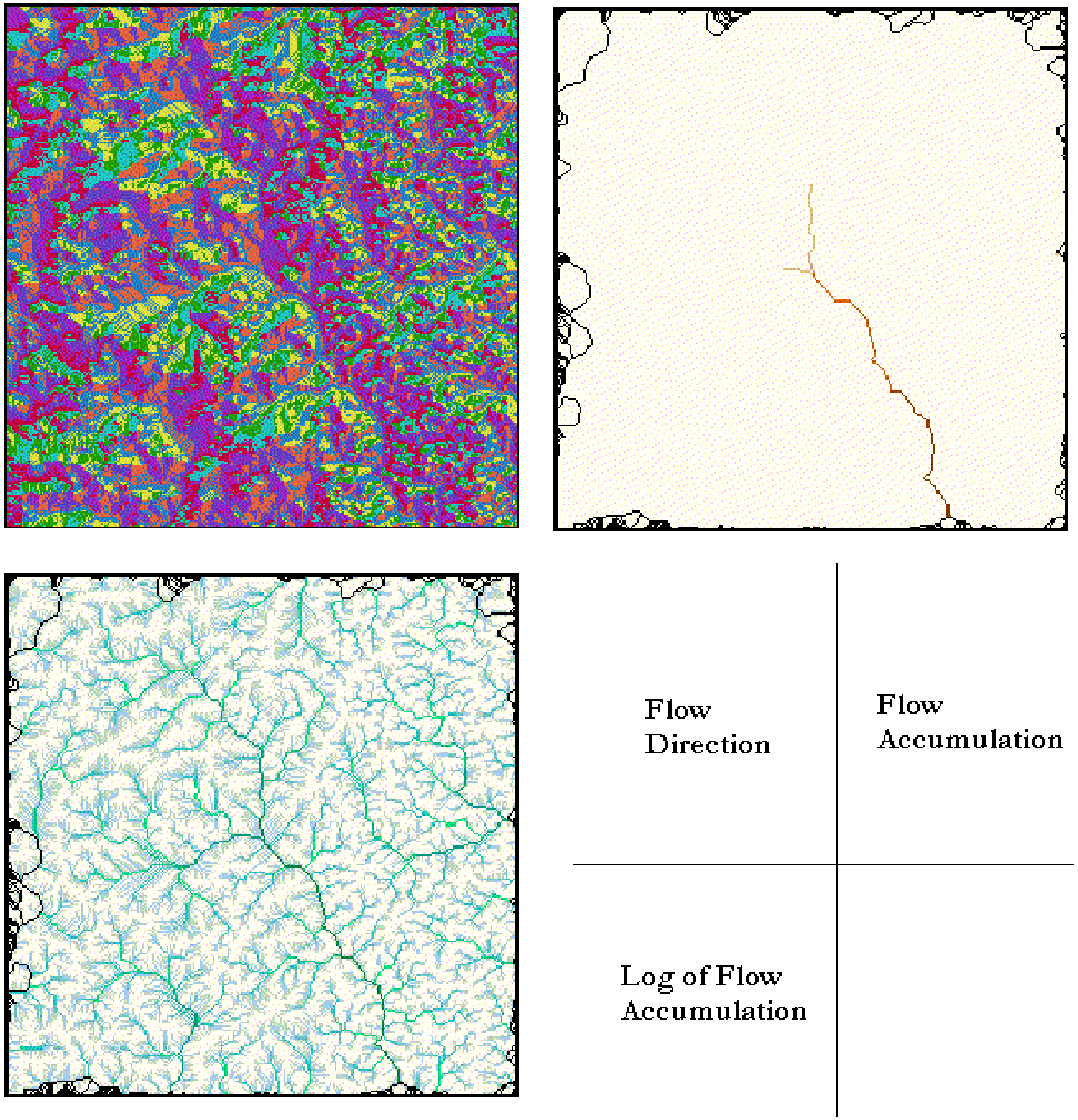
315.0	341.6	8.1	26.6	45.0	-1.0
270.0	288.4	11.3	45.0	26.6	
251.6	246.8	198.4	90.0	0.0	315.0
270.0	243.4	206.6	180.0	-1.0	-1.0
225.0	198.4	206.6	206.6	198.4	225.0
-1.0	-1.0	225.0	198.4	206.6	270.0

OUTGRID

Value = NODATA

White Cells Value = 0

Flow Direction and Accumulation



- Slope and aspect are needed to produce **flow direction**, which assigns each cell a **direction of steepest descent**
- **Flow accumulation** uses flow direction to find the **number of cells** that **drain to each cell**
- Taking the **log** of accumulation makes the **pattern** much easier to see

Flow Direction

- Flow Direction evaluates the **direction of steepest decent** for each cell in the grid by **comparing a cell with its eight neighbors** in the following fashion:
  - drop = change in z value / distance * 100
  - Note that diagonal neighbors are 1.414214 times as far away as 4-connected orthogonal neighbors
- ArcGIS **encodes** the resulting direction of steepest decent in the grid using **the following scheme**:

32	64	128
16	X	1
8	4	2

- For example:

From ArcView 3.2 Help

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

elevGrid

=

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

flowGrid

Fill Sinks

- A **sink** is a cell or set of spatially connected cells whose **flow direction cannot be assigned** one of the eight valid values in a flow direction Grid. This can occur **when all neighboring cells are higher** than the processing cell, or **when two cells flow into each other** creating a two-cell loop.
- To create an accurate representation of flow direction and therefore accumulated flow, it is best to use **a data set that is free of sinks**. A digital elevation model that has been processed to remove all sinks is referred to as a **depressionless DEM**.

From ArcView 3.2 Help

Flow Accumulation

- Flow accumulation find the **number of cells that drain to any cell** in the grid, taking the flow direction grid as input:
  - Output cells with a **high flow accumulation** are areas of concentrated flow and may be used to **identify stream channels**.
  - Output cells with a **flow accumulation of 0** are local topographic highs and may be used to **identify ridges**.
- For example:

From ArcView 3.2 Help

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

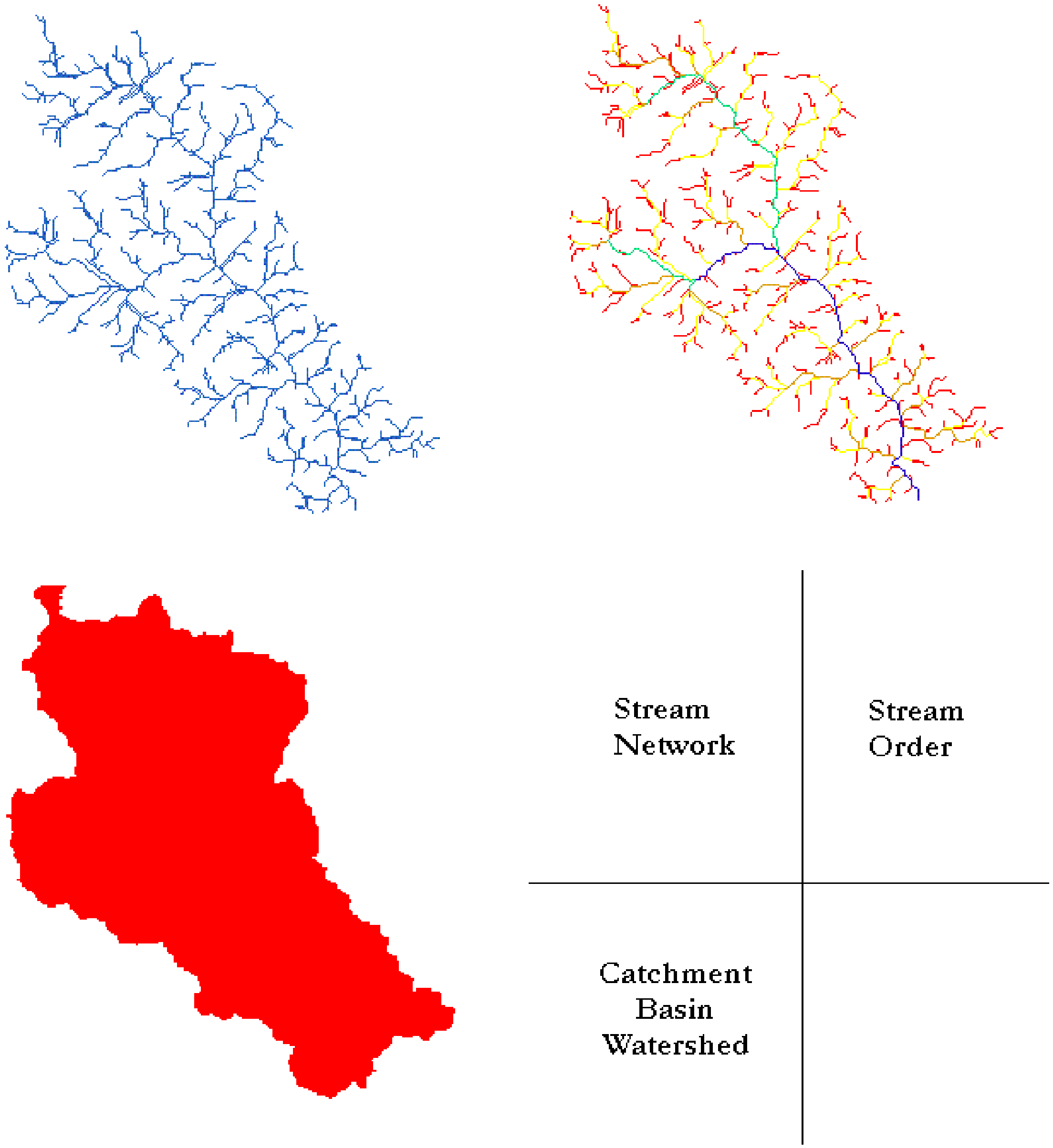
flowGrid

=

0	0	0	0	0	0
0	1	1	2	2	0
0	3	7	5	4	0
0	0	0	20	0	1
0	0	0	1	24	0
0	2	4	7	35	2

accumGrid

Stream Links, Order, and Basins



- By selecting a **threshold value** for flow accumulation, we can produce a **stream network**
- This network can **divided** into **stream links**, which can in turn be assigned **stream order** values using network analysis methods
- Threshold=1 gives the **watershed**

Products of D8 Analysis

- Producing a drainage network using D8 provides some very **useful descriptions** of the landscape from a sinkless raster DEM:
  - For each cell we can determine which neighboring cell will **receive its drainage** (flow direction)
  - We can use the flow directions to find the **flow accumulated** at each cell
  - We can threshold flow accumulation to find a **stream network**
  - Through network analysis we can find **stream links** and assign **order** values to links
  - Using flow accumulation we can also find the set of cells that drain to a cell, its **catchment/basin/watershed**