Spatial Tools in Water Resource Management

Susan Steele-Dunne

3. Watersheds and ArcGIS

Acknowledgements

- ESRI: (http://webhelp.esri.com/arcgisdesktop/9.2)
- HydroSHEDS
- Prof. Nick van de Giesen

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Learning objectives

By the end of this lecture, you will be able to:

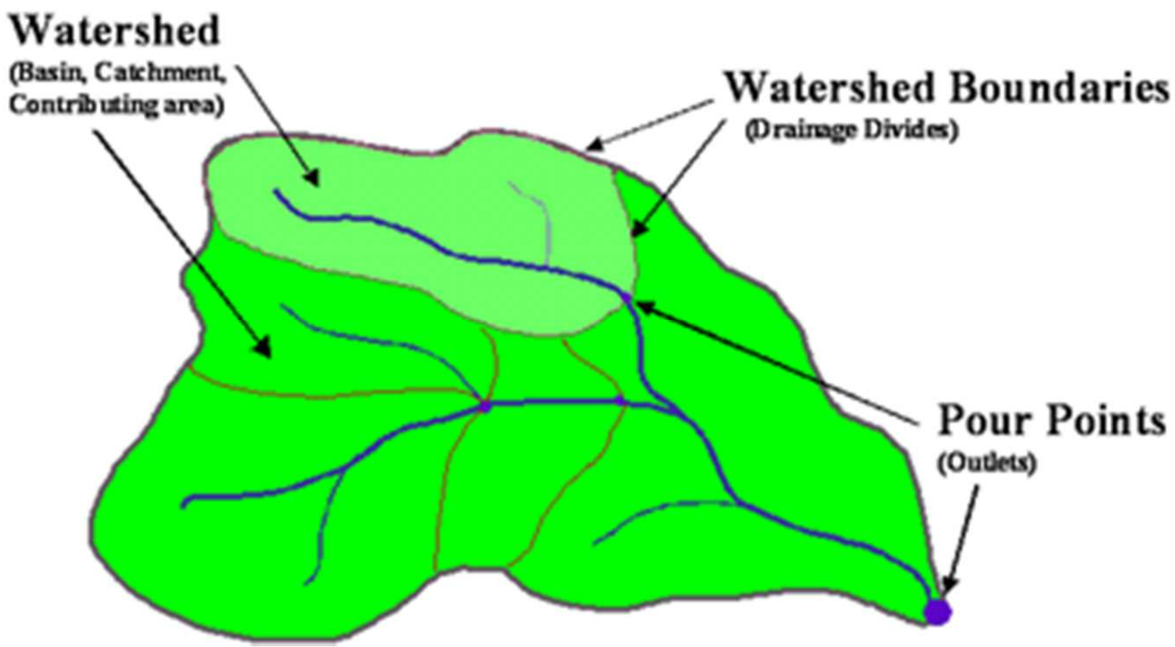
1) Explain what a watershed is
2) Explain how graph theory can be used to determine the watershed
3) Use ArcGIS to calculate the watershed from a digital elevation model.

Lecture 3: Watersheds and ArcGIS

- What is a watershed?
- Introduction to Graph Theory
- Determining watershed boundaries in ArcGIS
- HydroSHEDS

What is a watershed?

The area from which water drains to a common outlet.



A watershed is also known as a drainage basin, basin, catchment, or contributing area.

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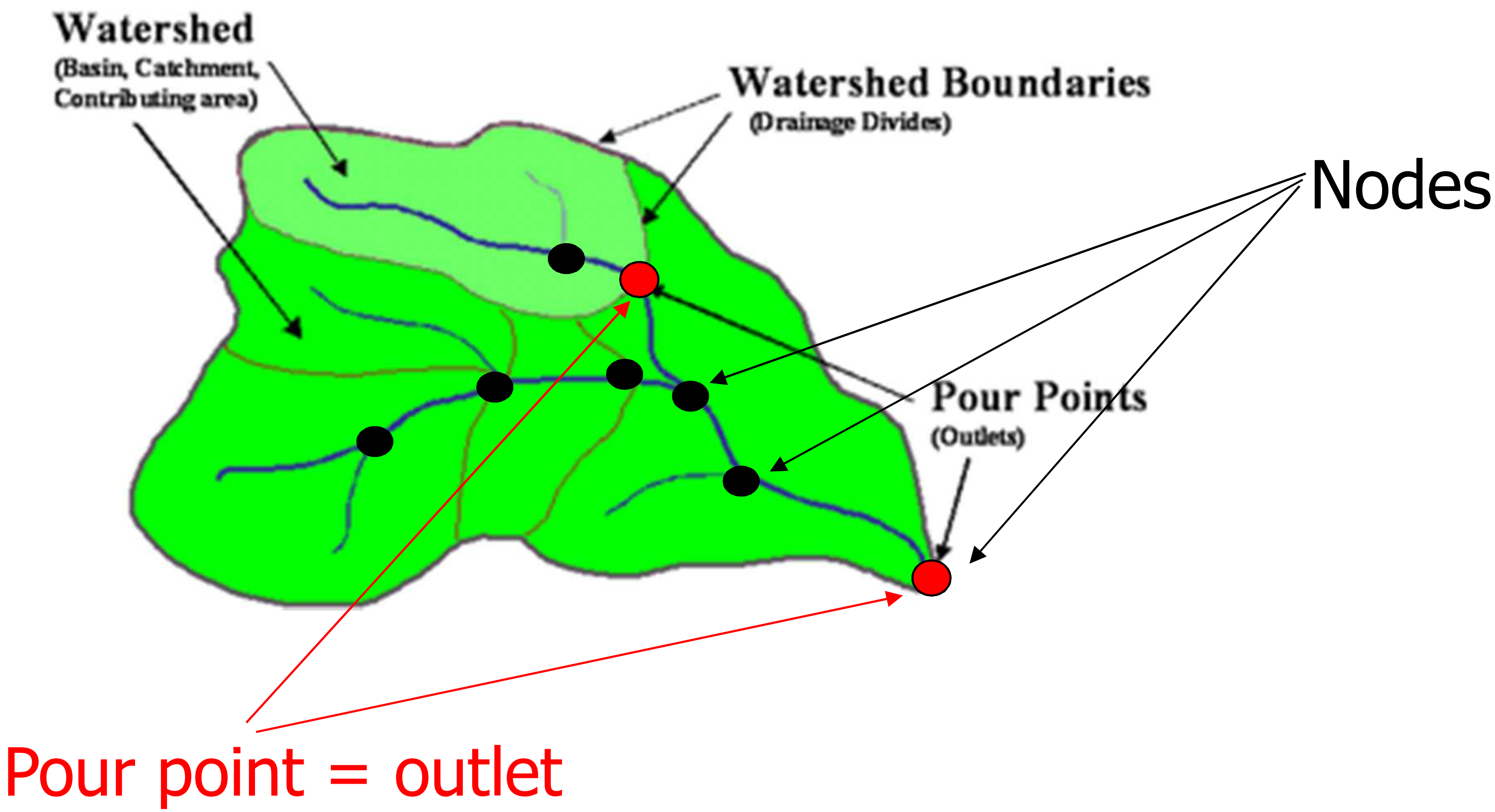
http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=Understanding_drainage_systems

What is a watershed?

A stream network is made up of nodes and links



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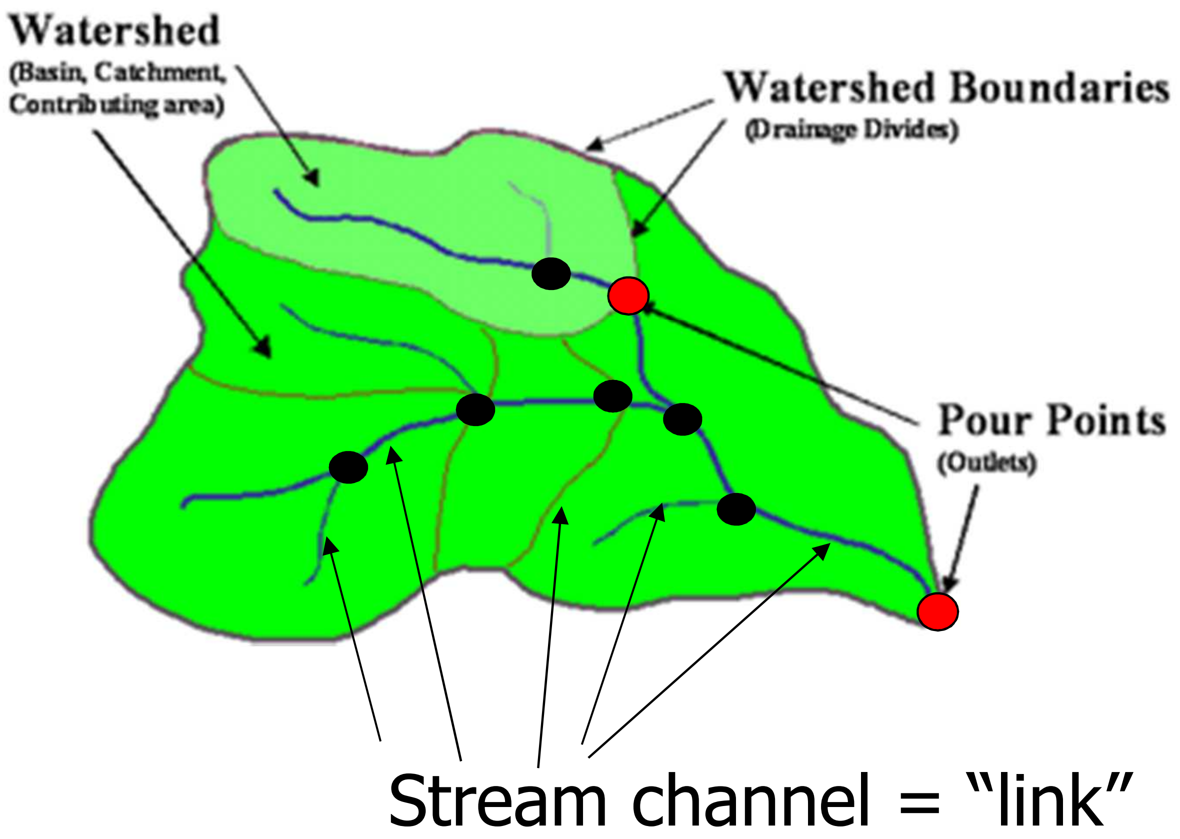

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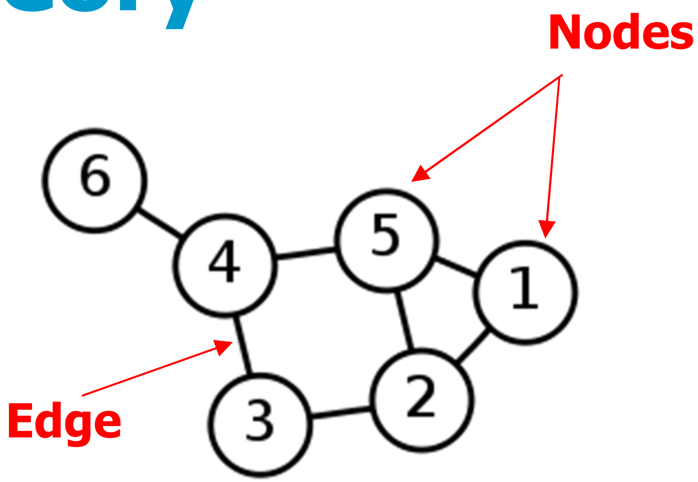
Introduction to Graph Theory

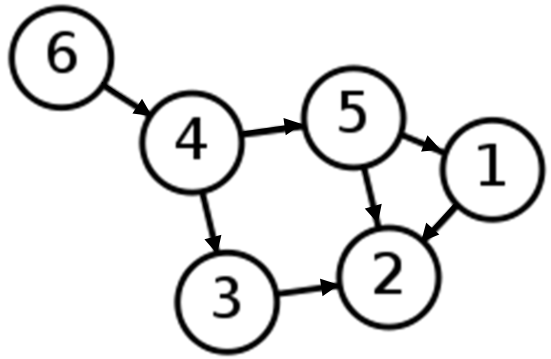
Graph theory = study of graphs

Graph = collection of ***nodes*** (aka vertices) and ***edges*** (links).

Graphs are used to model pairwise relations between objects



Undirected graph



Directed graph aka network

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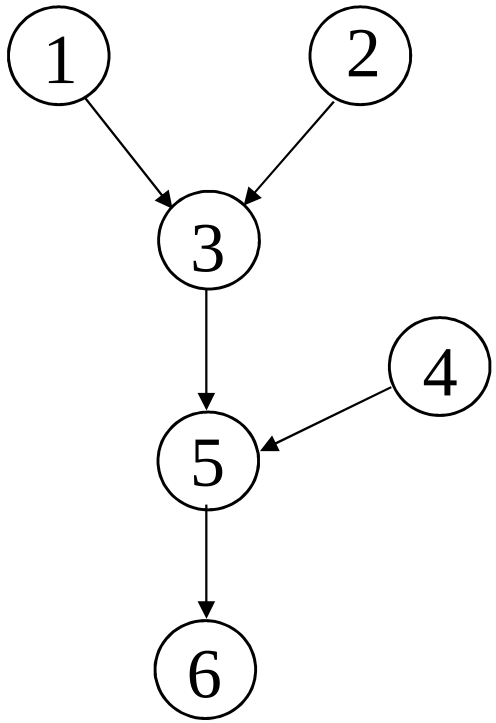
Introduction to Graph theory

Adjacency Matrix

Which nodes are adjacent to which other nodes

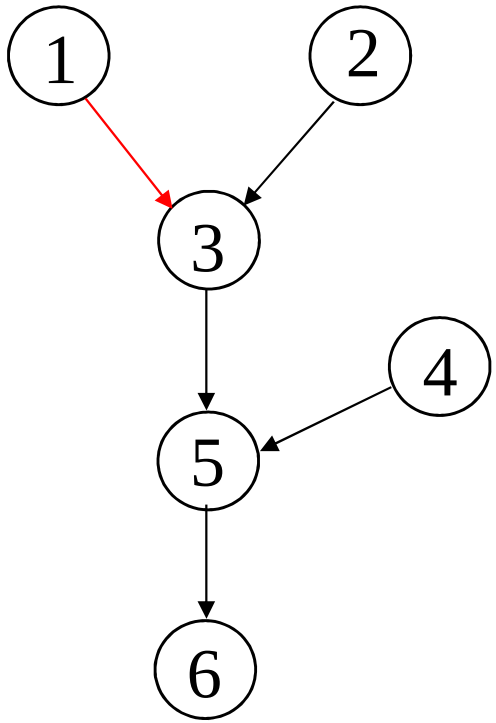


- n x n matrix
- If node i drains into node j, set A(i,j)=1.
- Otherwise, set to zero

Drainage patterns

Adjacency Matrix

Which nodes are adjacent to which other nodes:



$$A = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Drainage patterns

Adjacency Matrix

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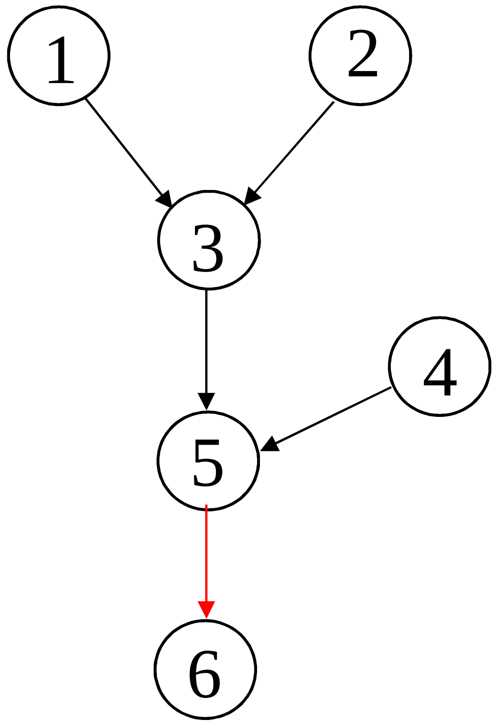

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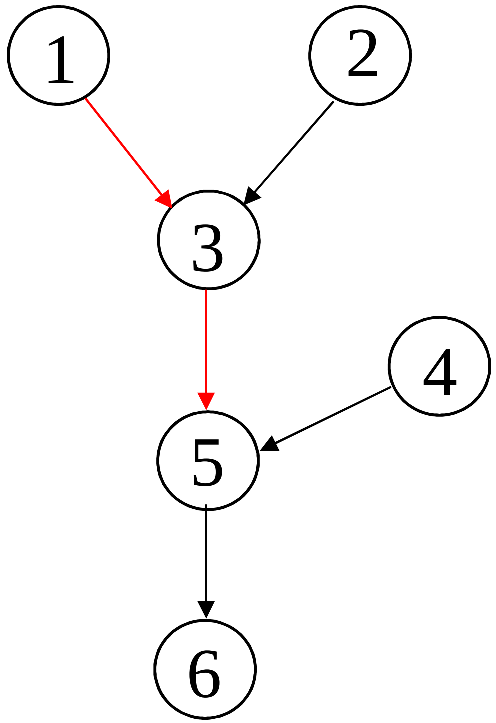
Drainage patterns

Adjacency Matrix²

Which nodes are connected by two steps:



$$A^2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Drainage patterns

Adjacency Matrix²

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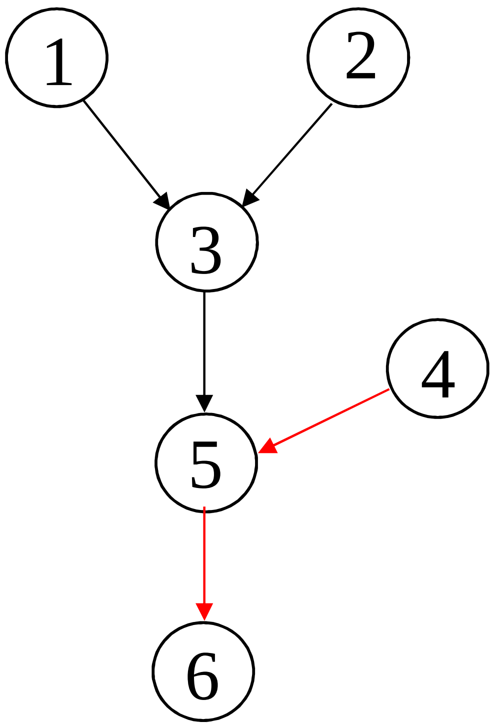
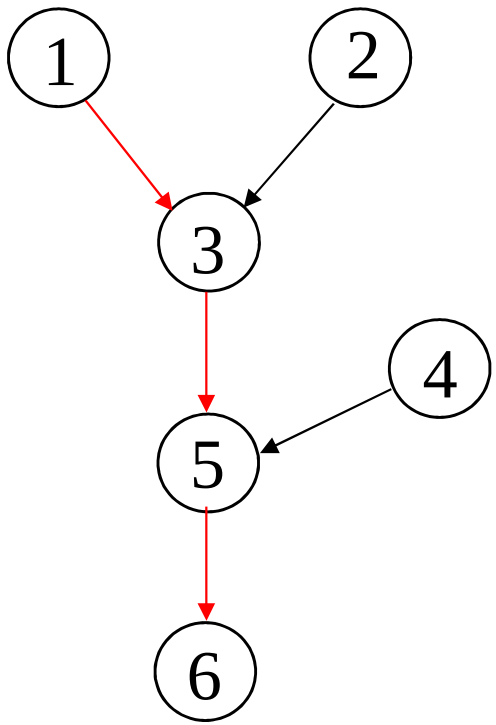


$$A^2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Drainage patterns

Adjacency Matrix³

Which nodes are connected by three steps:



$$A^3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

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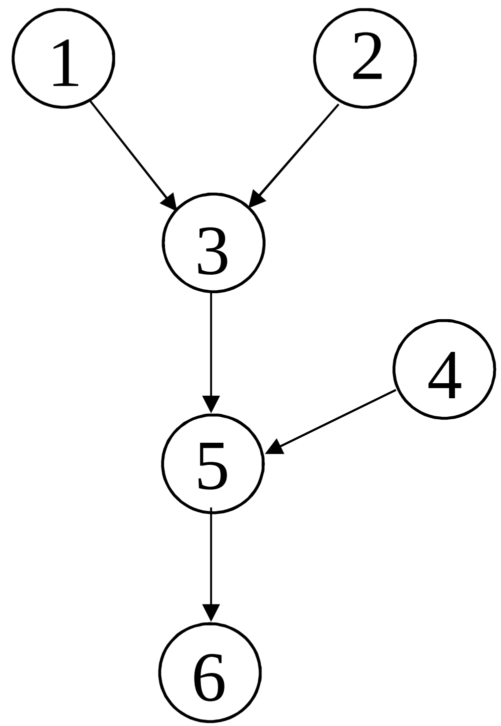
Drainage patterns

"Water availability matrix":

$$\Sigma = A + A^2 + A^3$$

Columns show "upstream" nodes!

$$\Sigma = \begin{bmatrix} 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$



Which nodes are upstream from node 3? Nodes 1 and 2

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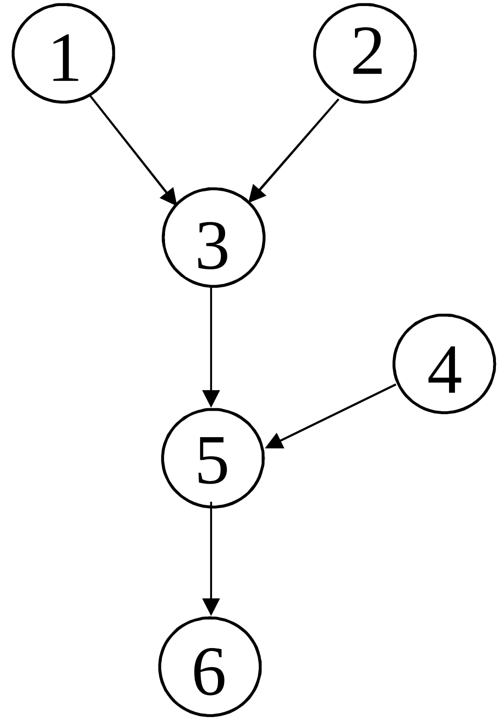
Drainage patterns

"Water availability matrix":

$$\Sigma = A + A^2 + A^3$$

$$\Sigma = \begin{bmatrix} 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Rows show "downstream" nodes!



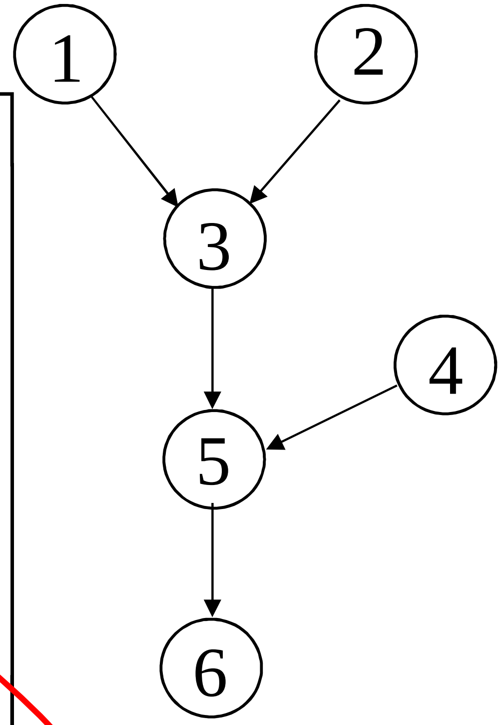
Which nodes are downstream from node 2? … Nodes 3, 5 and 6.

Drainage patterns

"Watershed matrix":

$$\Sigma + I = A + A^2 + A^3 + I$$

$$\Sigma + I = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$



We want to include the "zero-th" step, i.e. that a node drains itself
=> We get the real watershed matrix!

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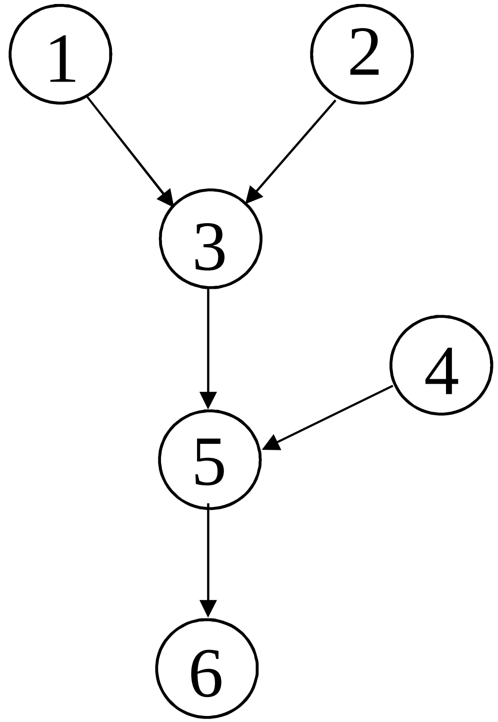
Drainage patterns

"Watershed matrix":

$$\Sigma + I = A + A^2 + A^3 + I$$

$$\Sigma + I = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\begin{matrix} 1 & 1 & 3 & 1 & 5 & 6 \end{matrix}$$



Summing the columns gives the "drainage area" or watershed size for each pixel

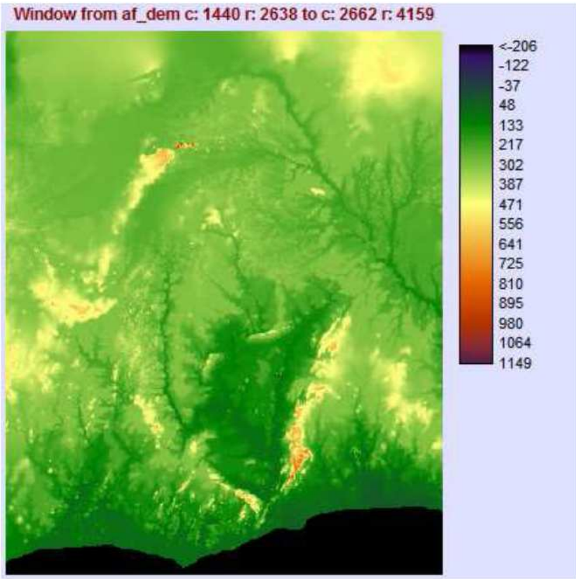
Drainage patterns

Adjacency/Watershed Matrix

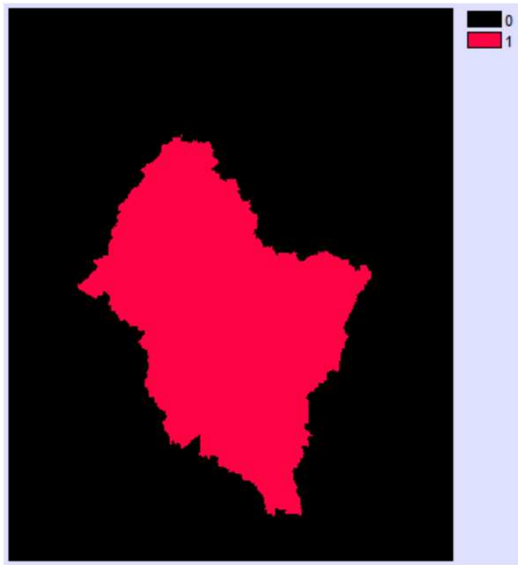
Interesting property:

$$I + A + A^2 + A^3 = (I - A)^{-1}$$

Used in GIS software!



GTOPO30 for the Volta Basin and environs



Watershed of the Akosombo dam.

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Drainage patterns

Adjacency/Watershed Matrix

Interesting property:

$$\underbrace{I + A + A^2 + A^3}_{} = (I - A)^{-1}$$

All the information needed to describe watershed

Adjacency Matrix

i.e. “local information”

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Drainage patterns

Flow accumulation

So far, we assumed all pixels generated same amount of input.

In practice run-off from pixels is variable

Build a row vector Q containing the run-off produced at each node:

$$\Sigma + I = A + A^2 + A^3 + I$$

$$\Sigma + I = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$Q = \begin{bmatrix} 3.2 & 2.3 & 0 & 0 & 0 & 0 \end{bmatrix}$$

e.g node 1 generates 3.2 units of water, node 2 generates 2.3 units

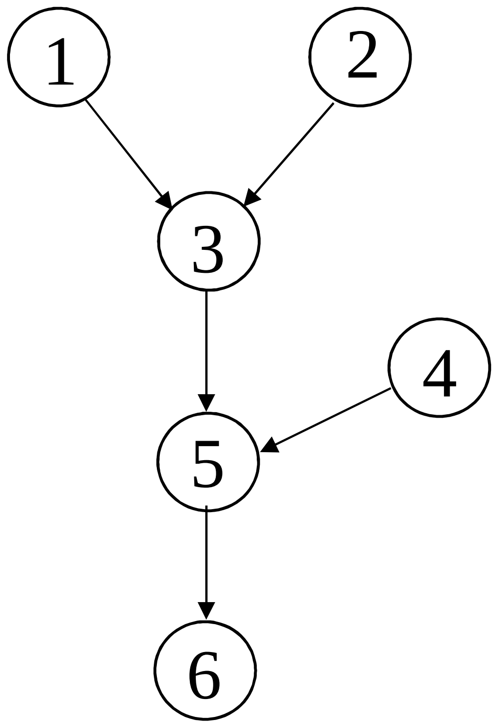
Drainage patterns

Flow accumulation

Build a row vector Q containing the run-off produced at each node:

$$Q = \begin{bmatrix} 3.2 & 2.3 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$Q * (\Sigma + I) = \begin{bmatrix} 3.2 & 2.3 & 5.5 & 0 & 5.5 & 5.5 \end{bmatrix}$$



This gives the total flow accumulated in each node

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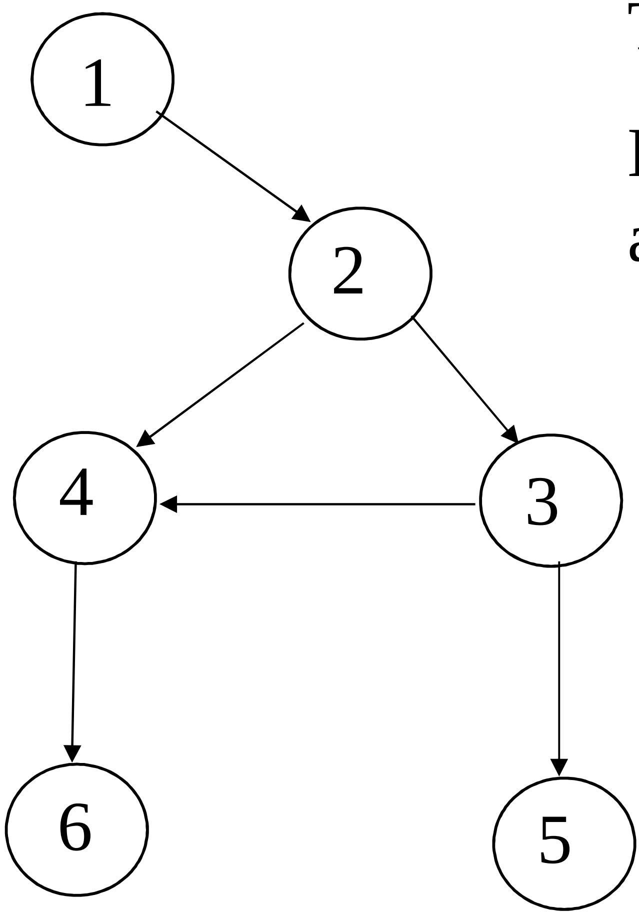
Water use along river network

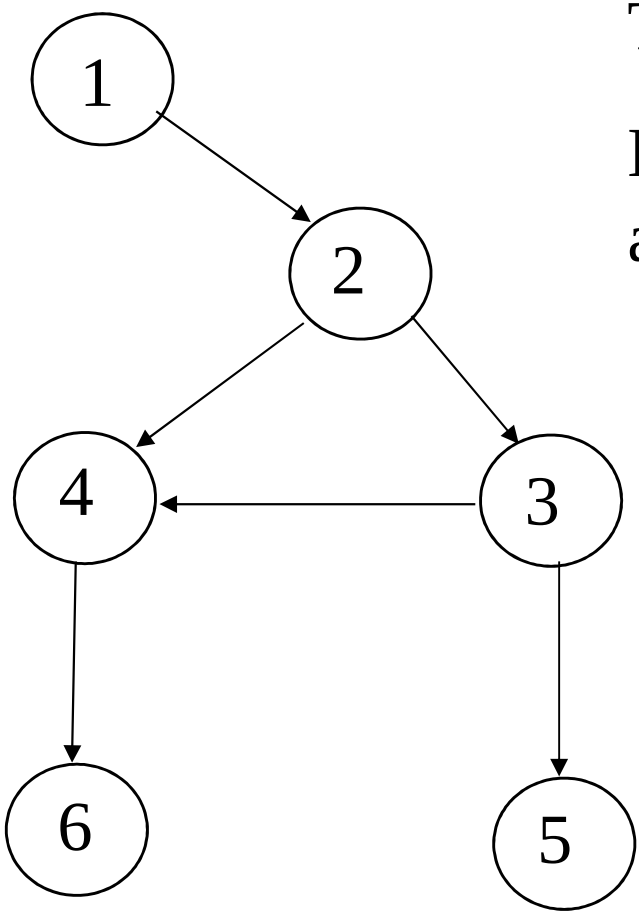


This case will be a bit more complicated.

Let's start by filling in the regular adjacency matrix ….

$W =$

Water use along river network



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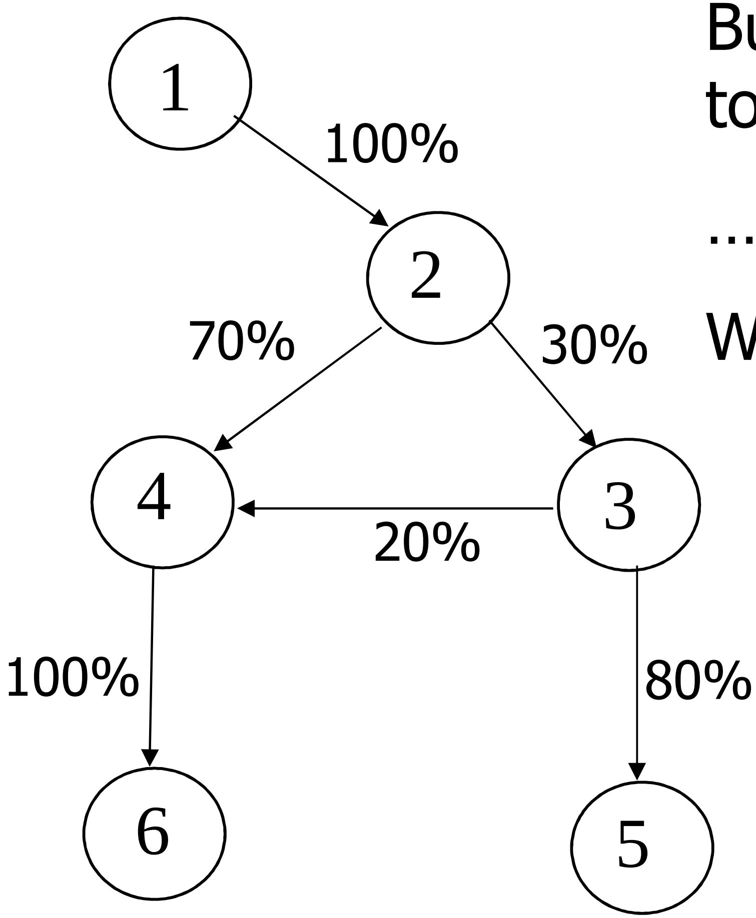
Let's start by filling in the regular adjacency matrix ….

$$W = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Water use along river network



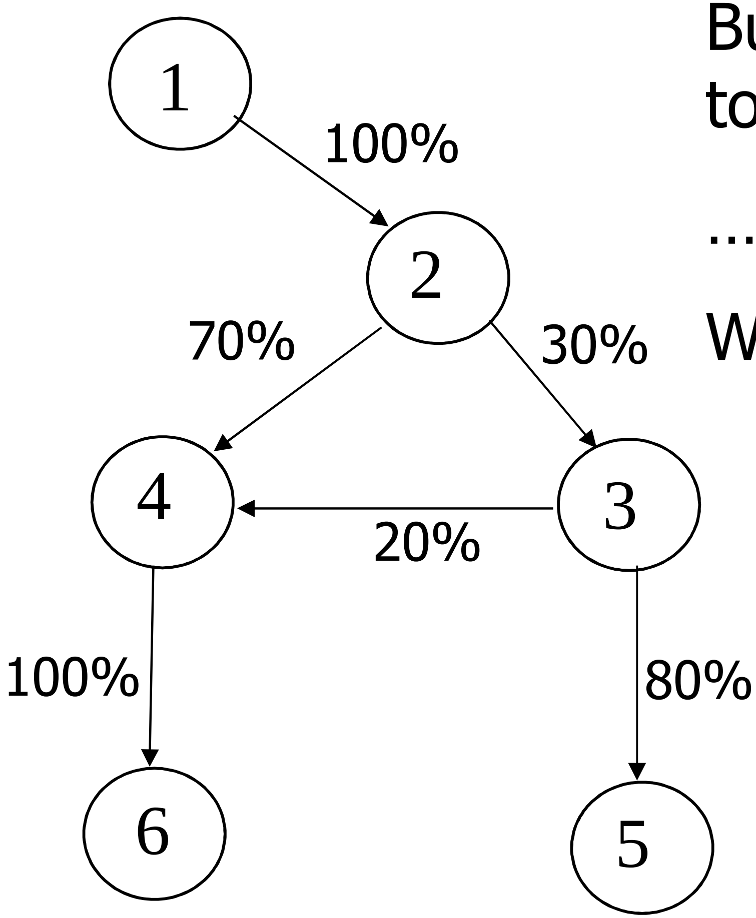
But how can all the water go from node 2 to both nodes 3 and 4?

… It doesn't!

What happens to our adjacency matrix?

$W =$

Water use along river network



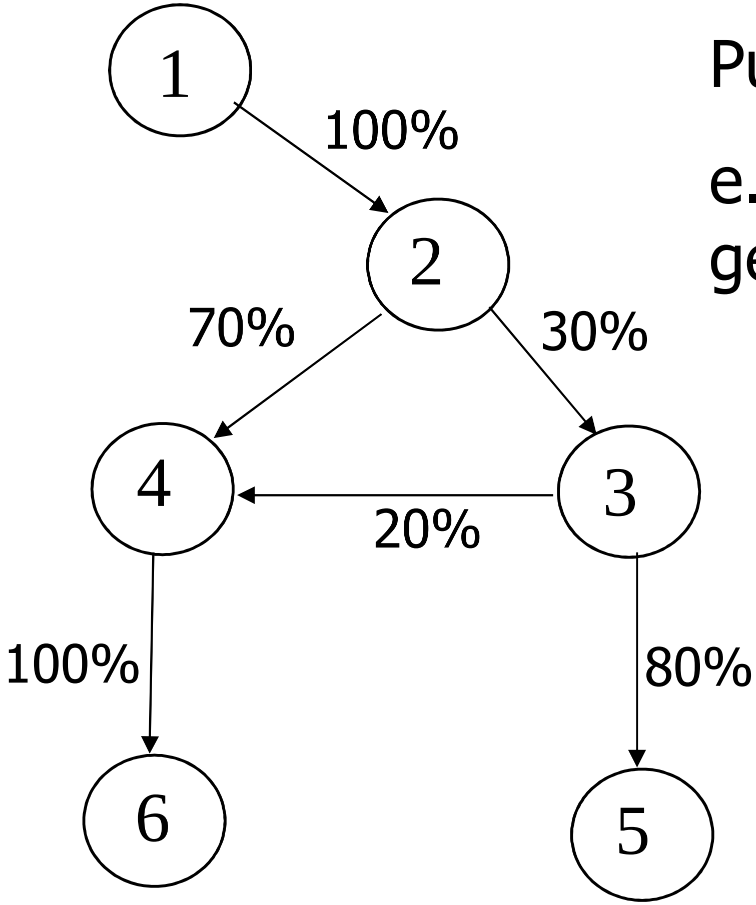
But how can all the water go from node 2 to both nodes 3 and 4?

… It doesn't!

What happens to our adjacency matrix?

$$W = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.3 & 0.7 & 0 & 0 \\ 0 & 0 & 0 & 0.2 & 0.8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Water use along river network

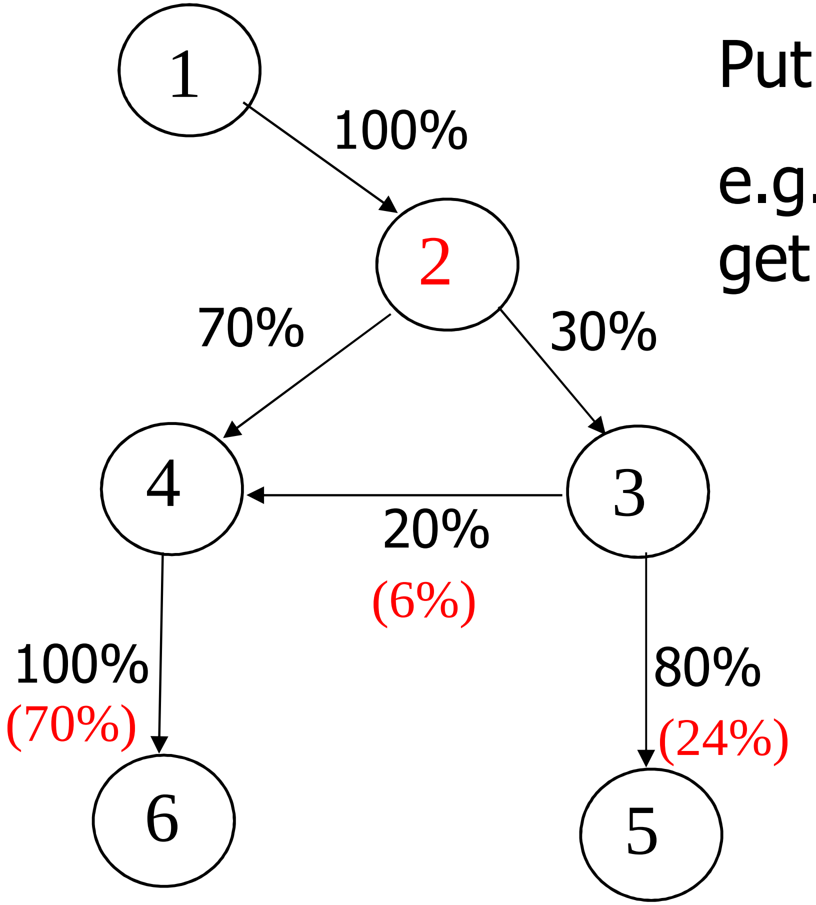


Put W into Matlab/excel and calculate W²:

e.g. Where does the water from node 2 get to in two steps?

$W^2 =$

Water use along river network



Put W into Matlab/excel and calculate W^2:

e.g. Where does the water from node 2 get to in two steps?

$$W^2 = \begin{bmatrix} 0 & 0 & 0.3 & 0.7 & 0 & 0 \\ 0 & 0 & 0 & 0.06 & 0.24 & 0.7 \\ 0 & 0 & 0 & 0 & 0 & 0.2 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

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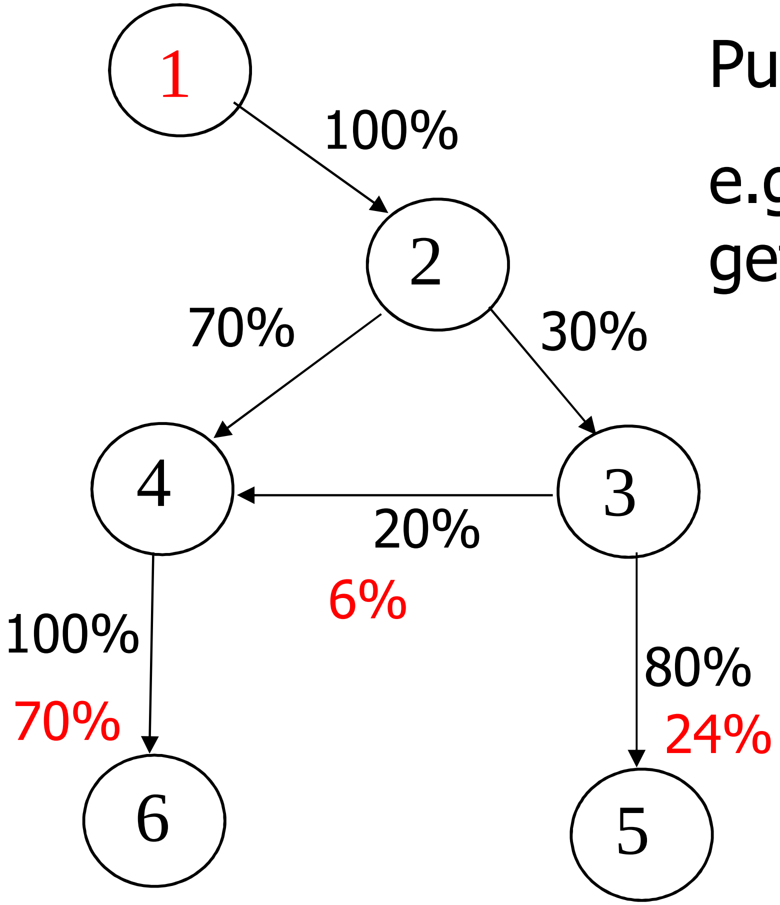
Water use along river network



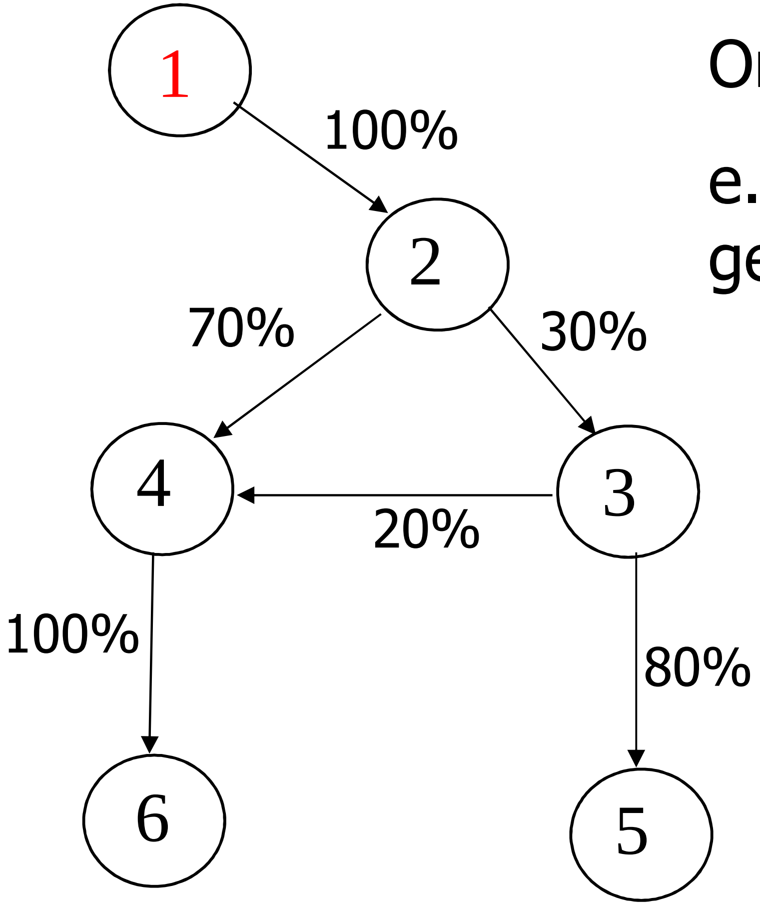
Put W into Matlab/excel and calculate W^3:

e.g. Where does the water from node 1 get to in three steps?

$$W^3 = \begin{bmatrix} 0 & 0 & 0 & 0.06 & 0.24 & 0.7 \\ 0 & 0 & 0 & 0 & 0 & 0.06 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

After 3 steps, 94% of the water from (1) has made it to an outlet, but 6% is just getting to node 4!

Water use along river network



One last time step, let's calculate W^4:

e.g. Where does the water from node 1 get to in four steps?

$W^4 =$ 

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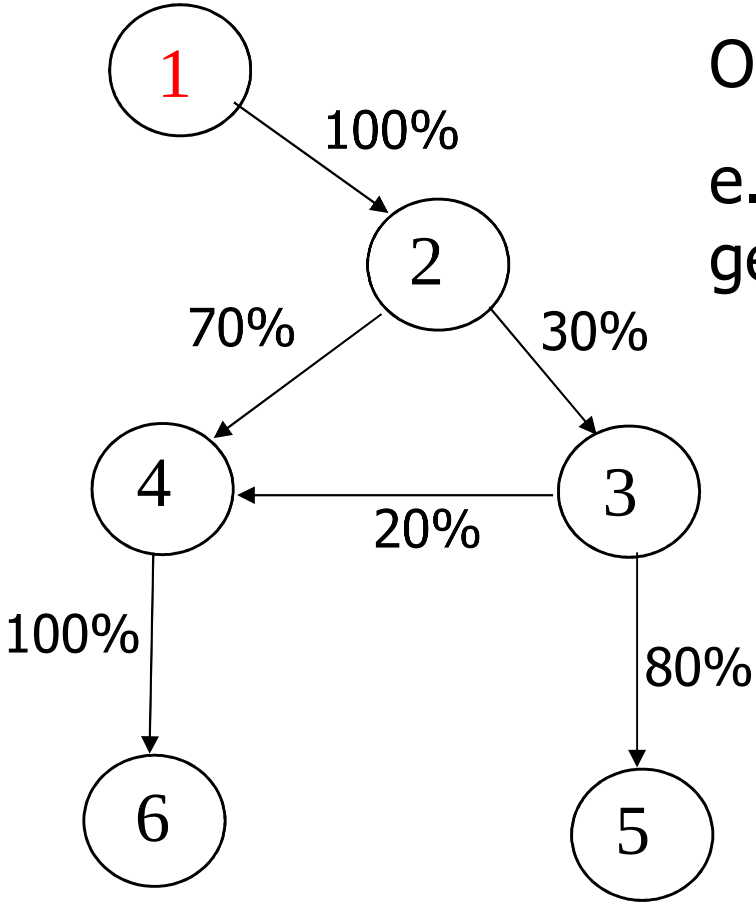
Water use along river network



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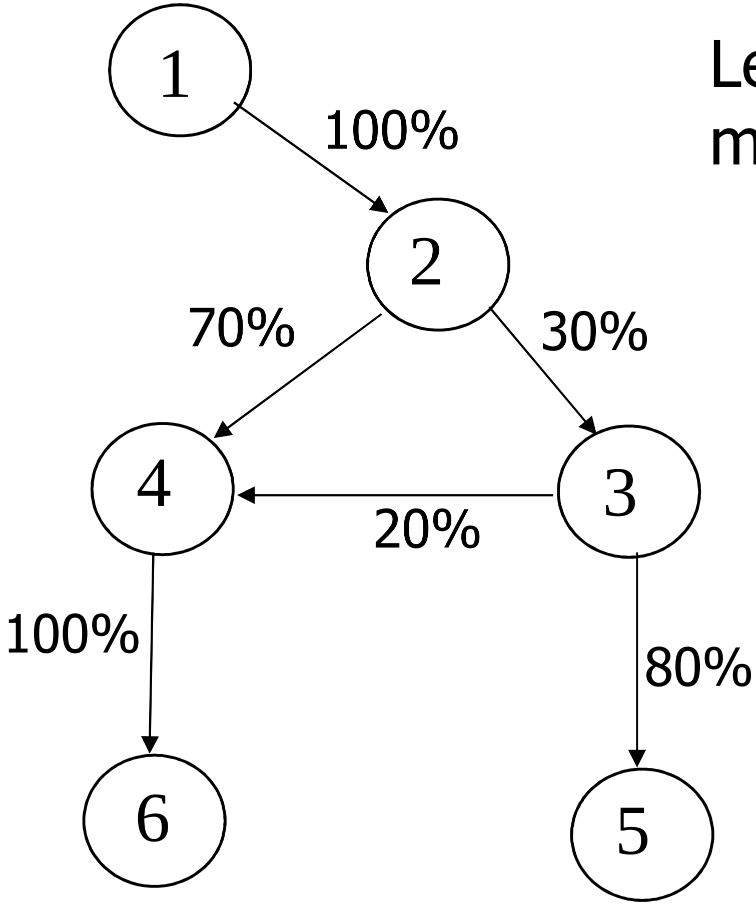
Water use along river network

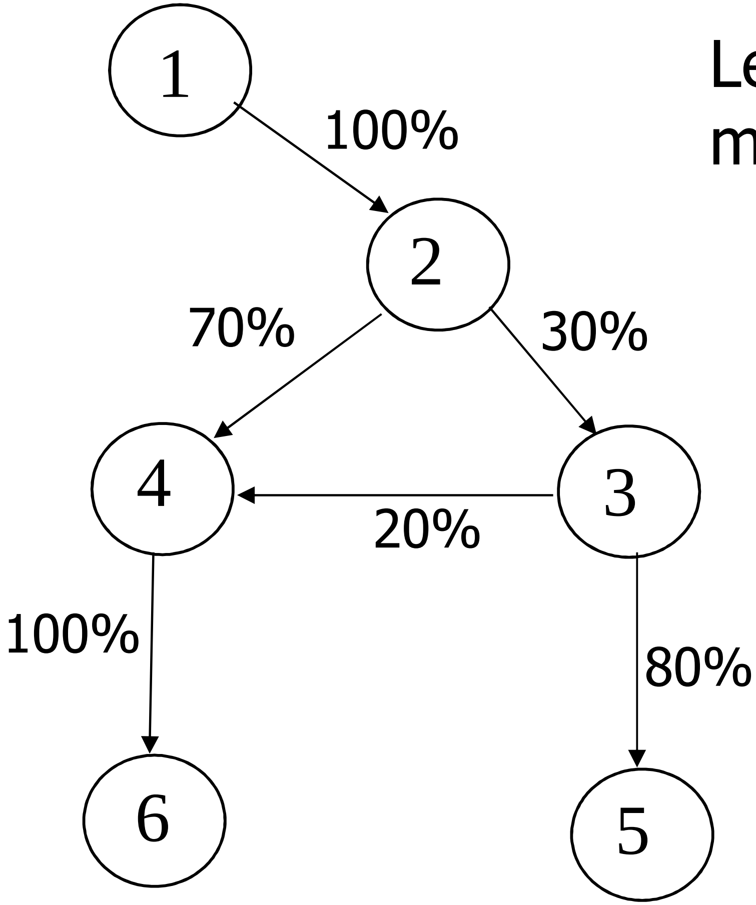


Let's calculate the water availability matrix, Ω, for this case:

$$\Omega = W + W^2 + W^3 + W^4$$

$$\Omega =$$

Water use along river network



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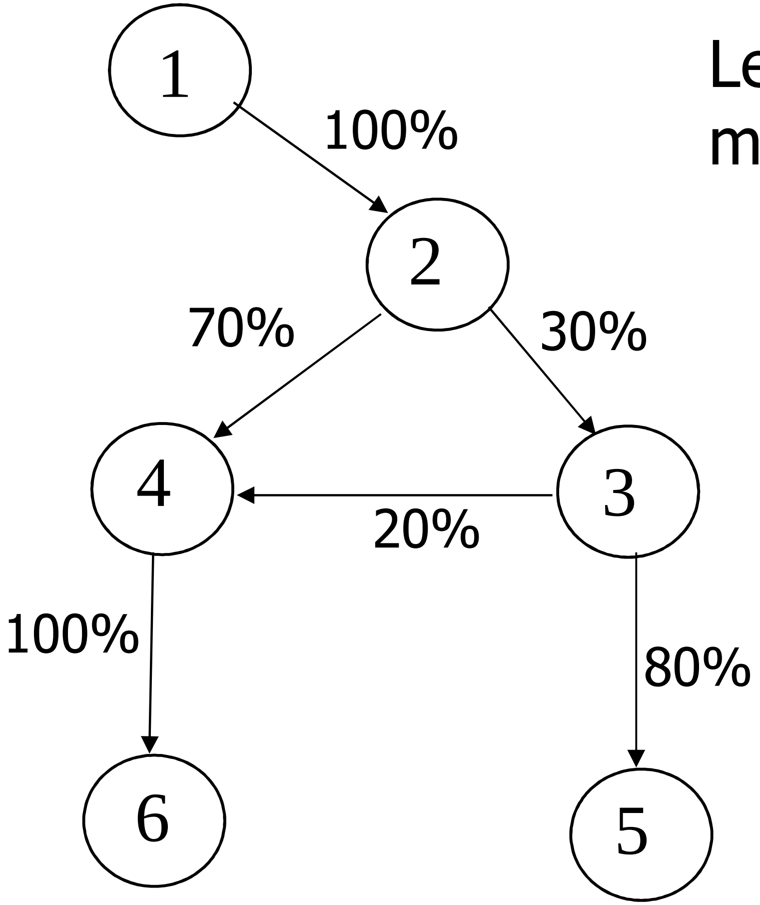
$$\Omega = \begin{bmatrix} 0 & 1.0 & 0.3 & 0.76 & 0.24 & 0.76 \\ 0 & 0 & 0.3 & 0.76 & 0.24 & 0.76 \\ 0 & 0 & 0 & 0.2 & 0.8 & 0.2 \\ 0 & 0 & 0 & 0 & 0 & 1.0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Water use along river network



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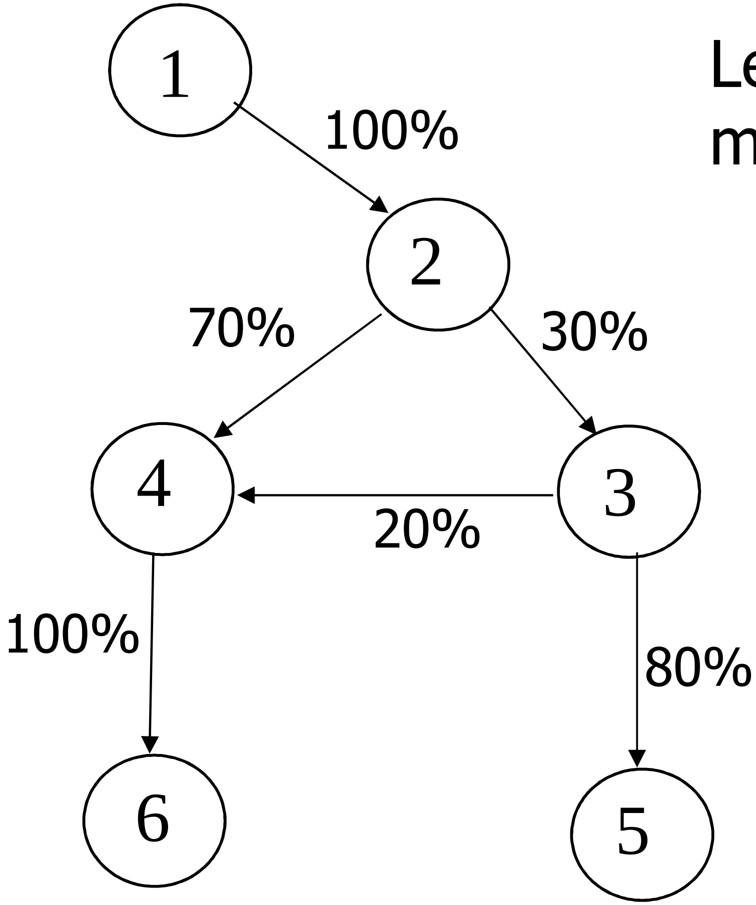
Water use along river network



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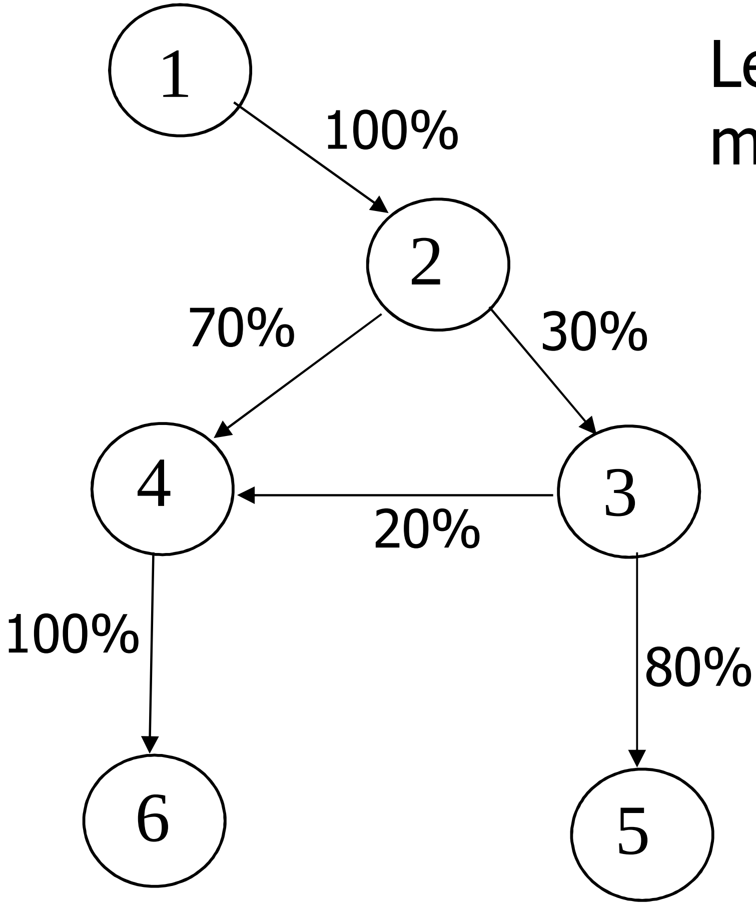
Water use along river network



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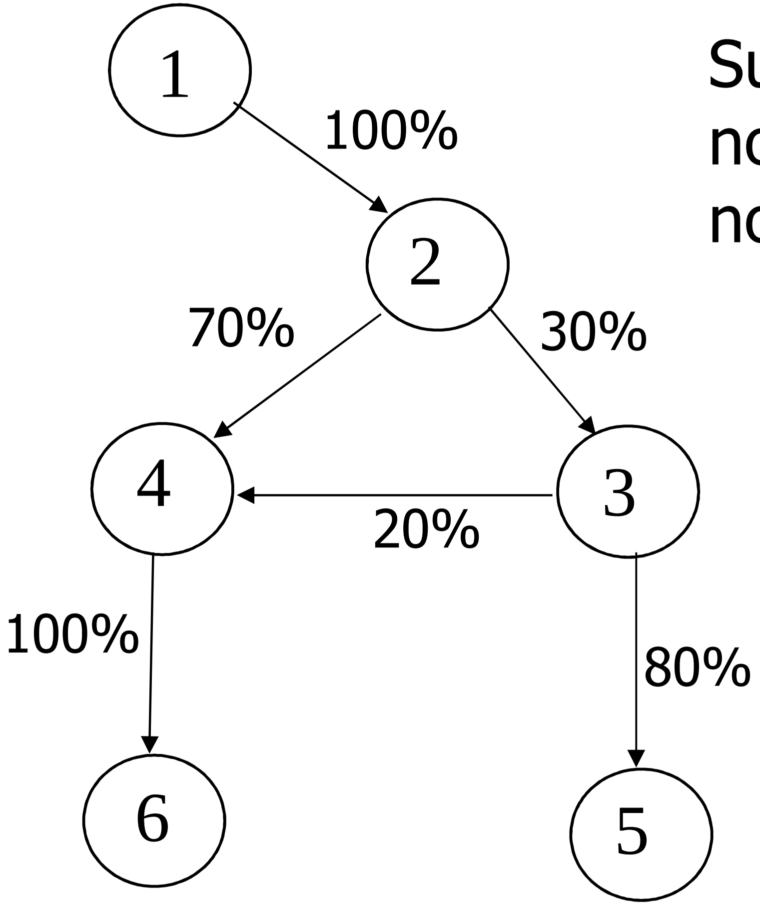
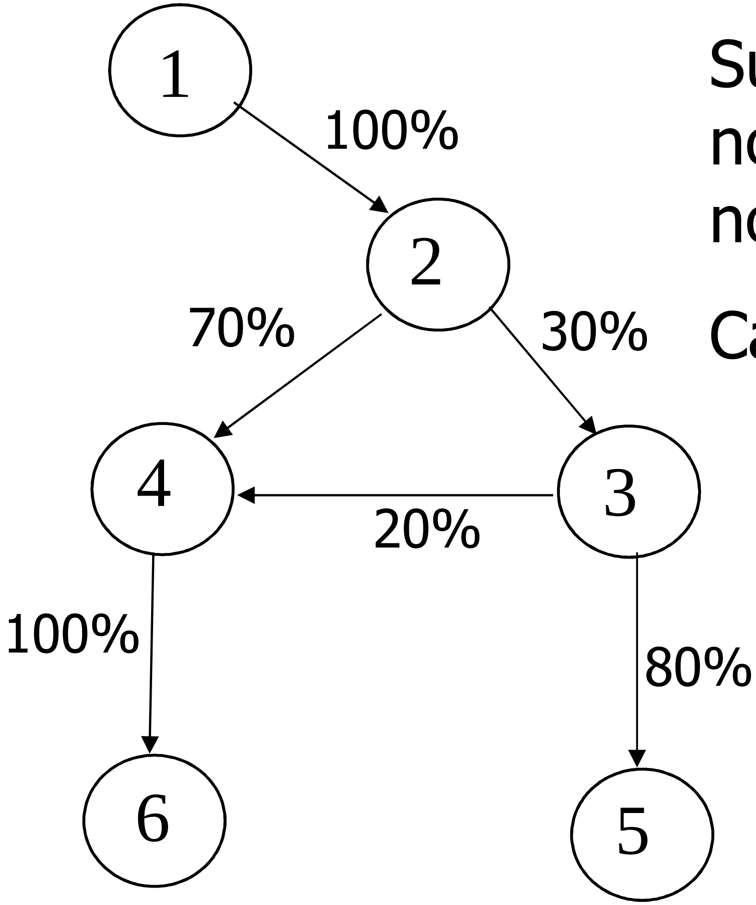
Water use along river network



Suppose we inject 200 units of water at node 1. How much will we see at each node?

Water use along river network



Suppose we inject 200 units of water at node 1. How much will we see at each node?

Calculate P*Ω where P=[200 0 0 0 0 0]

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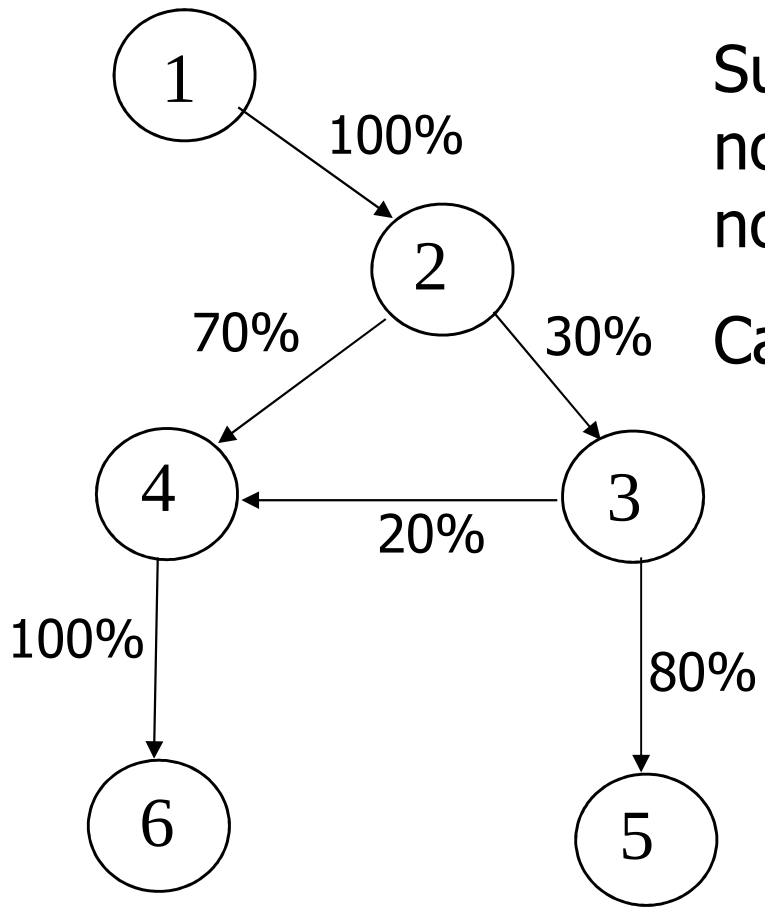
Water use along river network

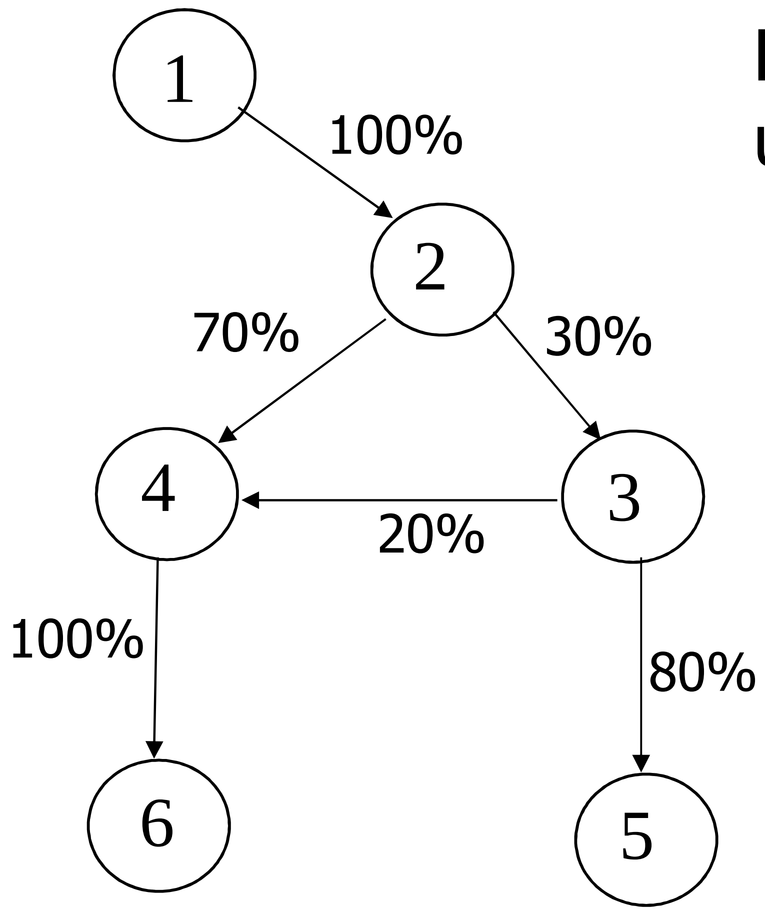


Suppose we inject 200 units of water at node 1. How much will we see at each node?

Calculate Q=P*Ω where P=[200 0 0 0 0 0]

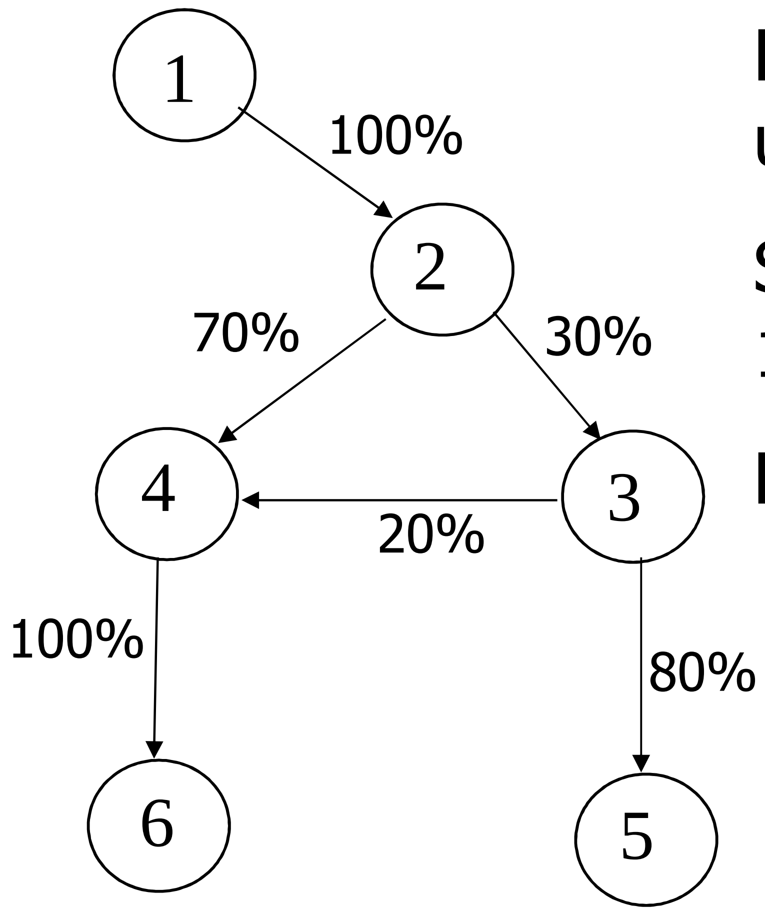
Q=[0   200   60   152   48   152]

Water use along river network



How do you account for water being used at a node?

Water use along river network

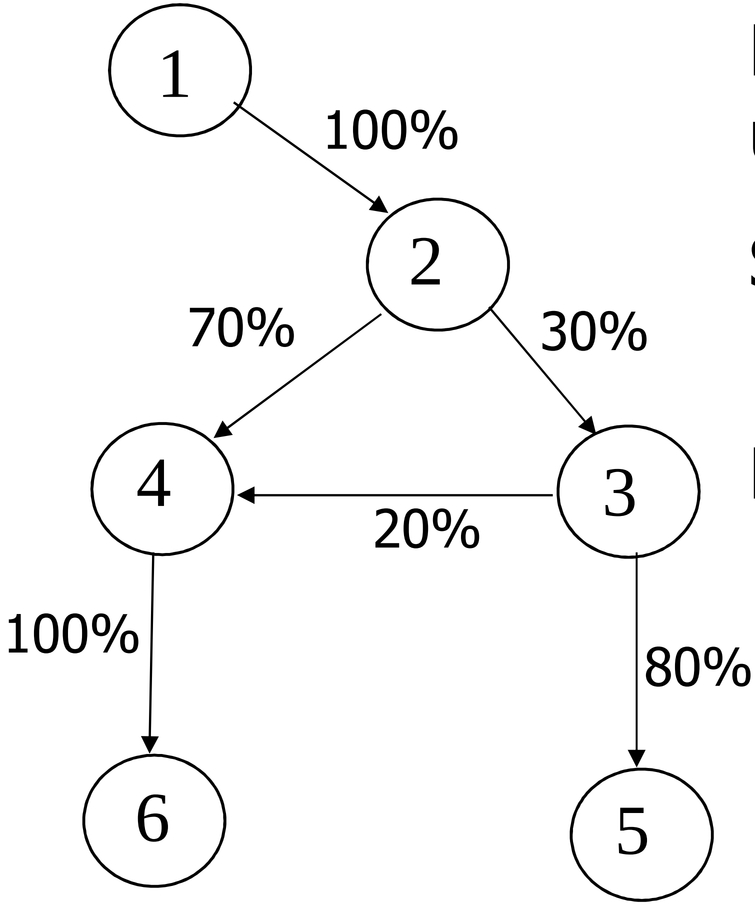


How do you account for water being used at a node?

Suppose we inject 200 units at node 1, but use 100 units at node 2:

P=?

Water use along river network

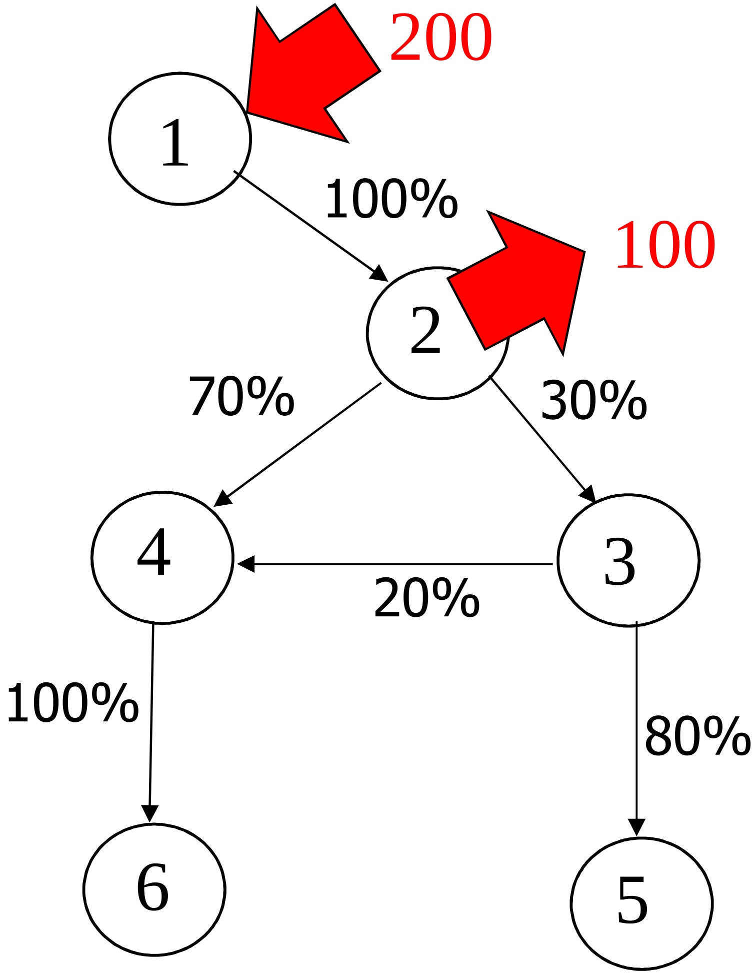


How do you account for water being used at a node?

Suppose we inject 200 units at node 1, but use 100 units at node 2:

P=[200 -100 0 0 0 0]

Water use along river network



P=[200 -100 0 0 0 0]

Q=P*Ω

Q=[0 200 30 76 24 76]

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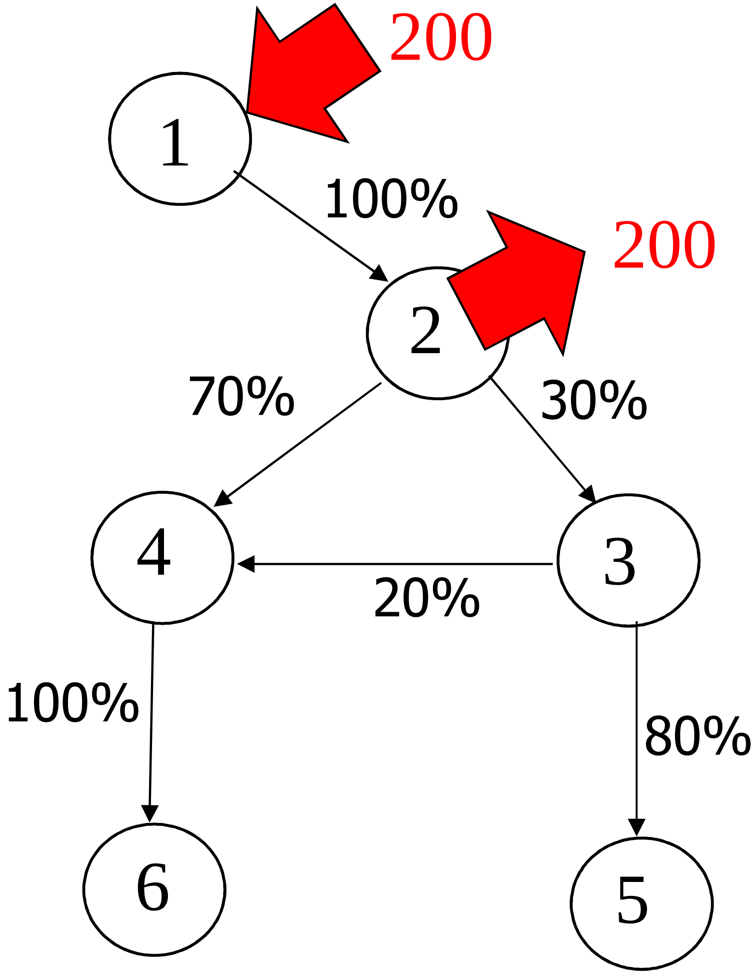
Water use along river network



P=[200 -200 0 0 0 0]

$Q=P*\Omega$

Q=??

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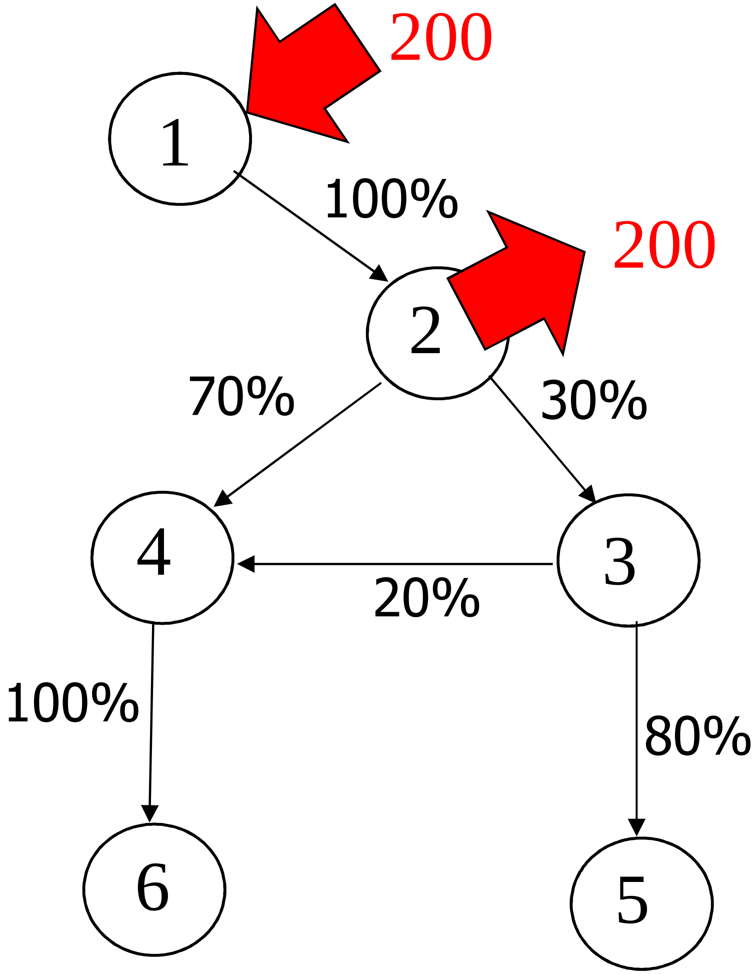
Water use along river network

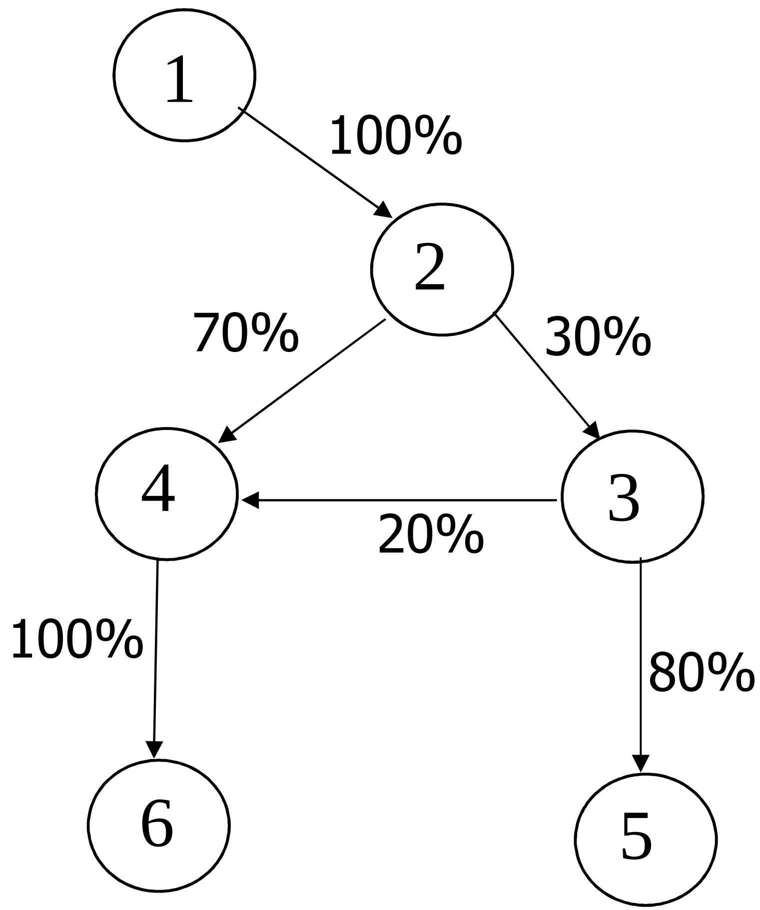


P=[200 -200 0 0 0 0]

Q=P*Ω

Q=[0 200 0 0 0 0]

Water use along river network



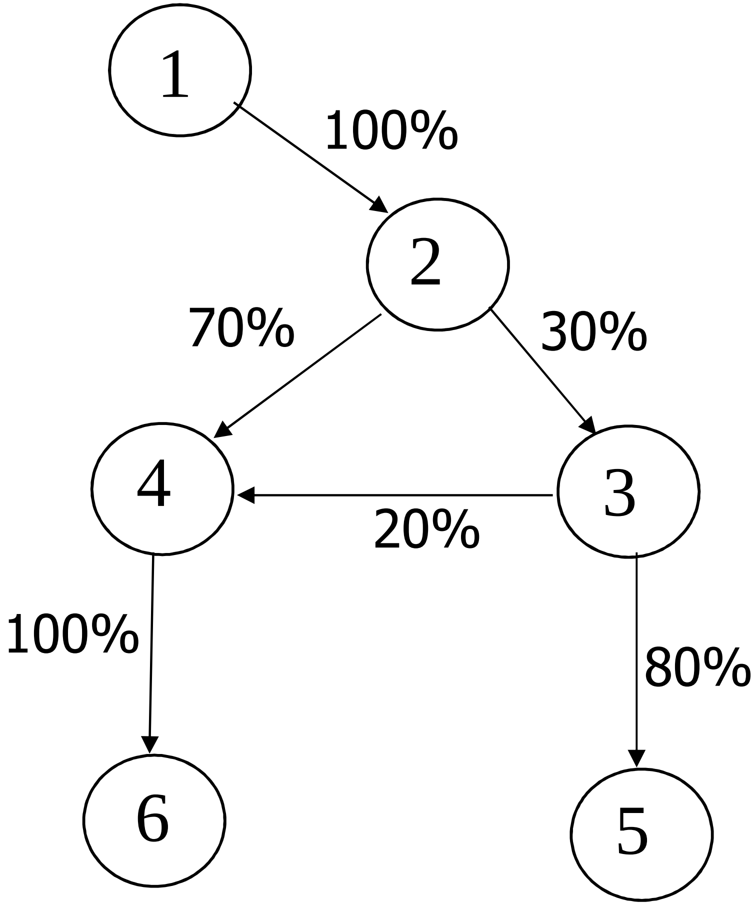
What if you demand too much water??

P=[200 -300 0 0 0 0]

Q=P*Ω

Q=?

Water use along river network



What if you demand too much water??

P=[200 -300 0 0 0 0]

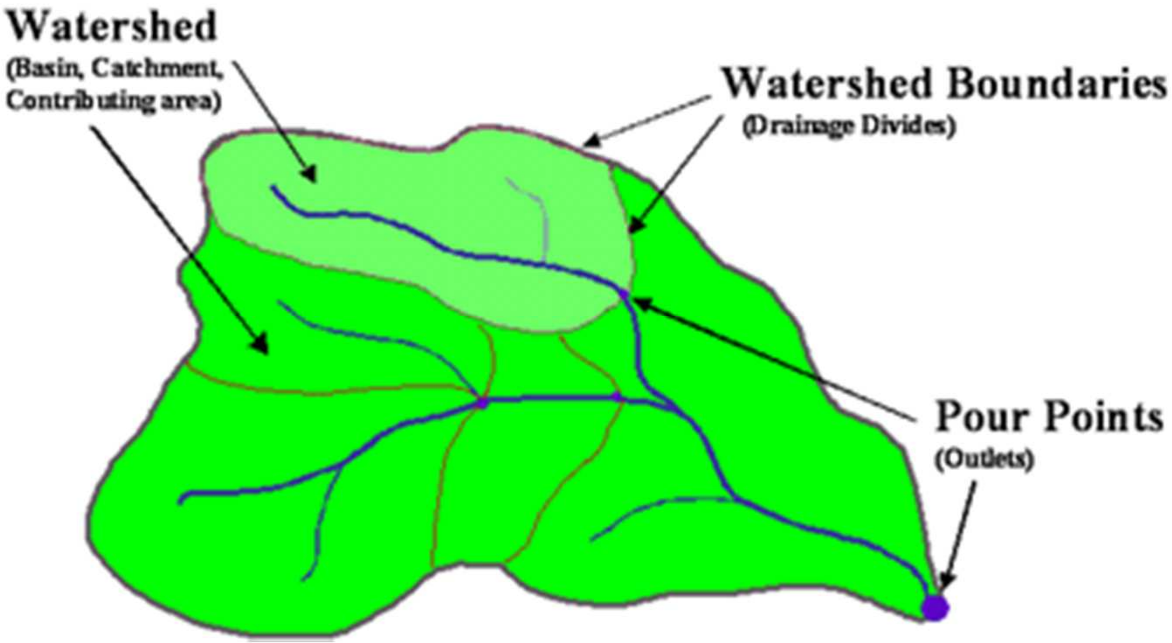
Q=P*Ω

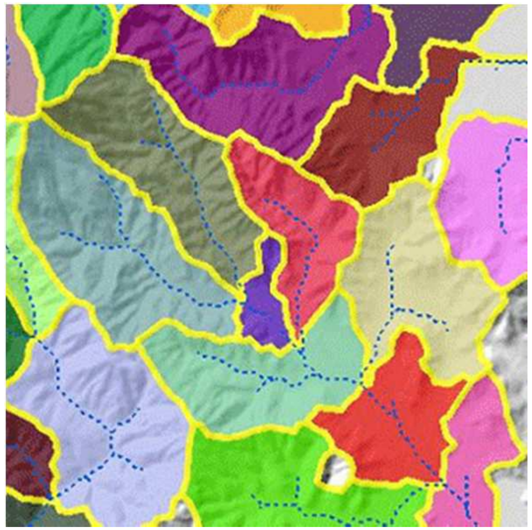
Q=[0 200 -30 -76 -24 -76]

Watershed delineation in ArcGIS

What is a watershed?

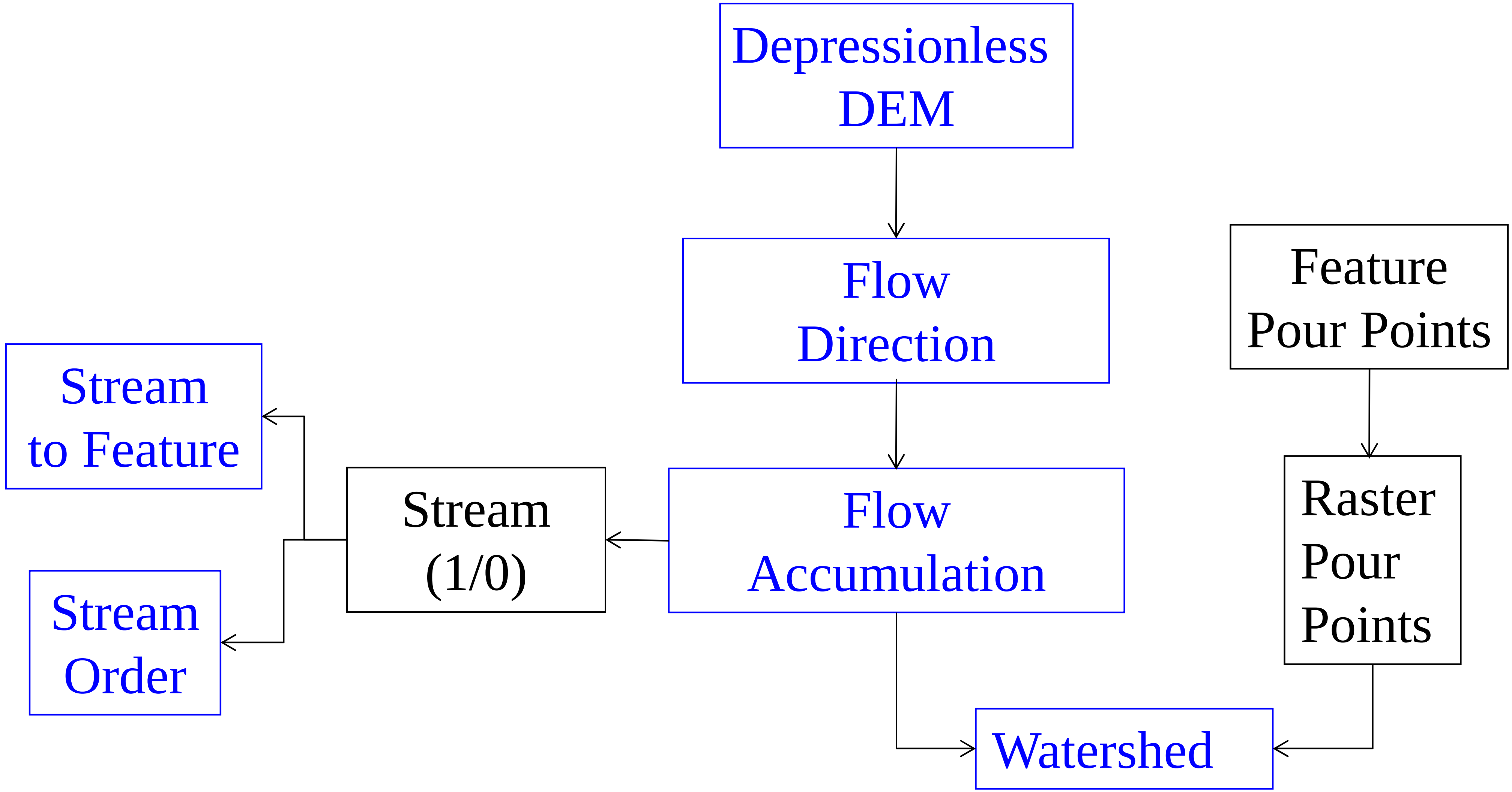
The area from which water drains to a common outlet.





AKA drainage basin, basin, catchment, or contributing area.

Watershed delineation in ArcGIS



Blue=> Hydrology Toolset
Black=> Standard ArcGIS

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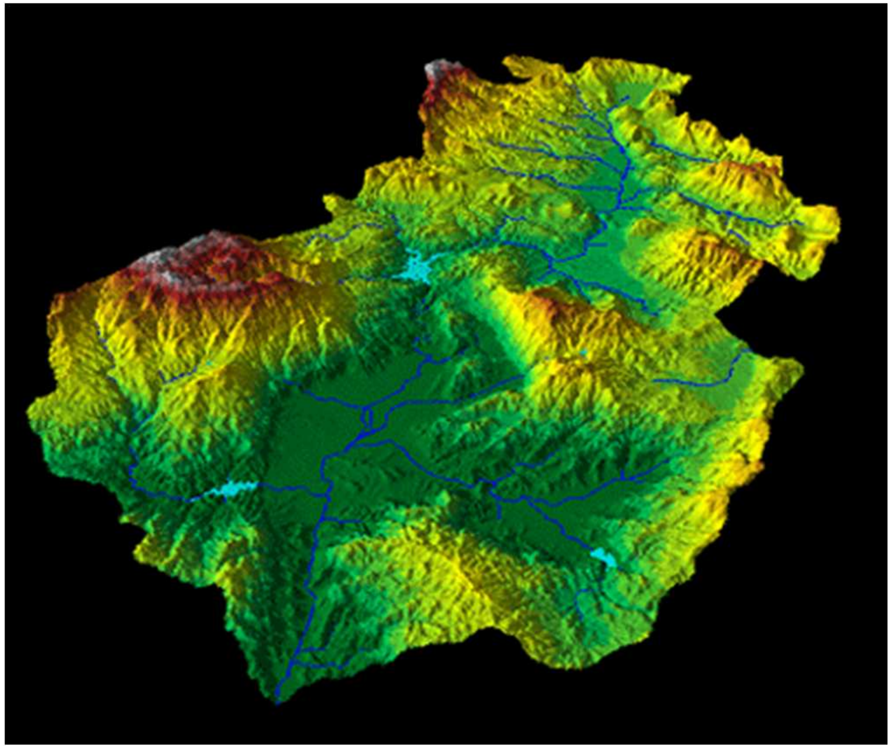
Watershed delineation in ArcGIS

Digital Elevation Model
Raster data describing surface of earth.



Accuracy depends on:

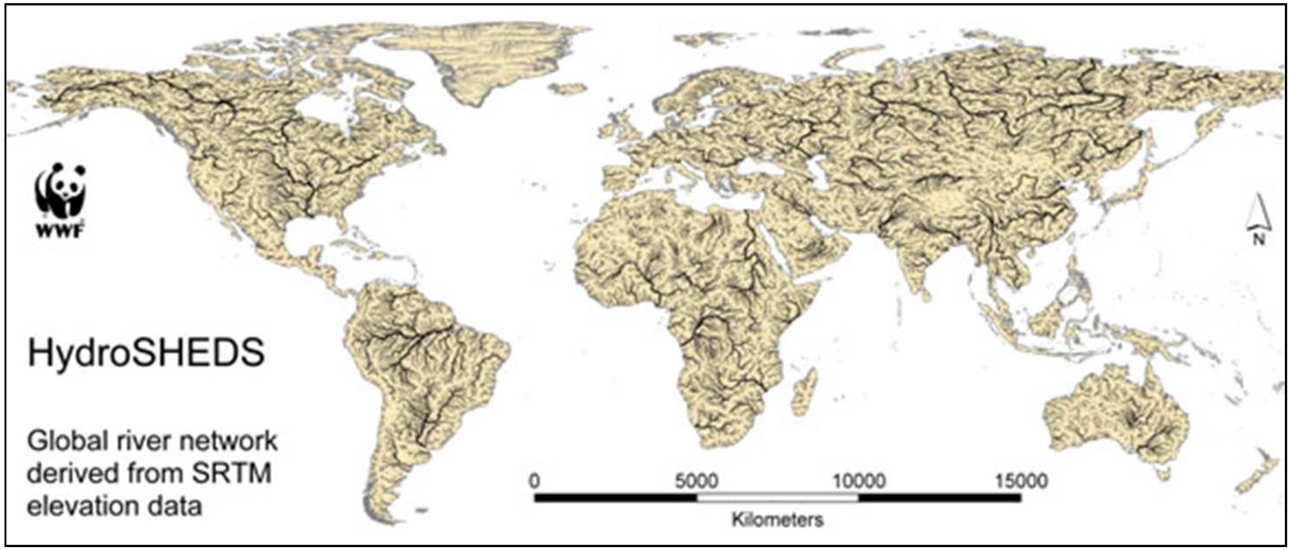
Resolution

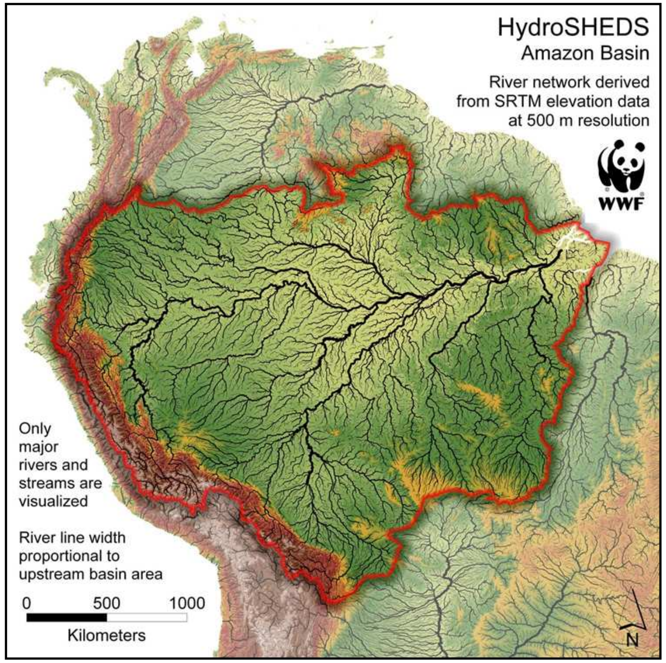
Data type

Observation method

HydroSHEDS

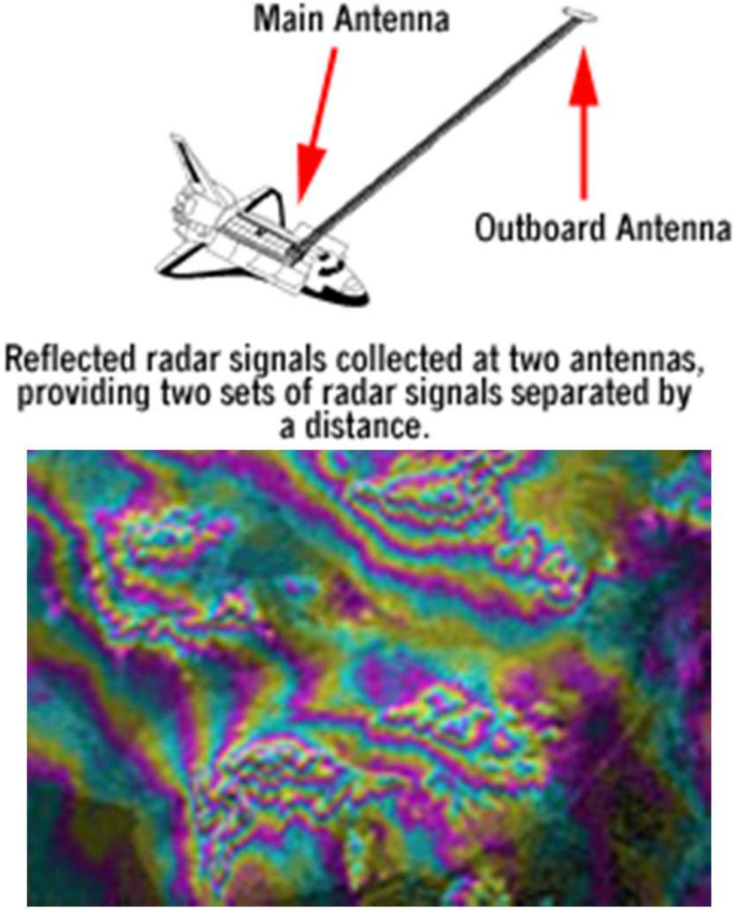
Hydrological data and maps based on **Sh**uttle **E**levation **D**erivatives at multiple **S**cales)

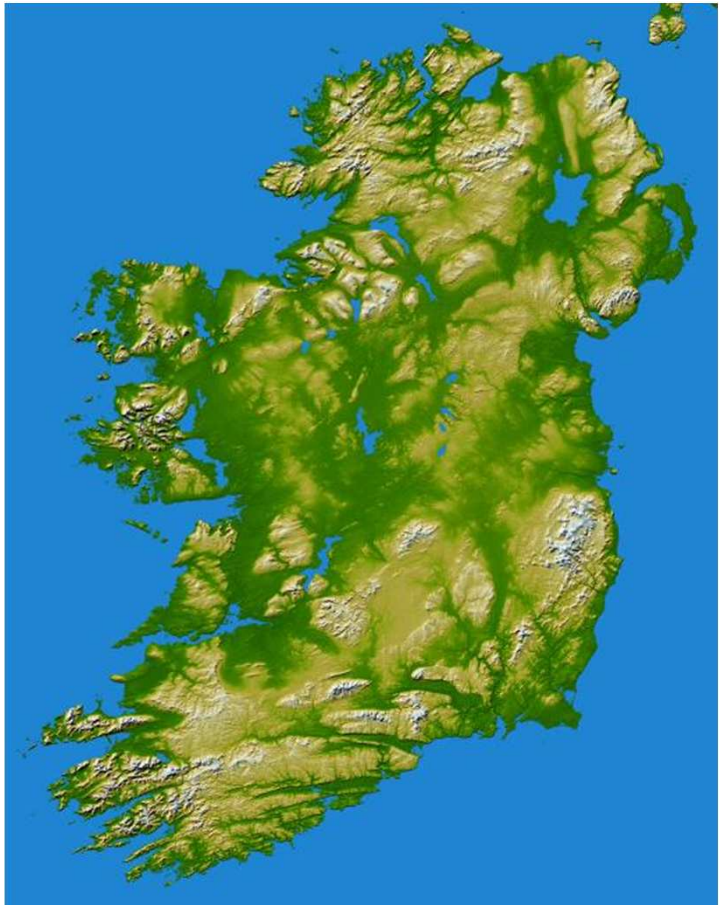




http://hydrosheds.cr.usgs.gov/

HydroSHEDS:
Shuttle Radar Topography Mission

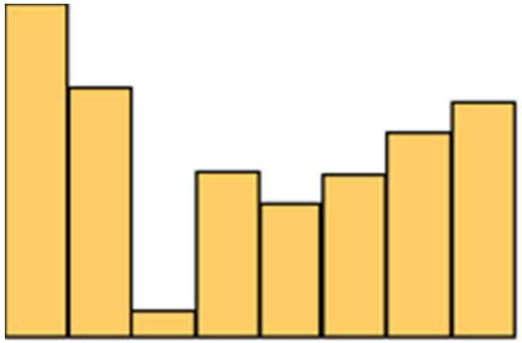




(http://www2.jpl.nasa.gov/srtm/index.html)

Watershed delineation in ArcGIS

Identifying and filling Sinks



Profile view of a sink

Sinks most likely to be imperfections in DEM

Remove before flow direction calculations!!

Coarser DEM => More sinks!

Peaks are more often natural, and cause fewer problems

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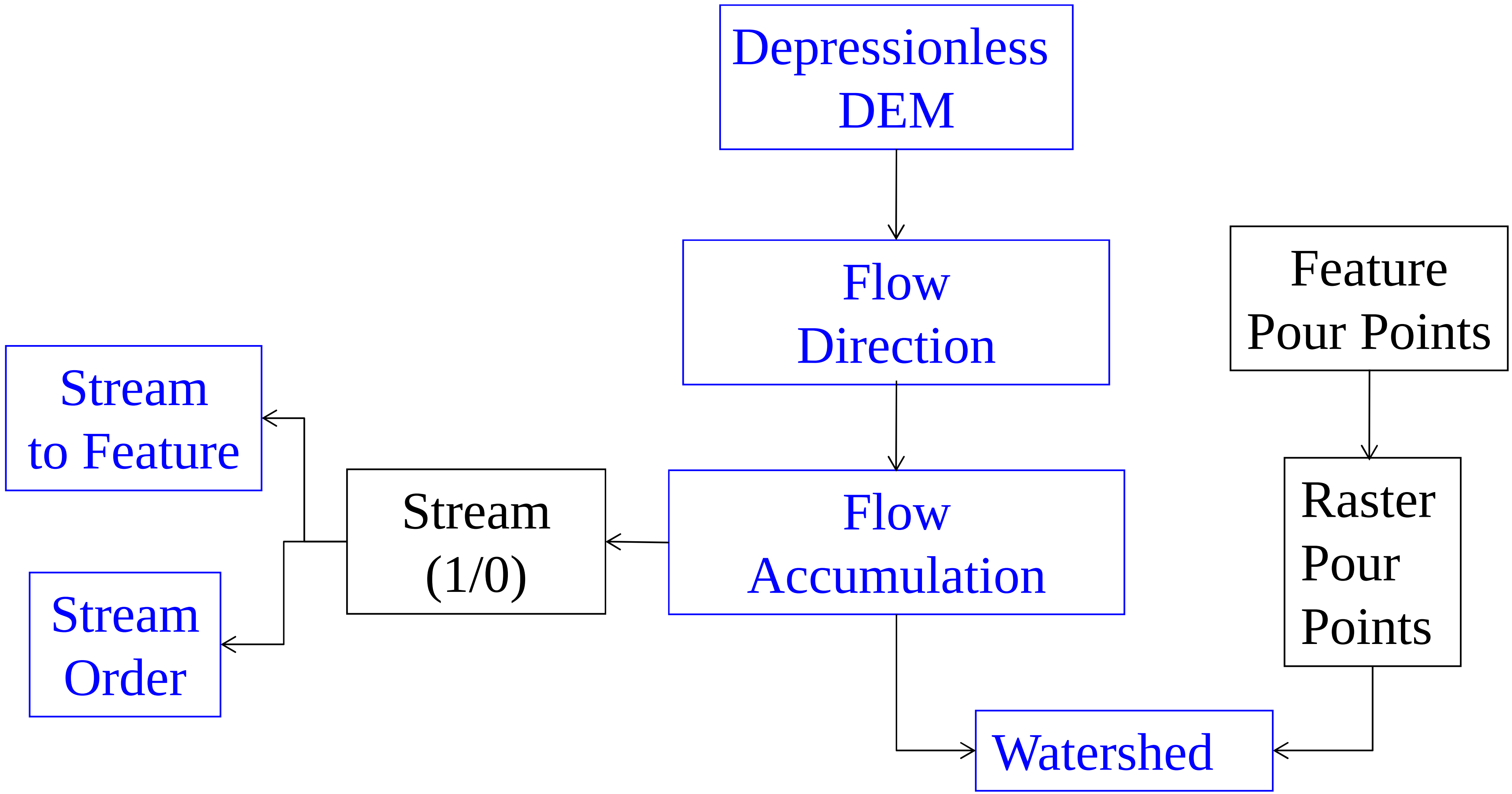
Watershed delineation in ArcGIS



Blue=> Hydrology Toolset

Black=> Standard ArcGIS

Watershed delineation in ArcGIS

Flow Direction

Where does the water flow from each cell?

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

Direction coding

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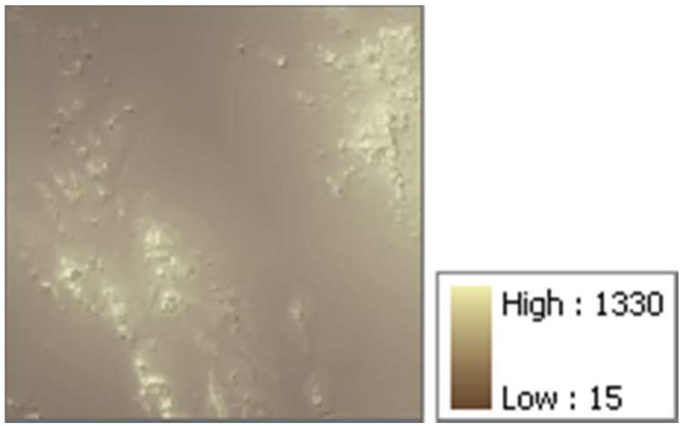
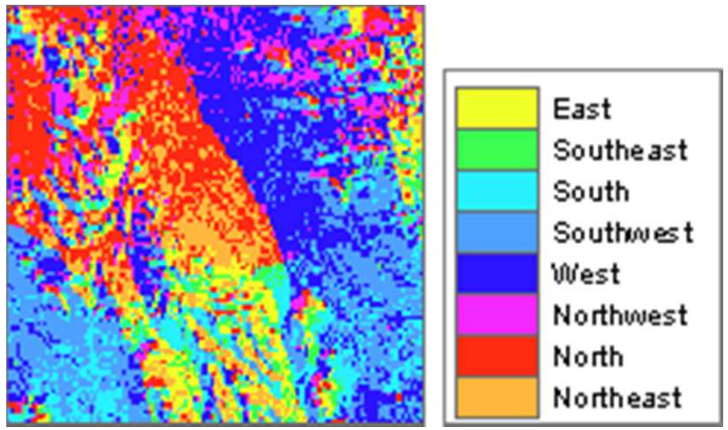
Watershed delineation in ArcGIS

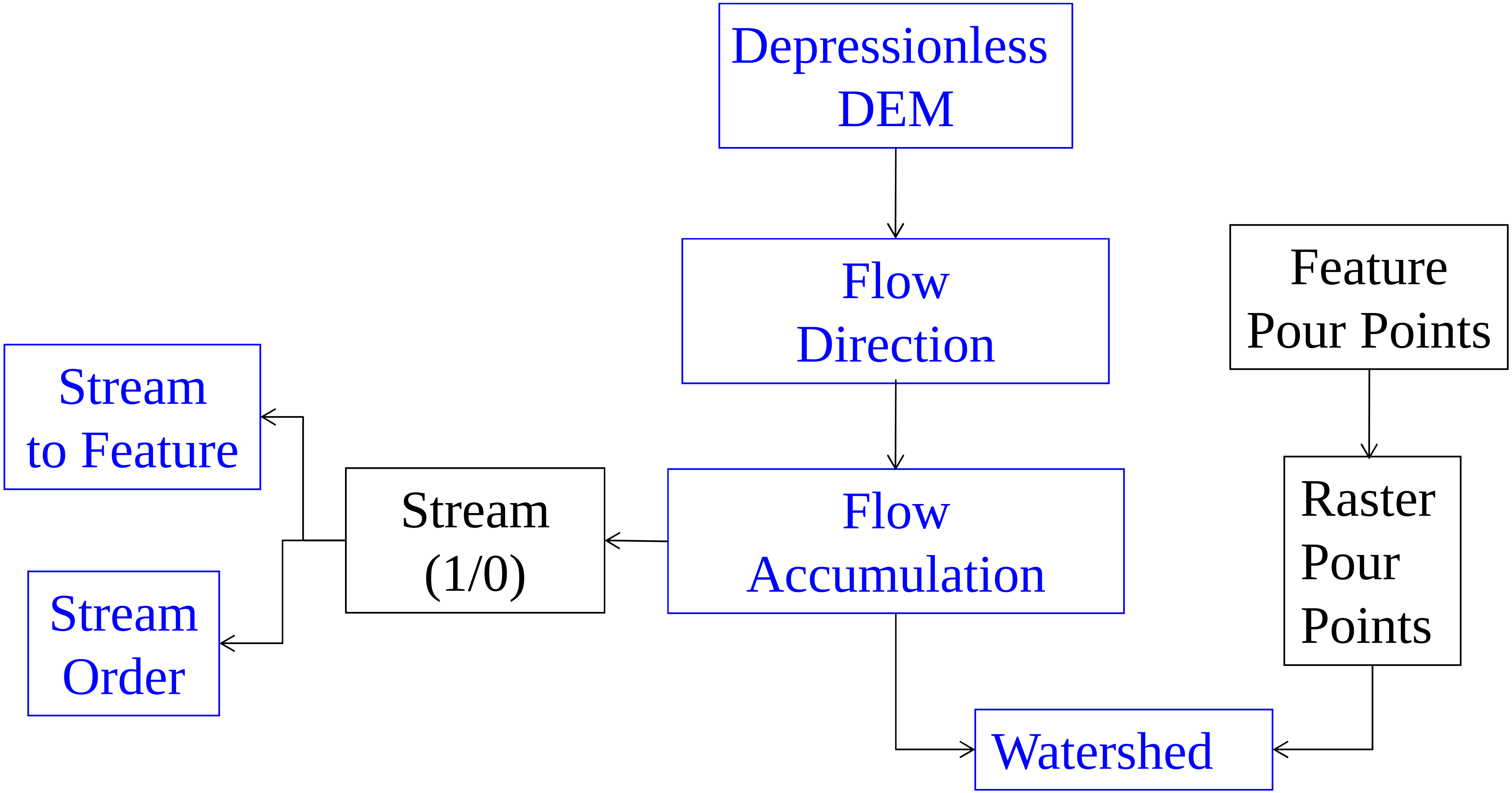
Flow Direction

Where does the water flow from each cell?





Watershed delineation in ArcGIS

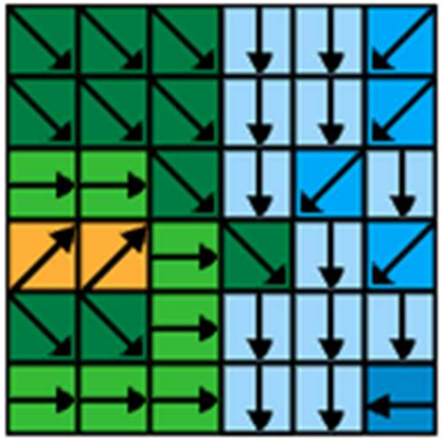


Blue=> Hydrology Toolset

Black=> Standard ArcGIS

Watershed delineation in ArcGIS

Flow accumulation



Flow direction

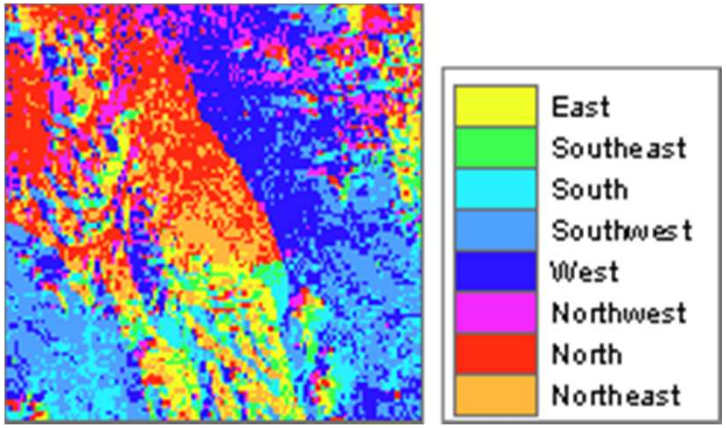
0	0	0	0	0	0
0	1	1	2	2	0
0	3	7	5	4	0
0	0	0	20	0	1
0	0	0	1	24	0
0	2	4	7	35	2

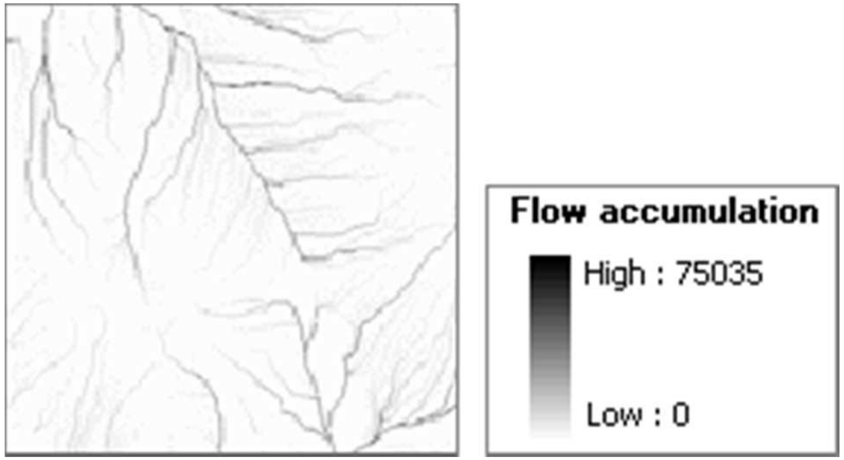
Flow accumulation

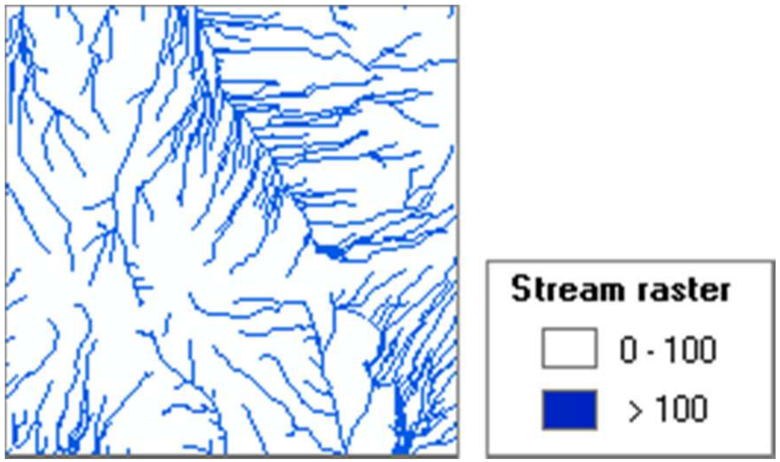
Direction coding

Watershed delineation in ArcGIS

Flow accumulation





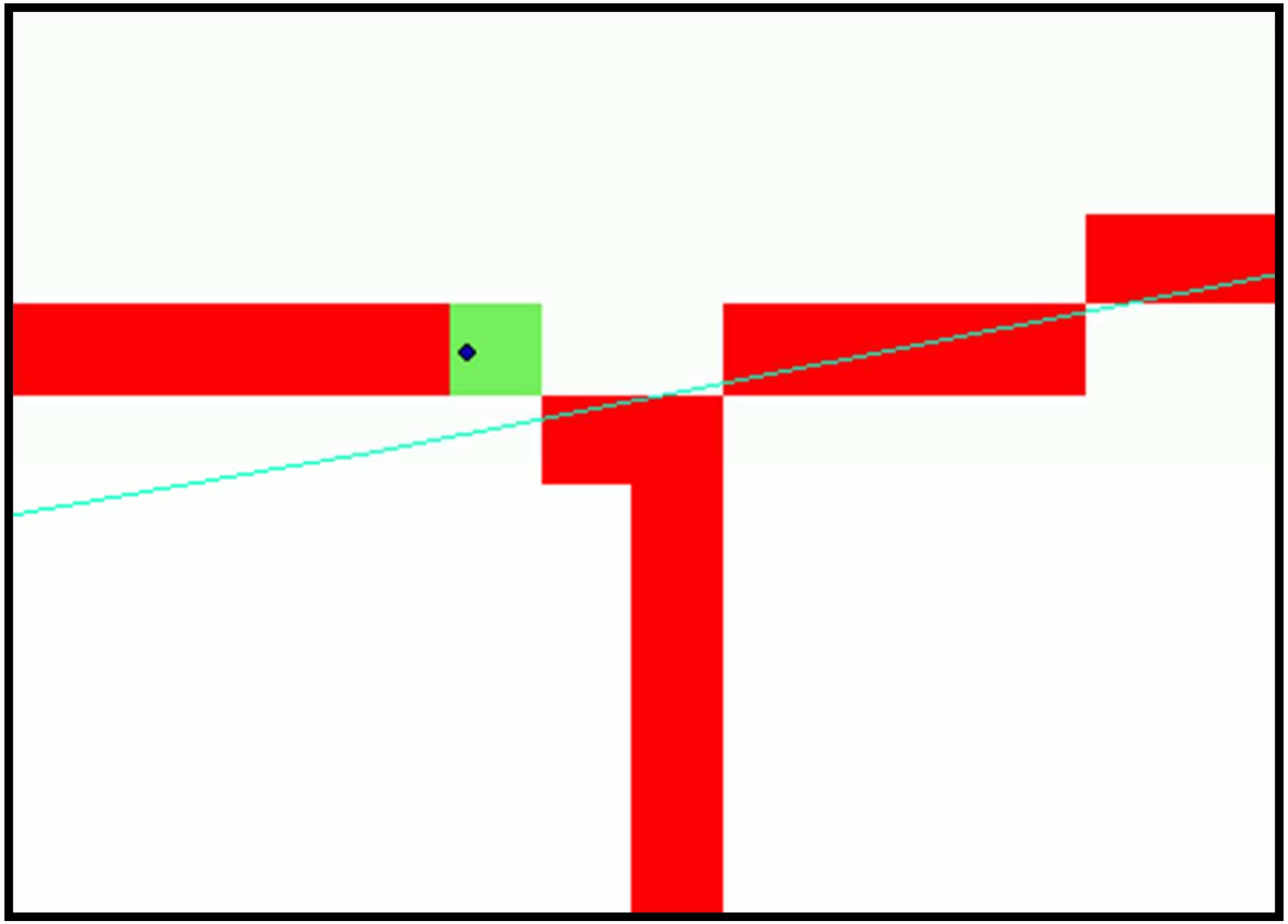


Watershed delineation in ArcGIS

Pour points:

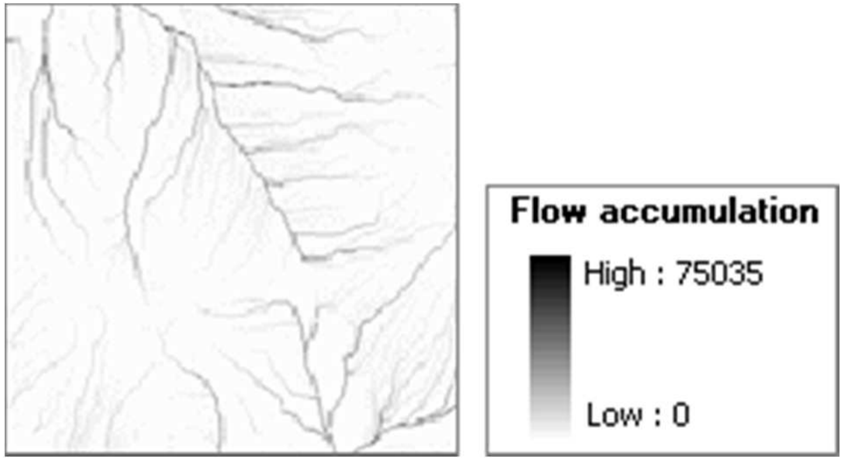
1) Create in a feature class
2) ***Convert to raster***

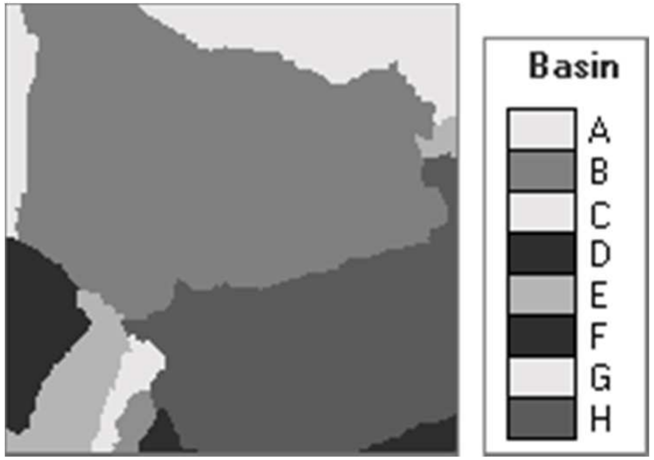
=> Ensure you are in a high flow accumulation grid cell!!



Watershed delineation in ArcGIS

Watershed





Flow accumulation

Pour point raster

→ Watershed tool → Watershed raster

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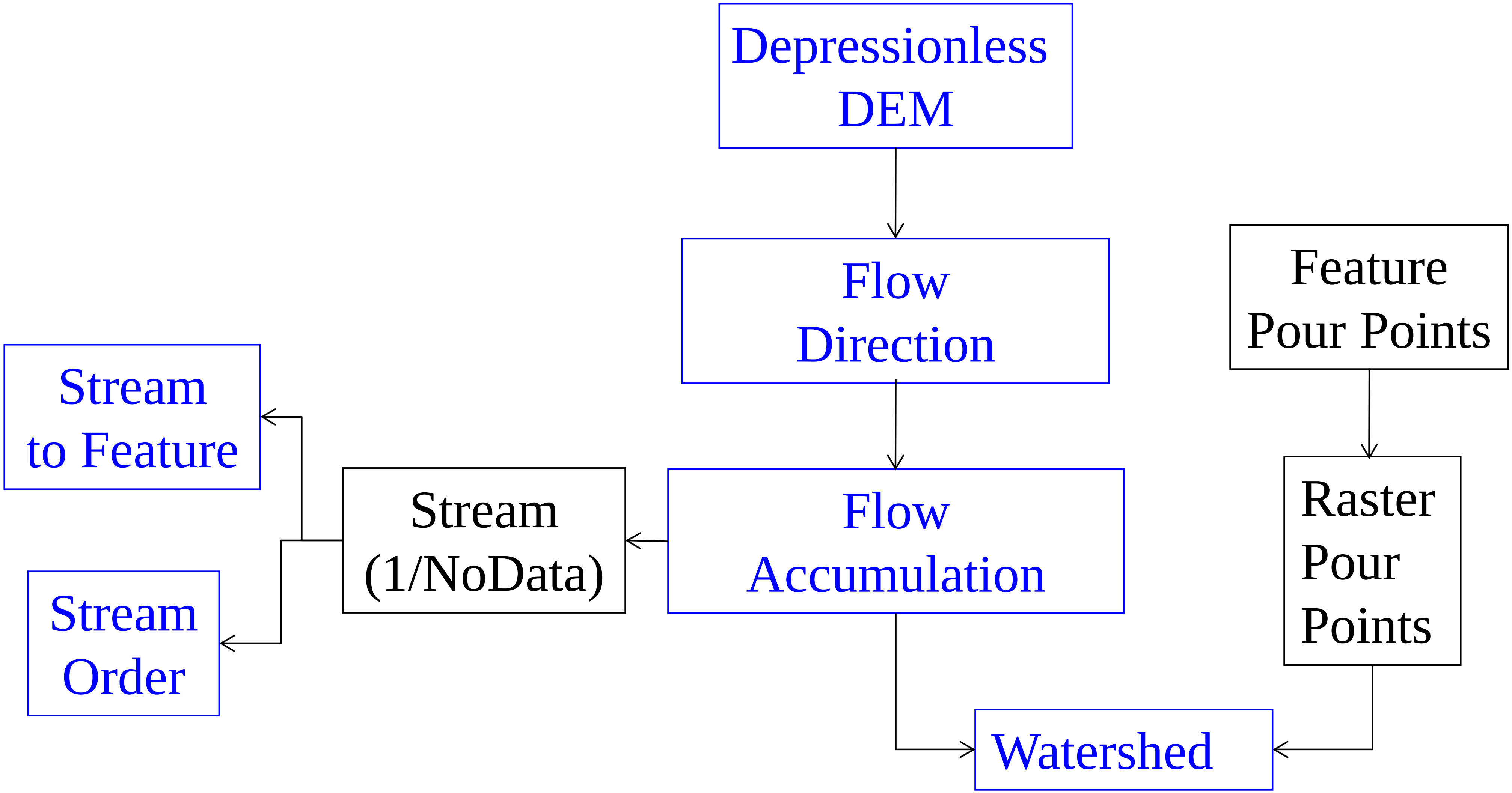

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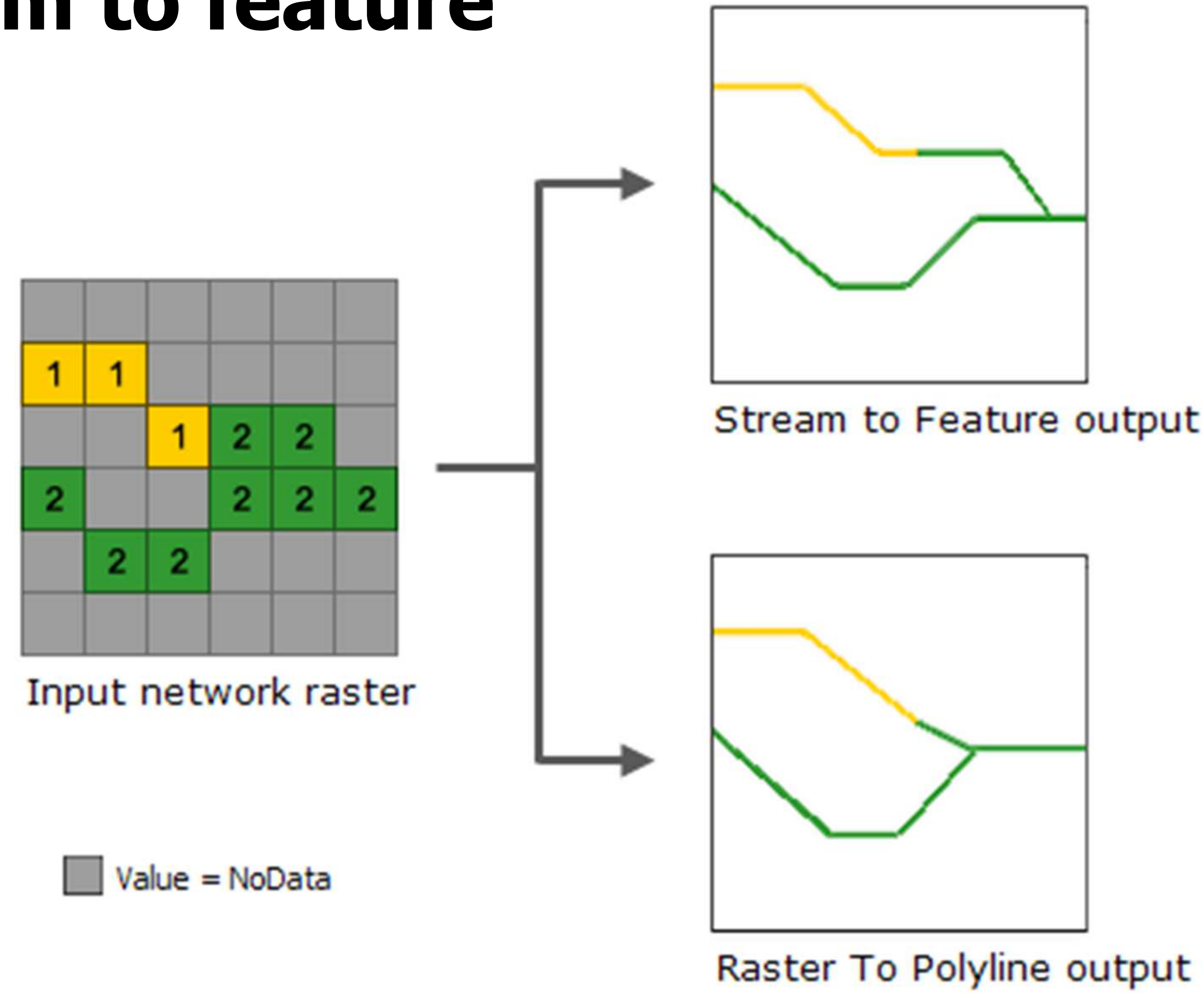
Watershed delineation in ArcGIS

Stream to feature



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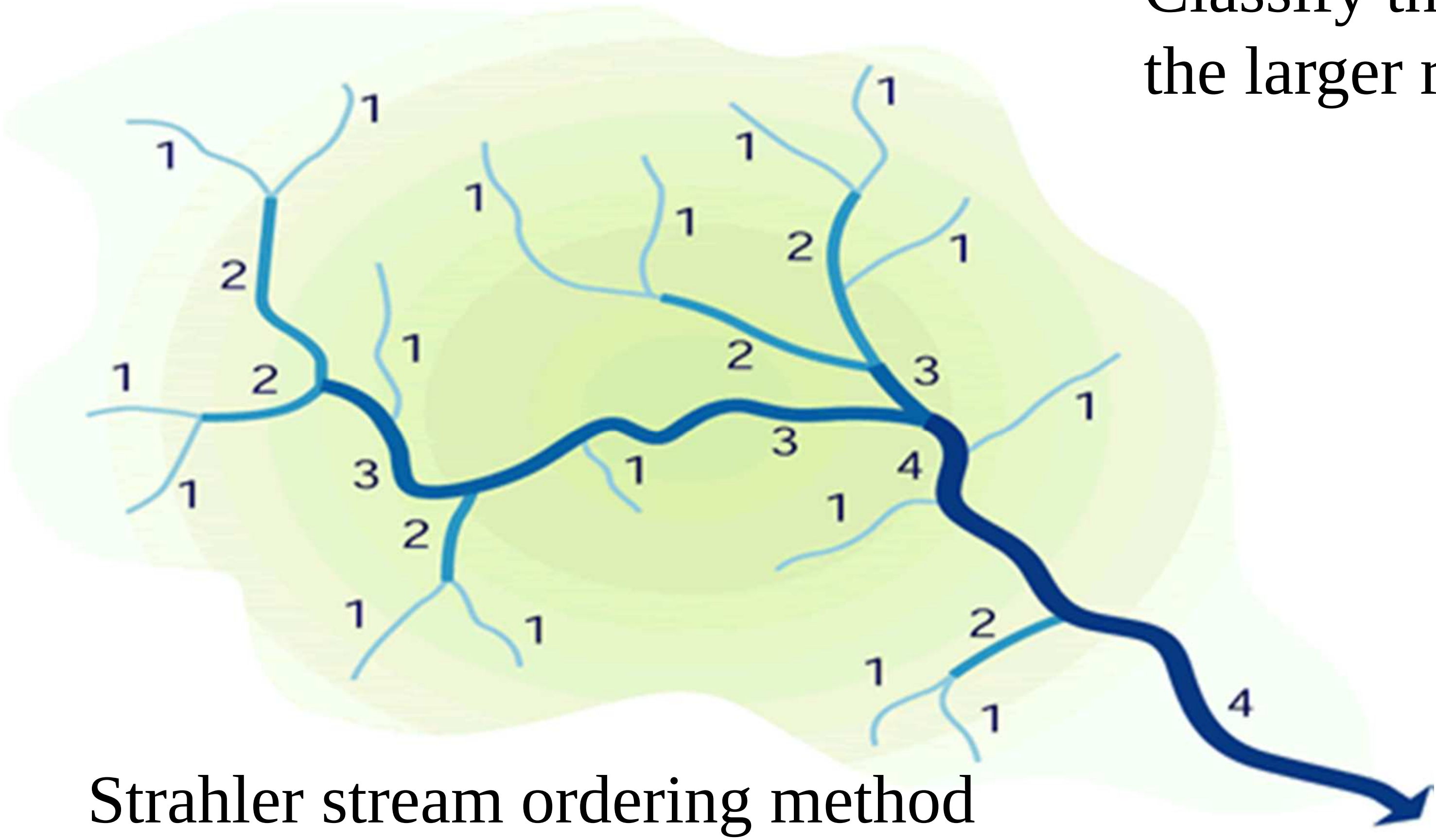
Watershed delineation in ArcGIS

Stream Ordering

Classify the reach within the larger river system



Strahler stream ordering method

http://www.fgmorph.com/fg_4_8.php

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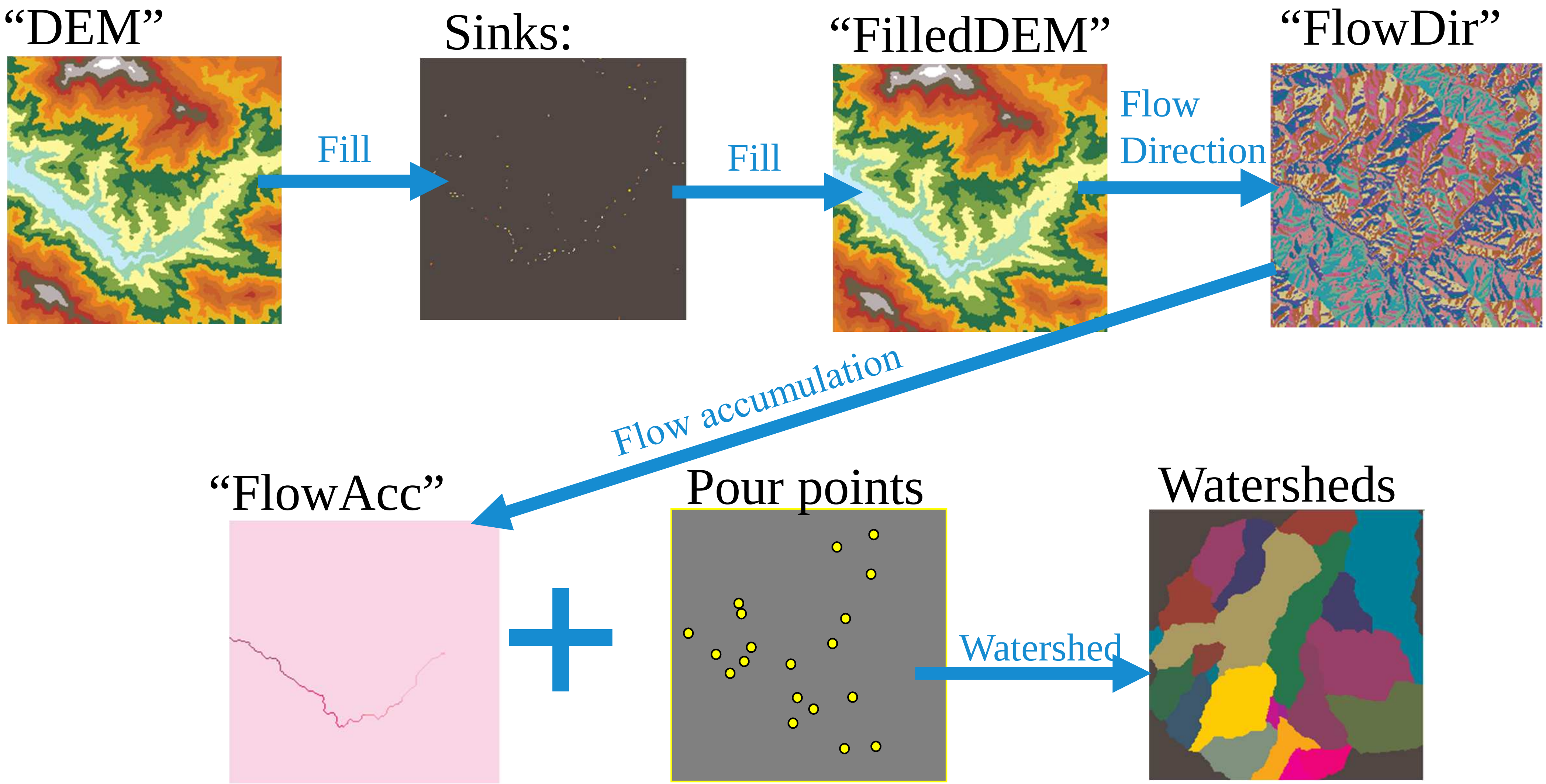
Watershed delineation in ArcGIS



Case Studies

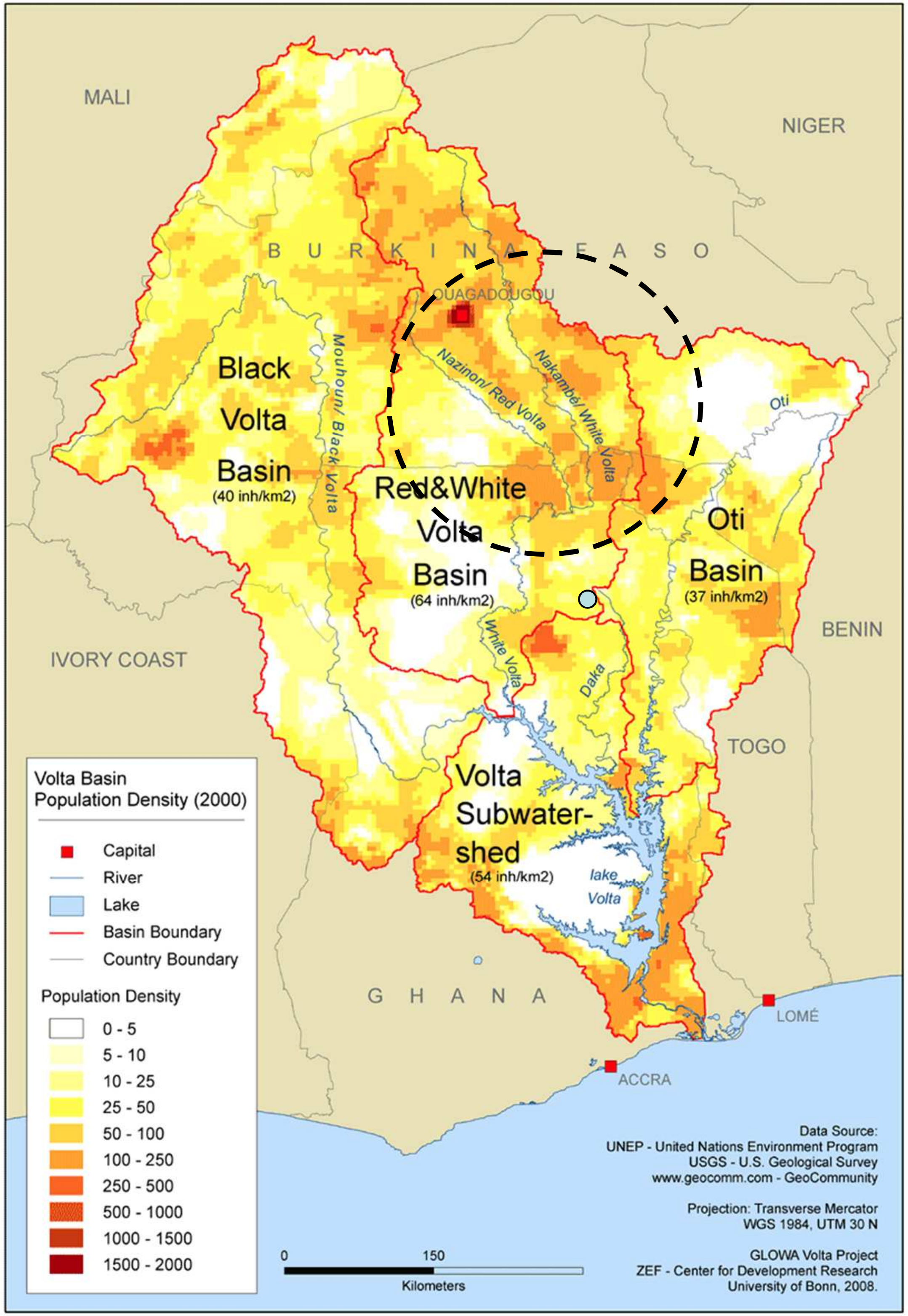
Dr. Markus Hrachowitz,
UD, Hydrology

Rolf Hut,
PhD student, Water Resources Management

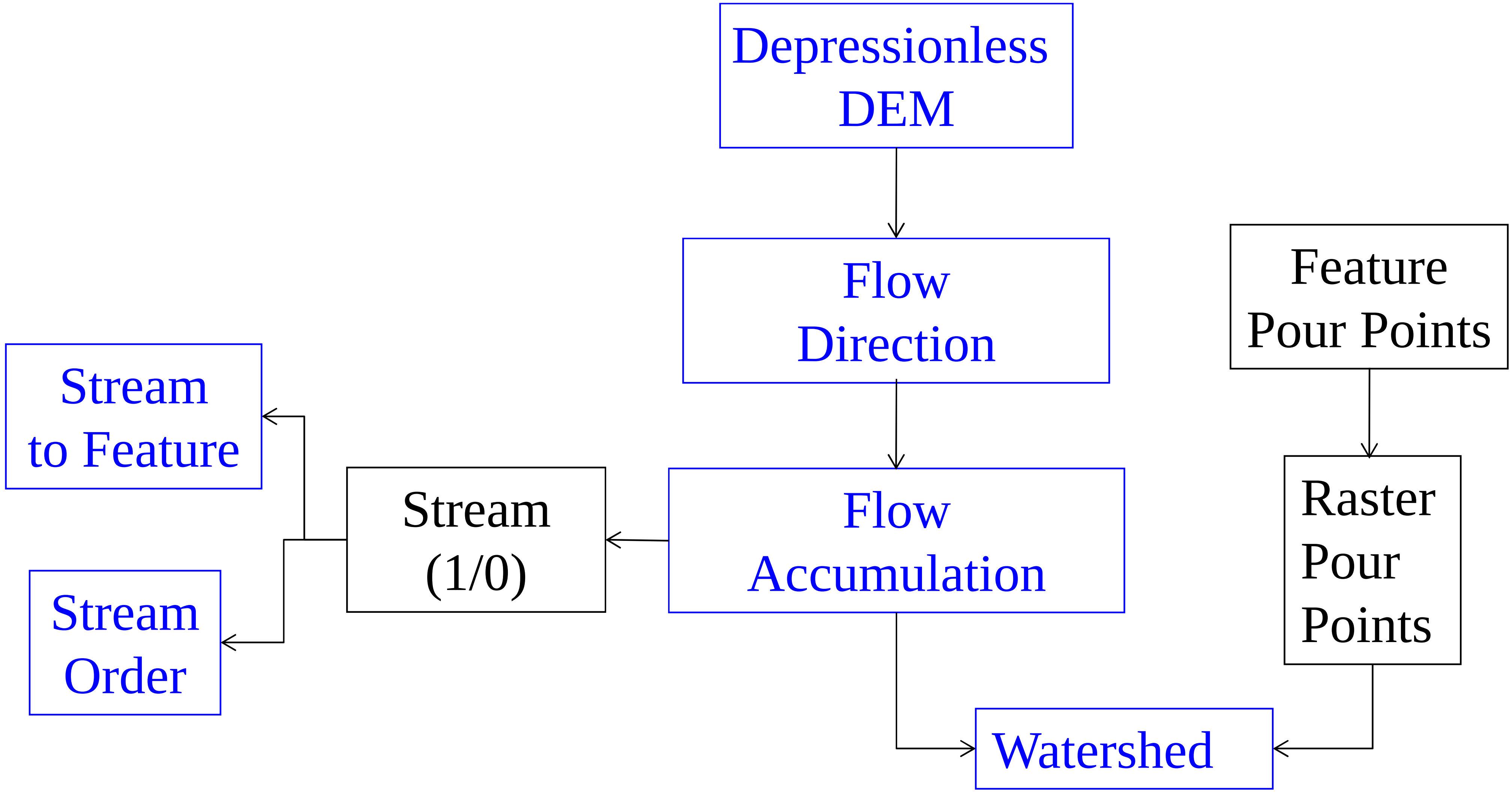
TU Delft

Assignment 3:

In this assignment, you will use ArcGIS to delineate the watershed of the Red and White Volta basin and to study the stream network.



Watershed delineation in ArcGIS



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Sources images

If a website or source is not added to a picture, then the image is taken from the ArcGIS software or from www.esri.com.