BJERKNES CENTRE for Climate Research

STEFAN SOBOLOWSKI

Hydrology and hydrosystems: key concepts, processes and modeling

UNIVERSITY OF BERGEN uni Research NERSC Nansen Center, Bergen HAVFORSKNINGSINSTITUTTET INSTITUTE OF MARINE RESEARCH

Lecture Overview

- Introduction
  - What is hydrology and why do we care?
  - Basic concepts: properties of water, drainage basins/catchments, scales, variability
  - Revisiting the terrestrial water balance
- Key processes in the hydrological system
  - Moisture transport
  - Precipitation
  - Groundwater
  - Land surface/sub-surface runoff
- Modeling the terrestrial branch of the hydrological system
  - Conceptual models (e.g. HBV)
  - Physical models (e.g. WRF-Hydro)
  - Uncertainties/trade-offs
- Conclusions/outlook

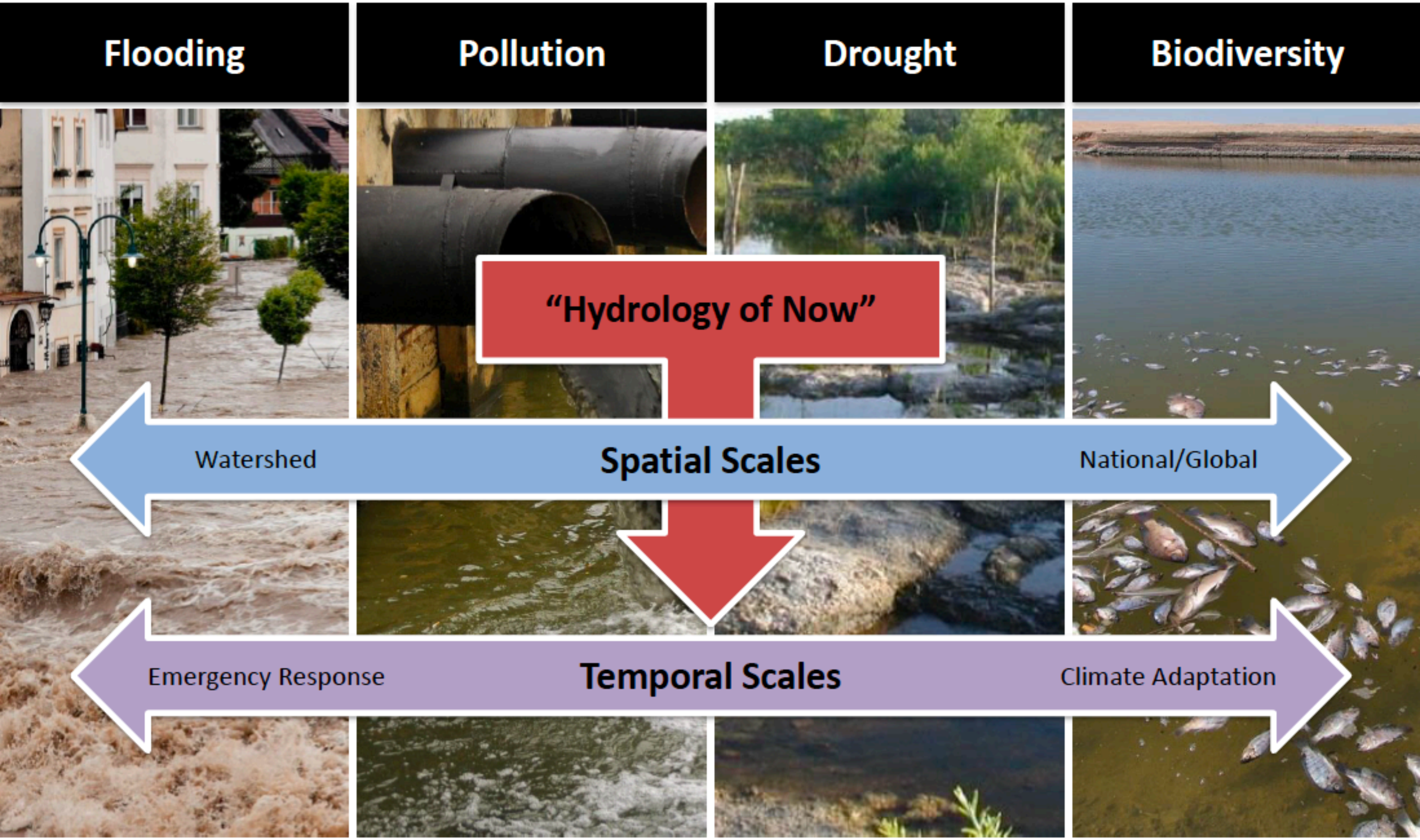
What is Hydrology?

› *"Hydrology is broadly defined as the geoscience that describes and predicts the occurrence, circulation and distribution of the water of the earth and its atmosphere"* – S. Lawrence Dingman in Physical Hydrology, Waveland Press

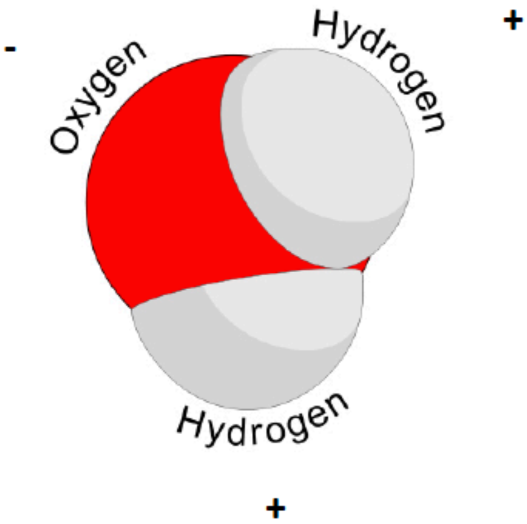
› Two main areas of focus:
- The global hydrological cycle concerned with the variations and transport of water through the oceanic, terrestrial and atmospheric arms of the global water system
- The land phase of the hydrological cycle concerned with the movement of water on and under the earth's land surfaces

2 very good textbooks:
Dingman, S.L. (3rd ed. 2014) *Physical Hydrology.* Waveland Press, USA
Brutsaert, W. (2005) *Hydrology: An Introduction*. Cambridge U. Press, UK

Motivation: An Array of Water Issues

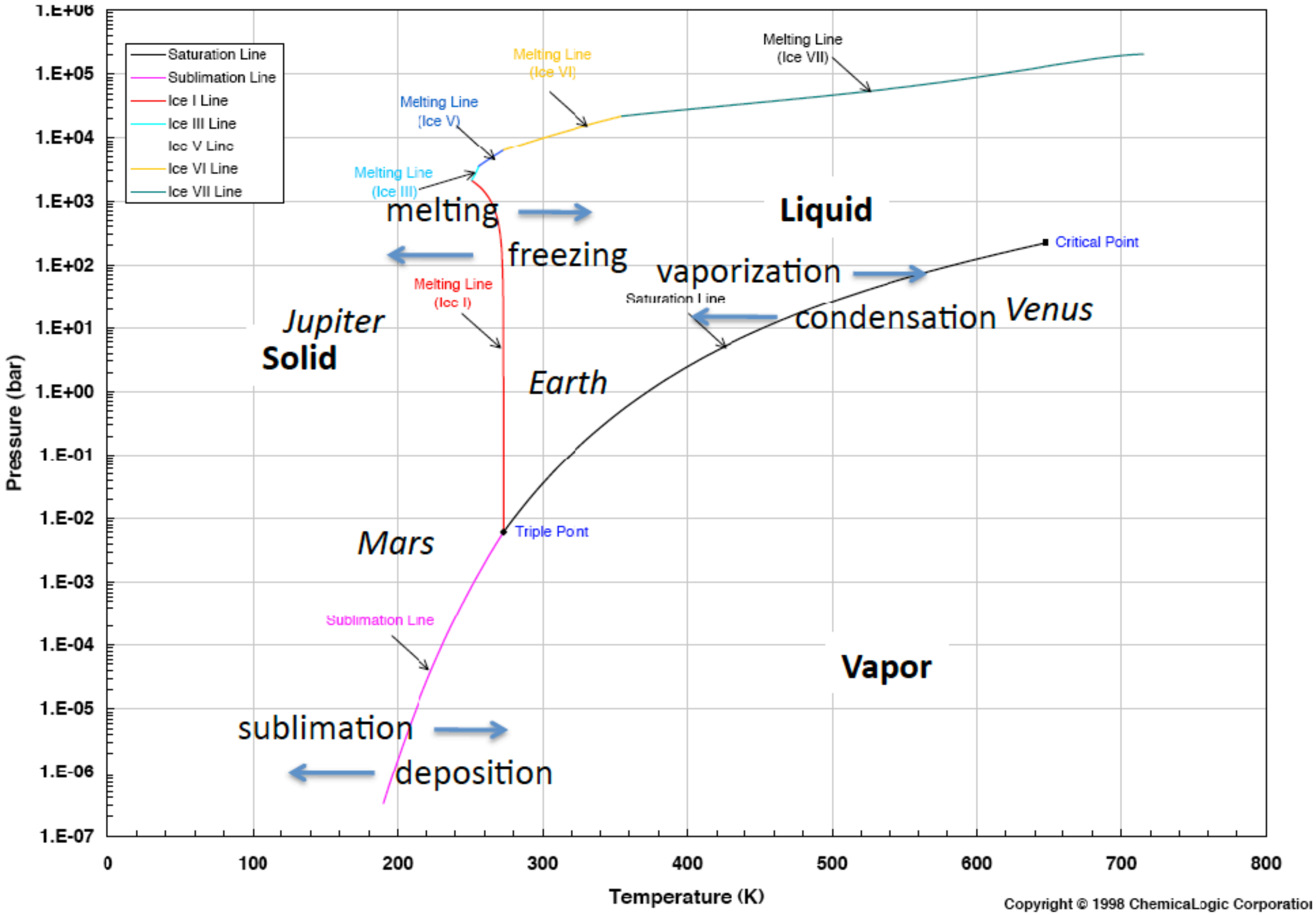


Water as a substance



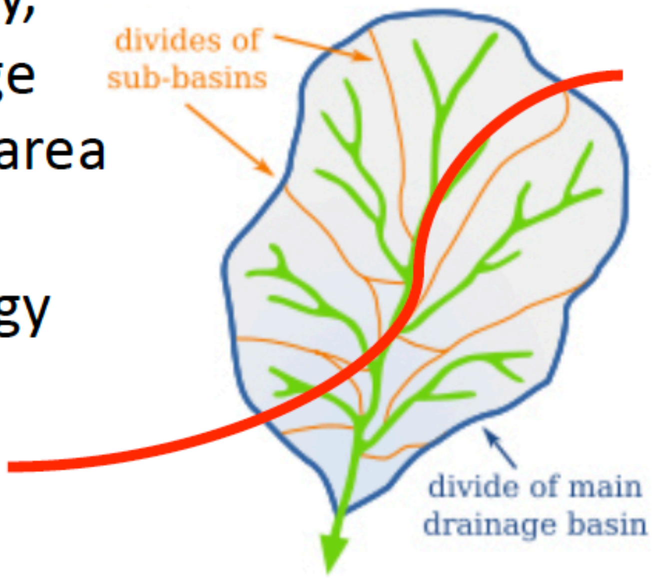
Water covers 71 % of the Earth's surface, oceans contain 97.2 % of the total water amount

Water Phase Diagram

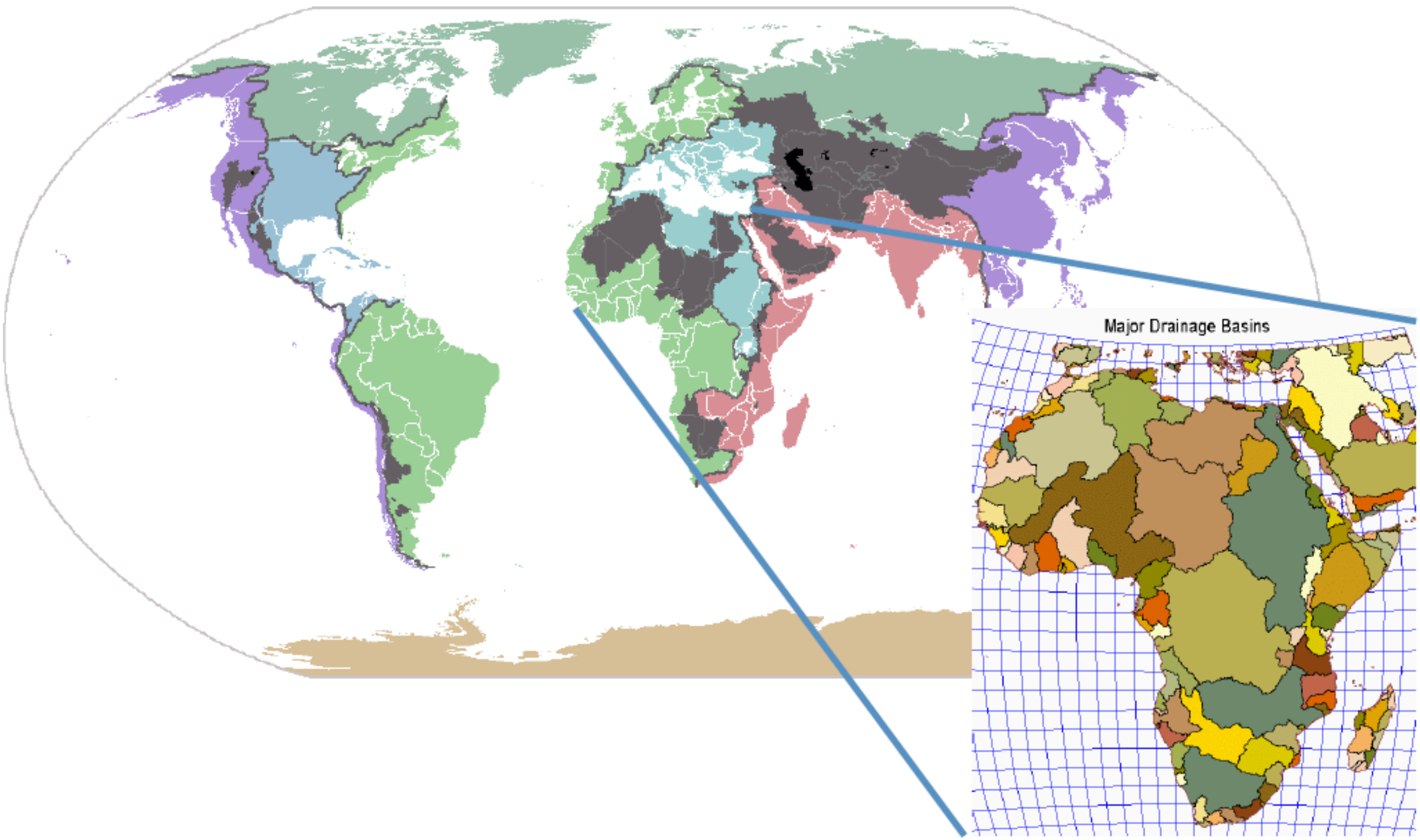


Basic Concepts: The drainage basin/watershed/catchment

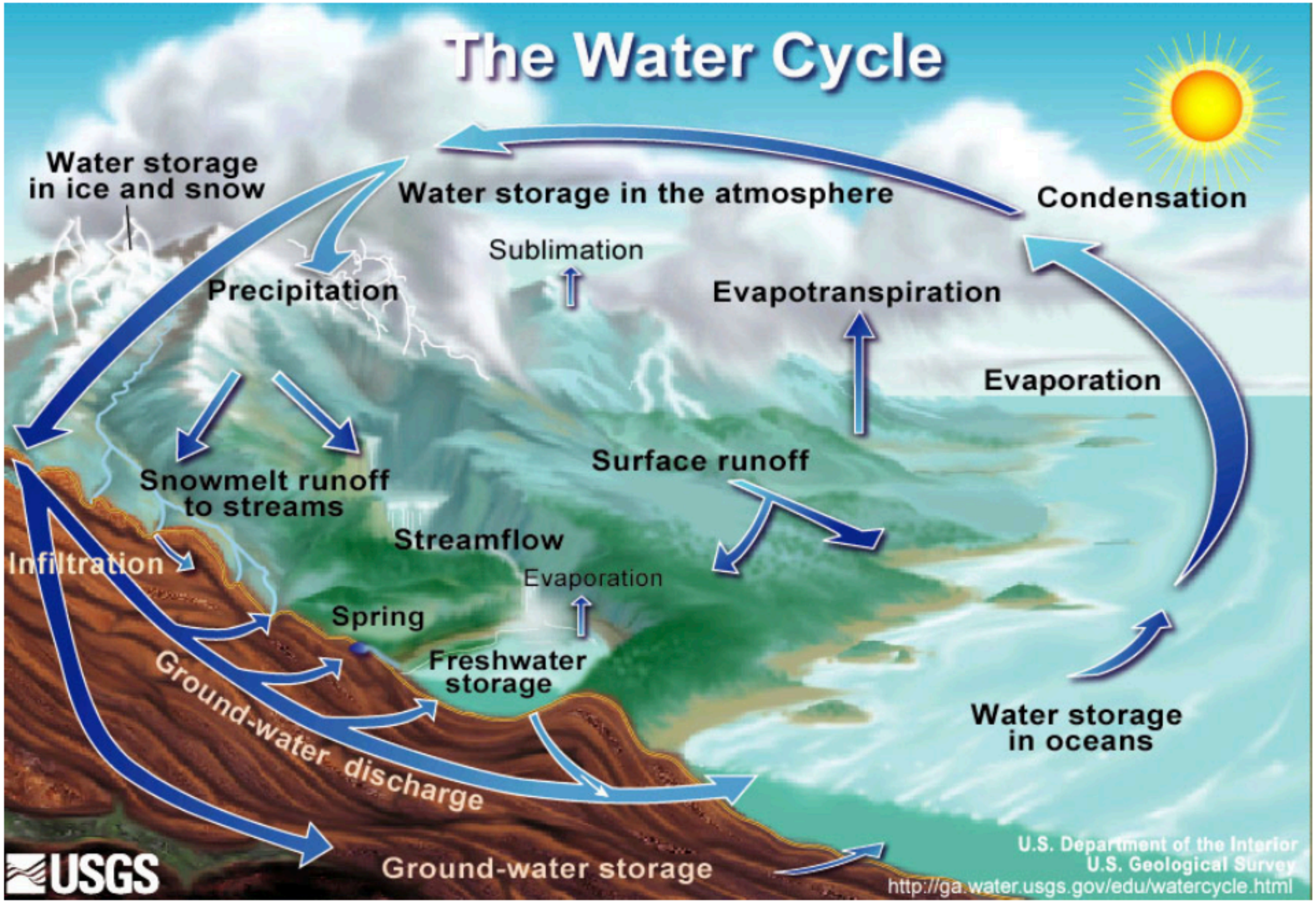
- The watershed (drainage basin)
  - A **drainage basin** is a region of land where water from rain or snow melt drains downhill into a body of water, such as a river, lake, dam, estuary, wetland, sea or ocean. A drainage basin provides a limited surface area within which physical processes pertinent to the general hydrology may be considered.



Example: Major Surface Water Drainage Basins of the World



Basic Hydrological Concepts: the global water cycle



The terrestrial water balance in its simplest form

$$P = E + R + \Delta S$$

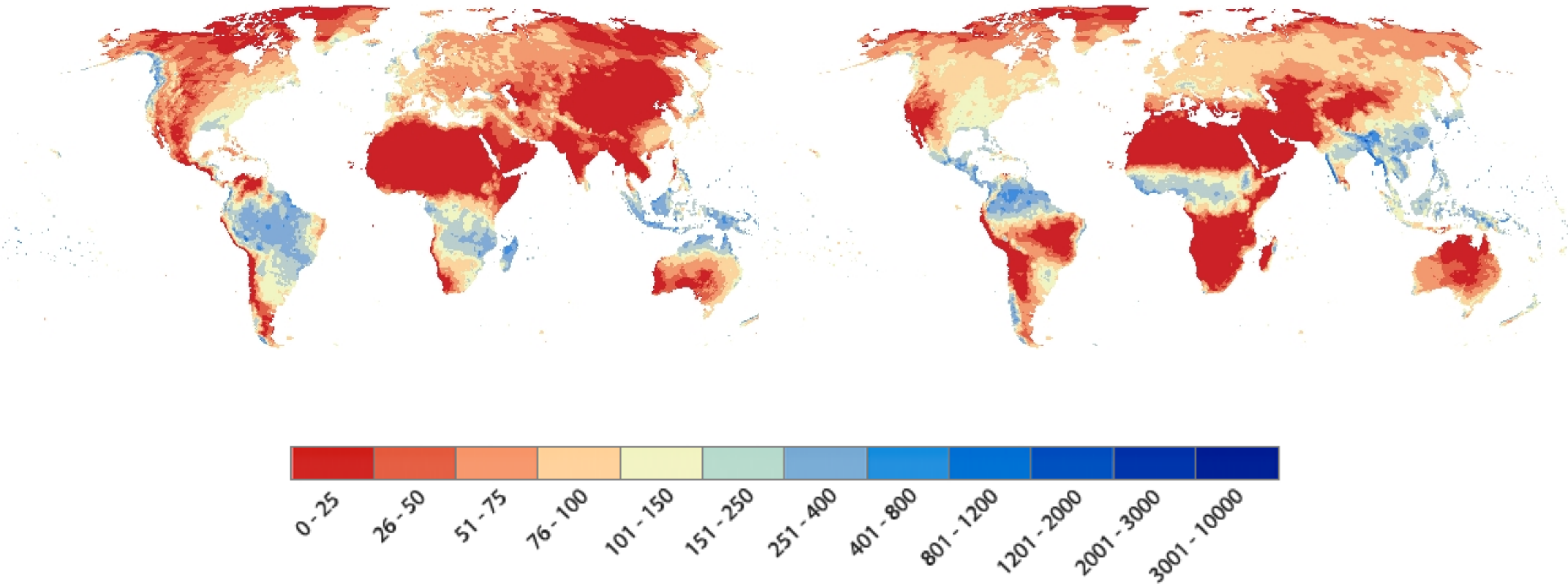
P = Precipitation

E = Evapotranspiration

R = Runoff (often written as q)

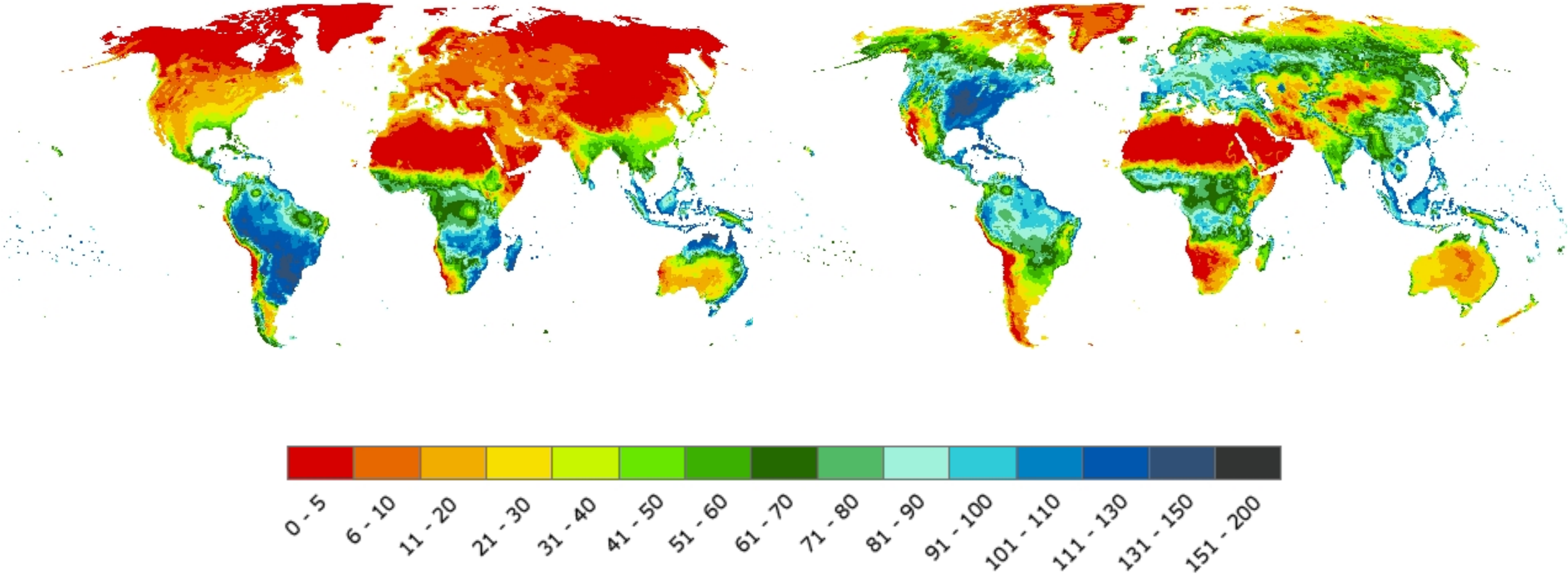
ΔS = Change in storage

Average (1985-99) precipitation in January and June from WATCH dataset

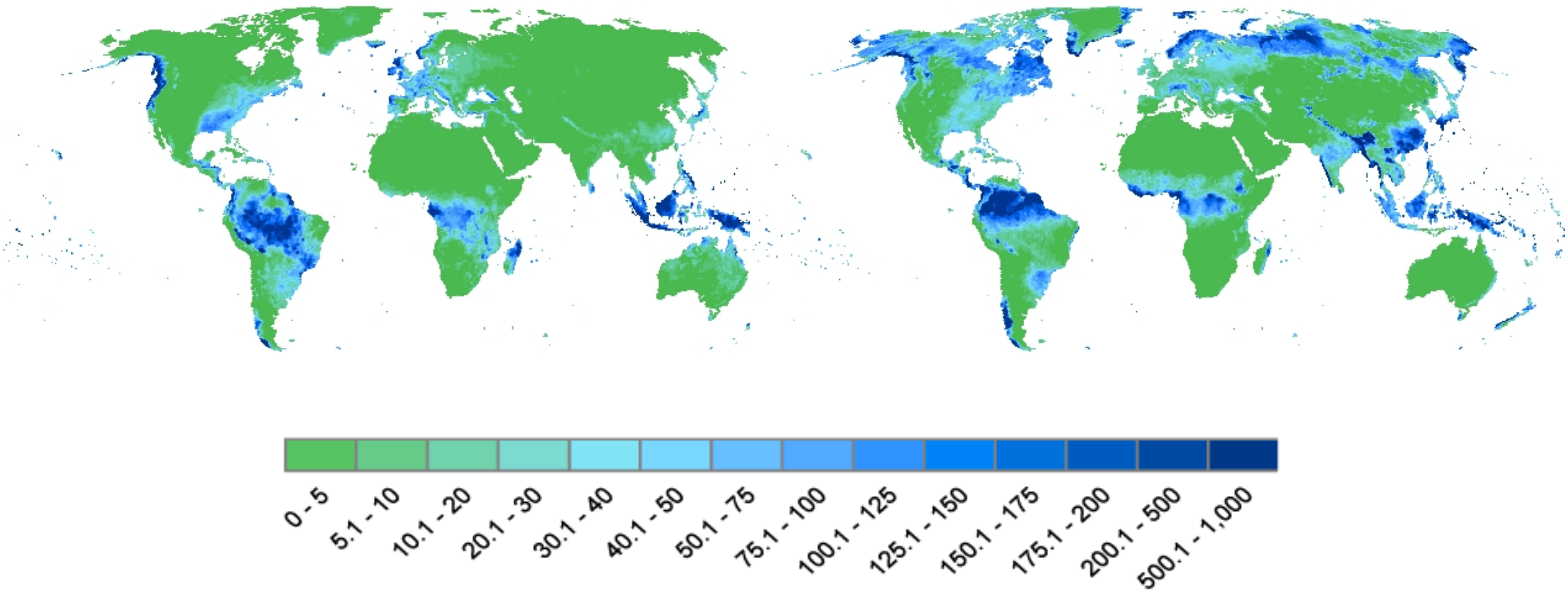


http://www.waterandclimatechange.eu/evaporation/average-monthly-1985-1999

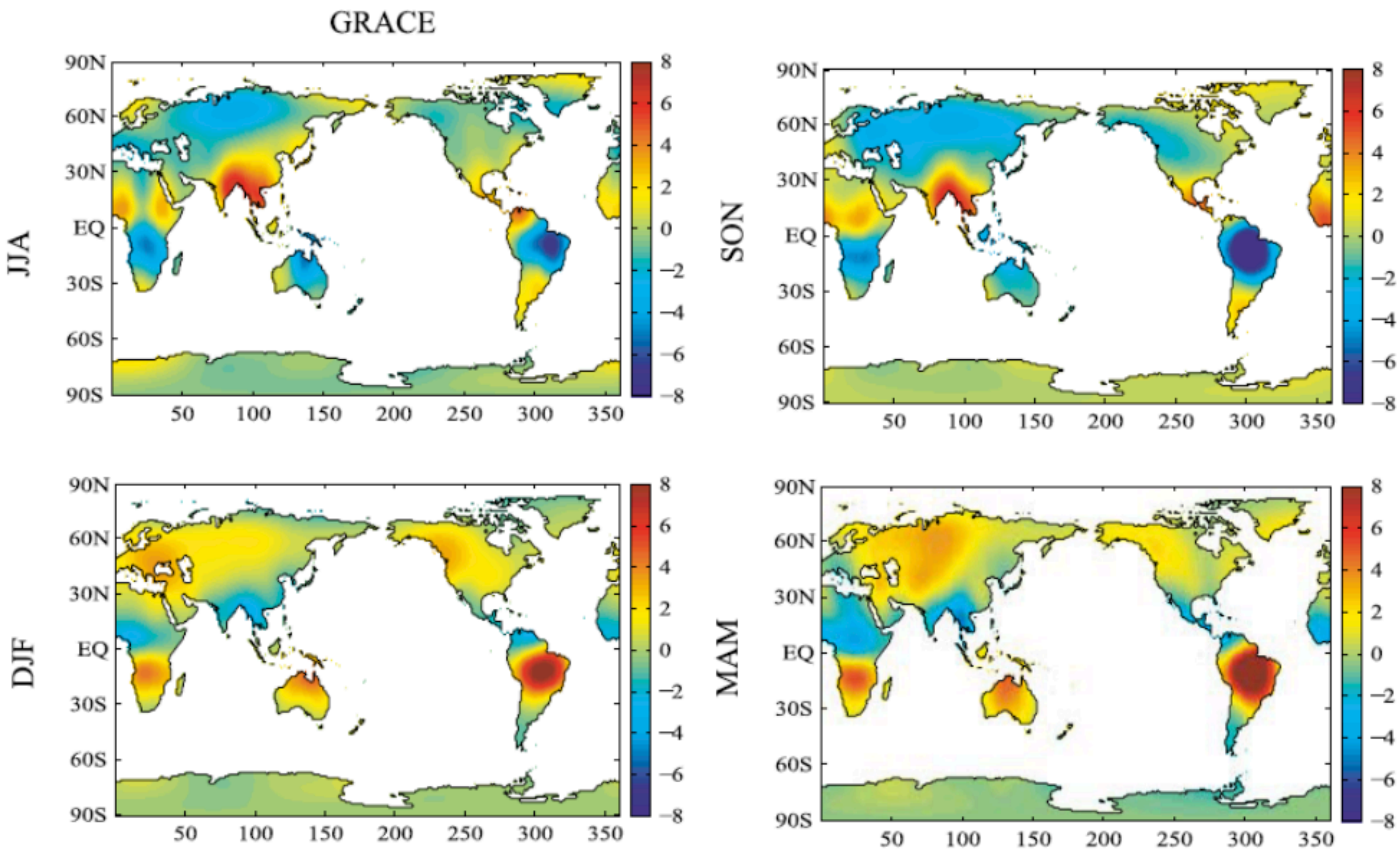
Average (1985-99) evaporation in January and June from WATCH dataset



Average (1985-99) runoff in January and June from WATCH dataset



Seasonal terrestrial water storage from GRACE (Gravity Recovery and Climate Experiment)

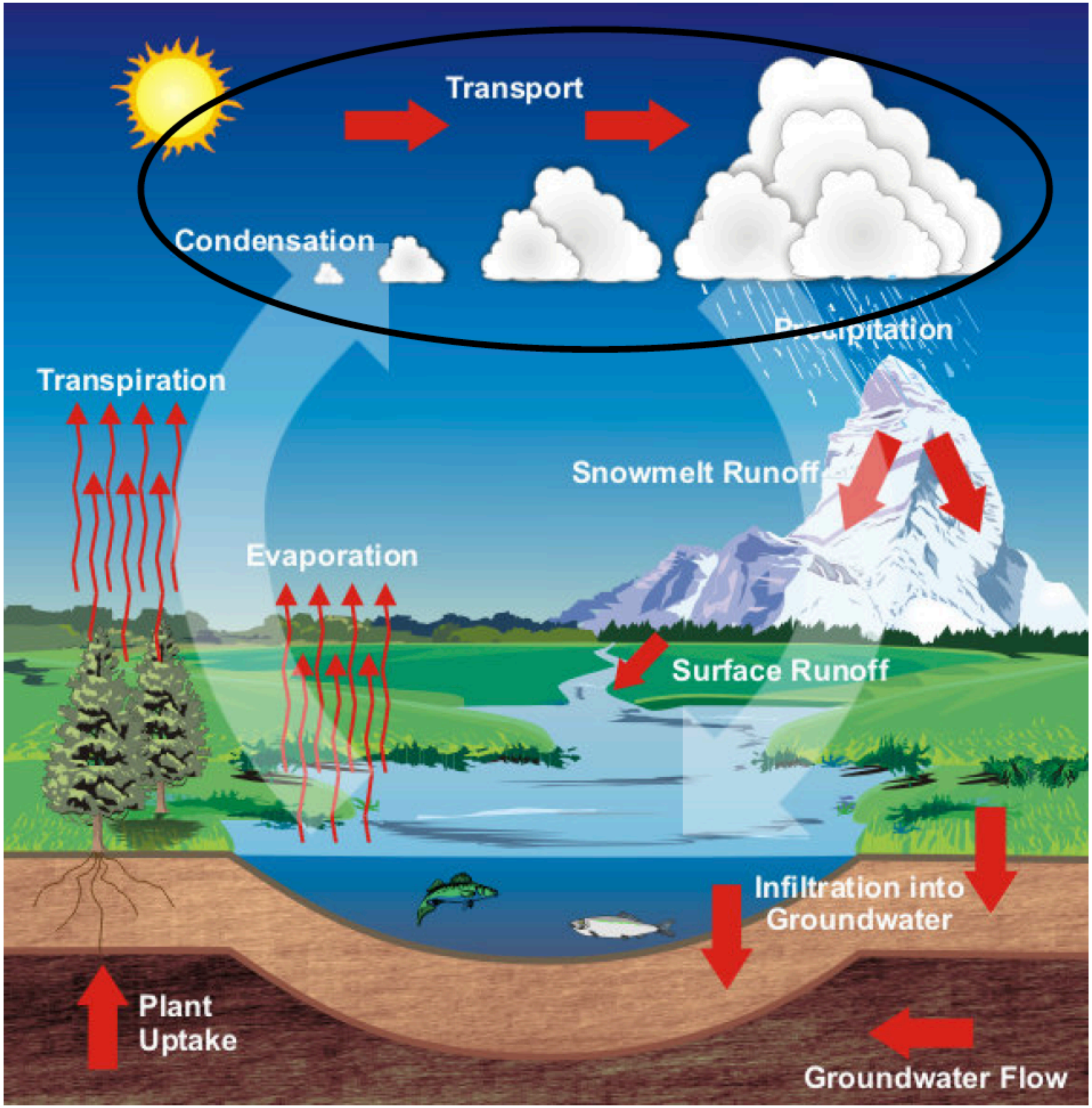


Units: cm/month

Syed et al., WRR, 2008

Hydrologic Cycle:

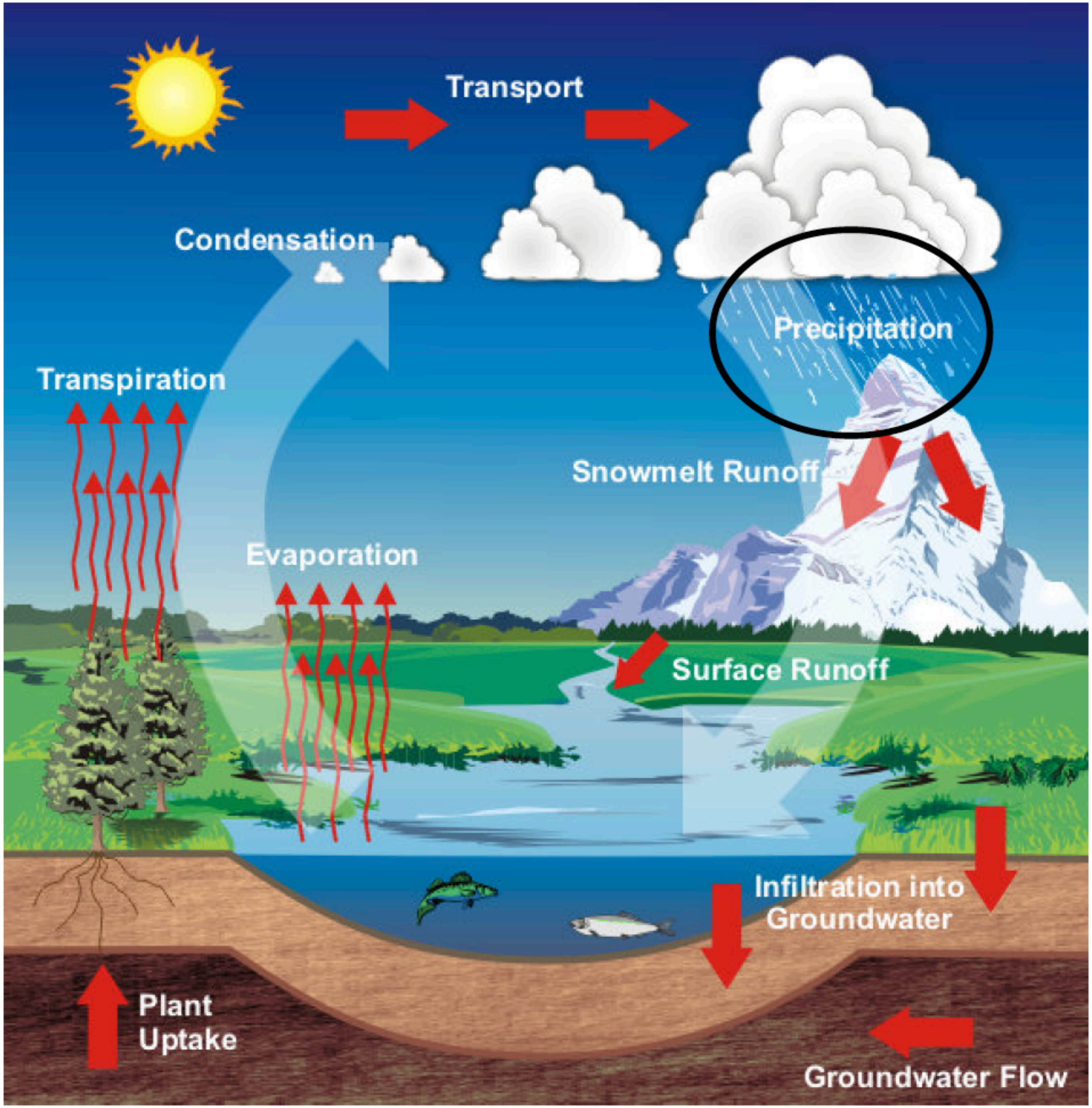
Atmospheric Moisture



Before it rains, before it floods; moisture must be transported

› https://vimeo.com/148867815

Odda flooding Oct. 2014 (Photo: Marit Hommendal/NTB scanpix)

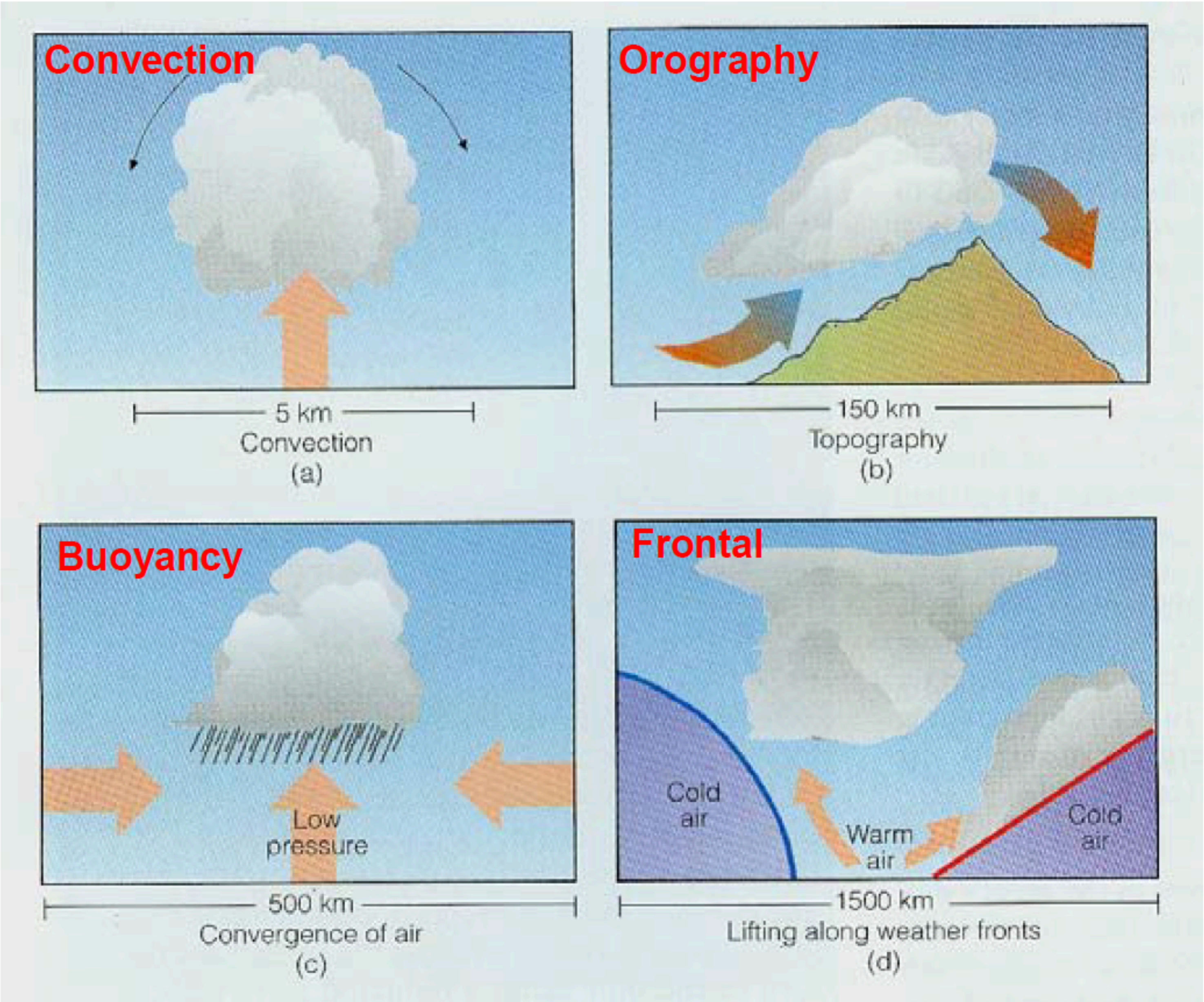


Hydrologic Cycle:

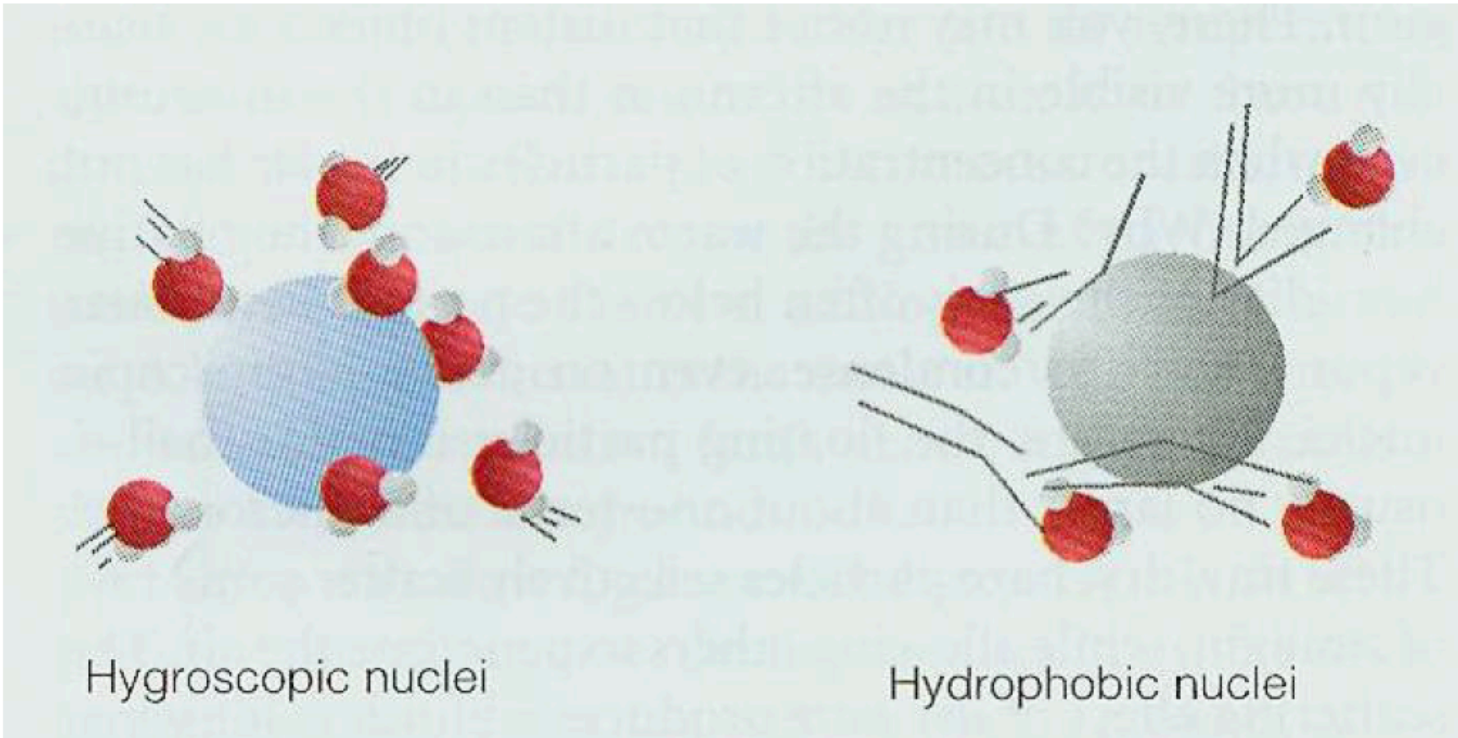
Precipitation

HOW TO MAKE RAIN:

1) Adiabatic Lifting/Cooling Mechanisms



3) Cloud Condensation Nuclei



"water-seeking"

Salt
Sulfuric/nitric acid
Dust
Seed particles

"water-repelling"

Oils
Gasoline
Paraffin waxes

HOW TO MAKE RAIN:

4) Raindrop Growth

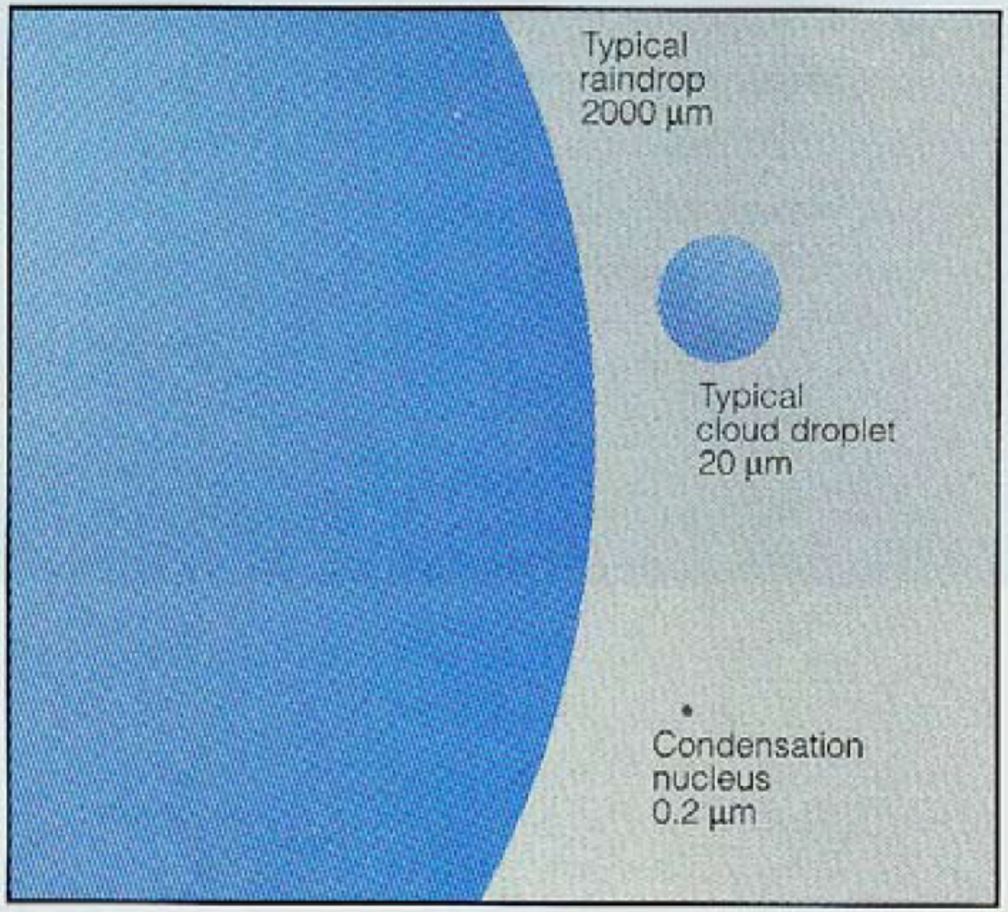


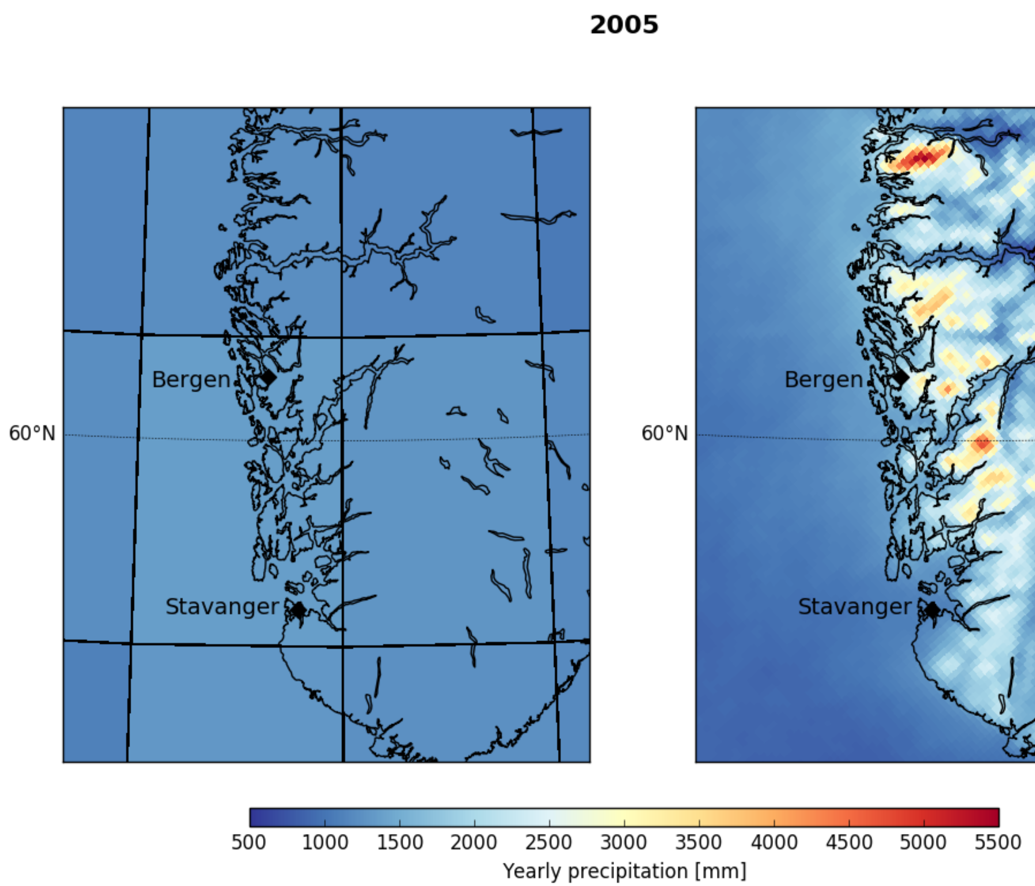
FIGURE 8.1
Relative sizes of raindrops, cloud droplets, and condensation nuclei.

Subject to gravity

Must overcome:
- cloud updrafts
- evaporation

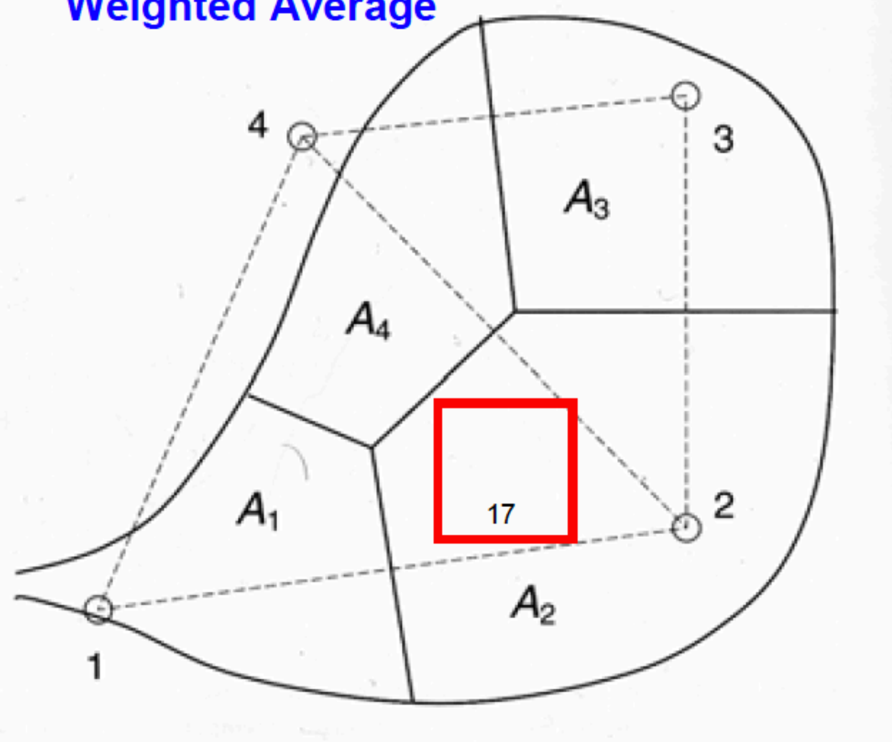
Precipitation process is very complicated; highly variable in space and time

And example of variability of precipitation and its dependence on model resolution



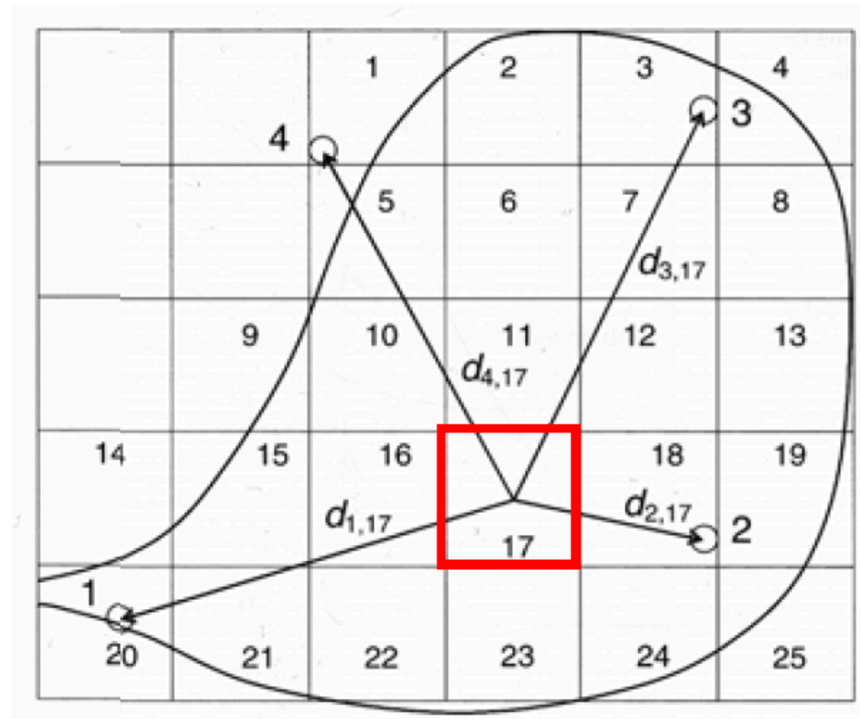
Areal Average Precipitation

Nearest Neighbor
Thiessen Polygons
Weighted Average



$$P_{17} = P_2$$

Inverse Distance

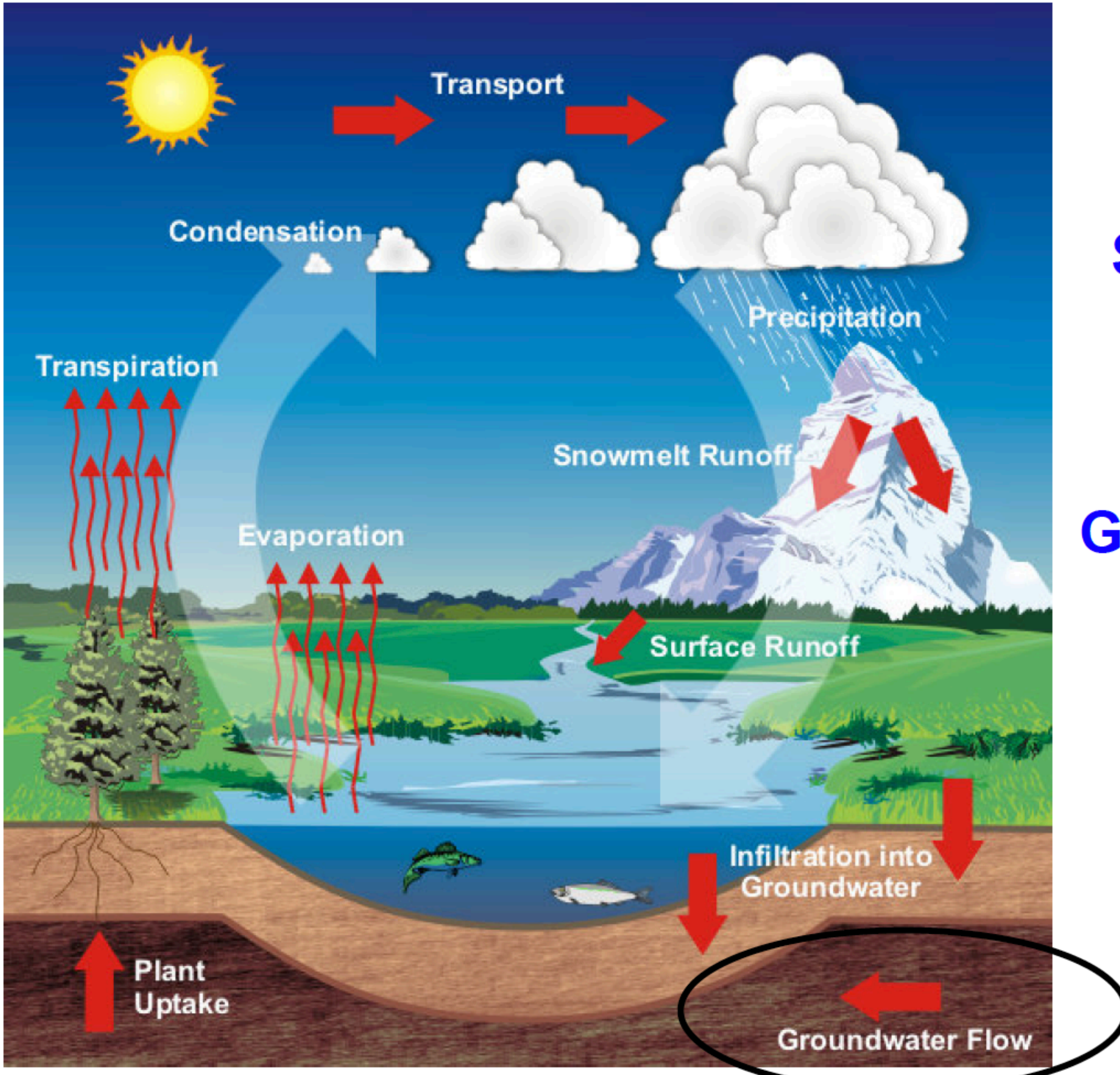


$$P_{17} = \frac{d_{1,17}^{-2}P_1 + d_{2,17}^{-2}P_1 + d_{3,17}^{-2}P_1 + d_{4,17}^{-2}P_1}{d_{1,17}^{-2} + d_{2,17}^{-2} + d_{3,17}^{-2} + d_{4,17}^{-2}}$$

Hydrologic Cycle:

Subsurface Water

(Saturated Groundwater)



Groundwater Flow

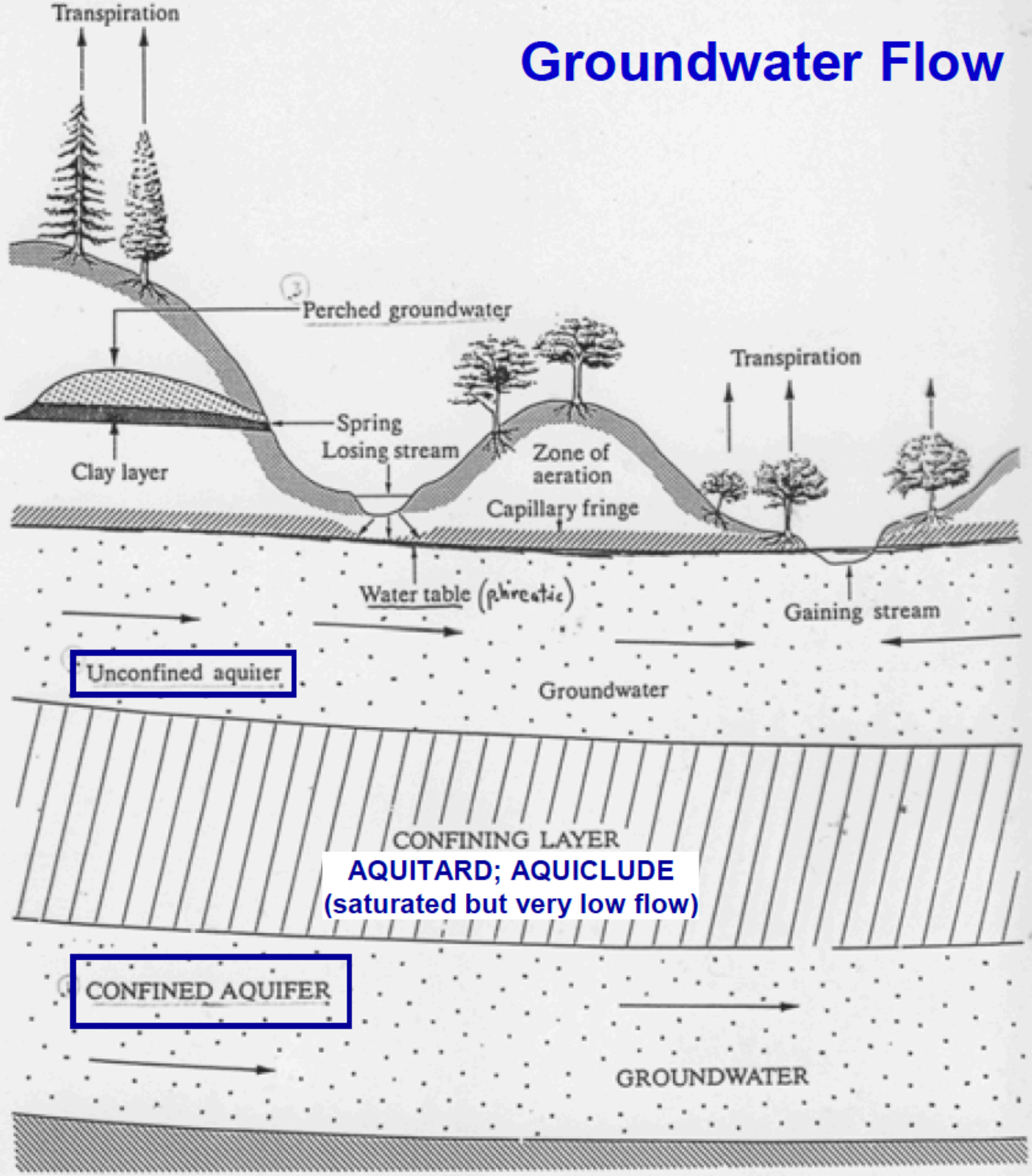


FIGURE 7.4 Schematic cross section showing occurrence of groundwater.

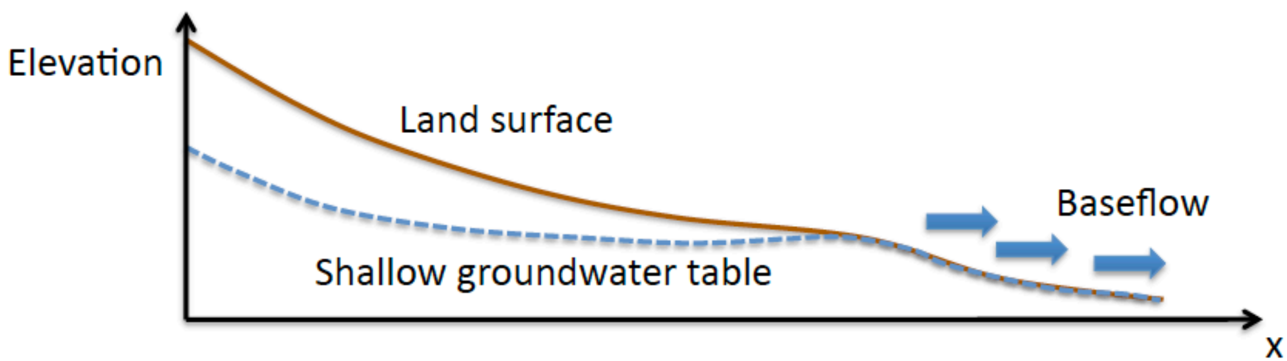
Objective:
Understand, quantify and predict flow of saturated subsurface water, i.e.

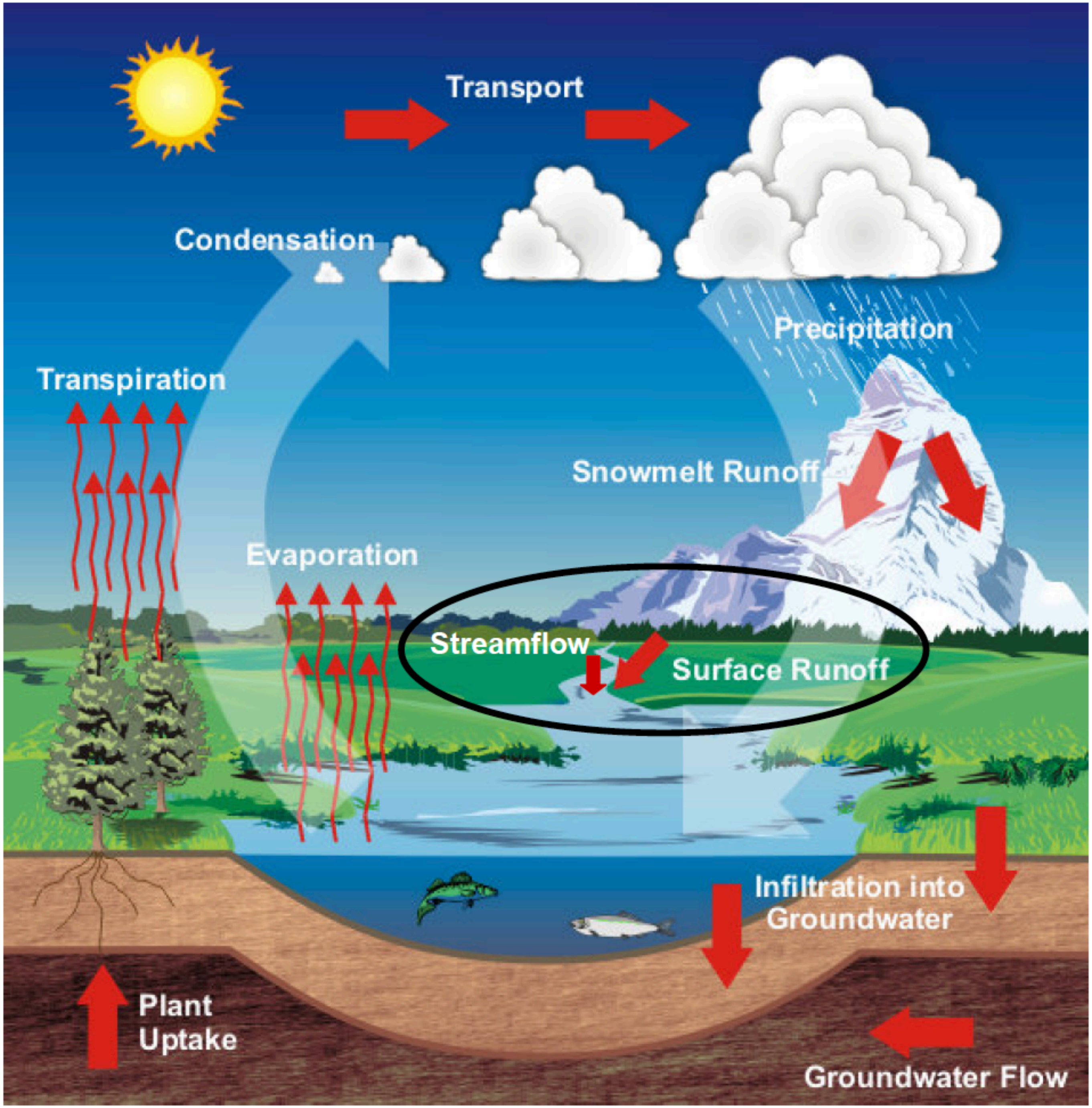
Groundwater flow through aquifers

very slow
~ 0.1 km/day or less

Soil Hydrology
Subsurface return flow (Baseflow)

- Portion of surface runoff that exfiltrates from groundwater.
- Even after extended periods of drought, rivers receiving sufficient amounts of water from baseflow continue to flow. Important from a ecological perspective!



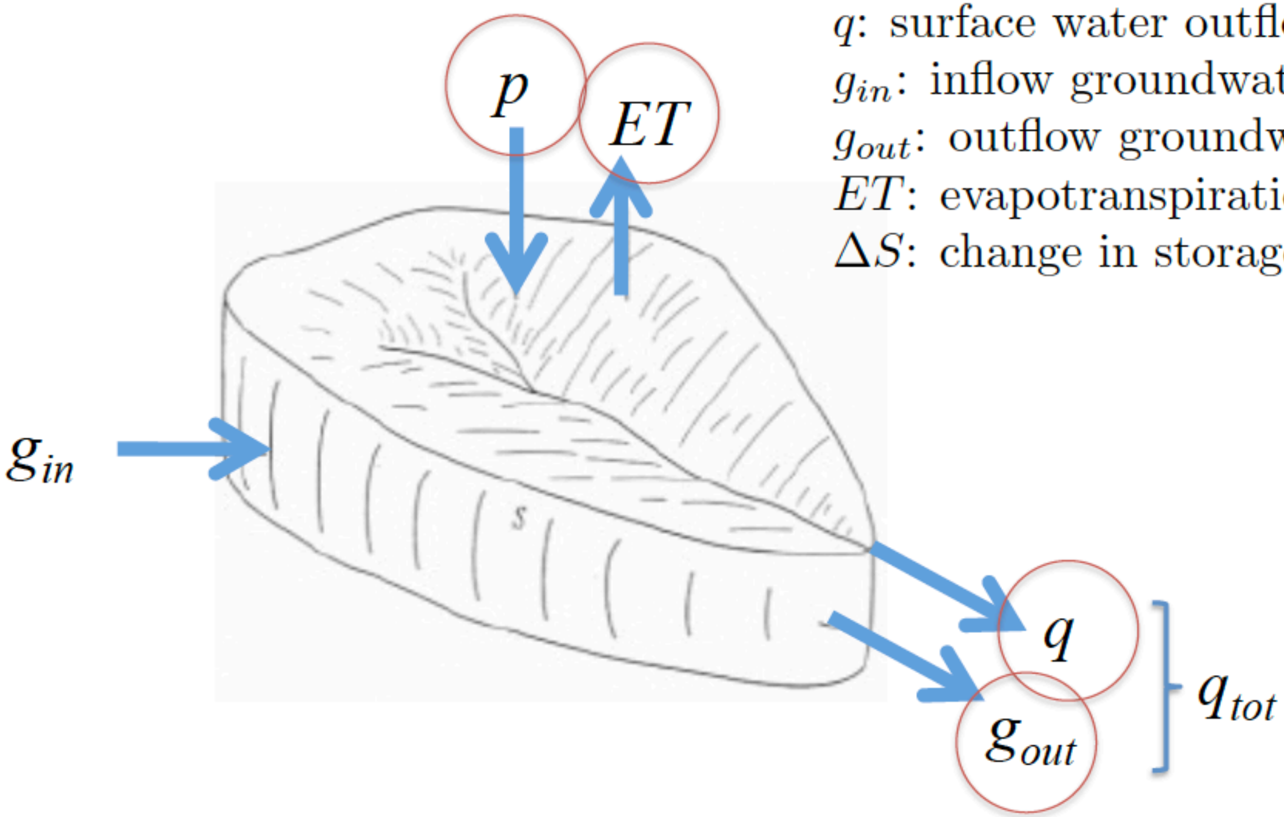


Hydrologic Cycle:

Surface Runoff and Streamflow

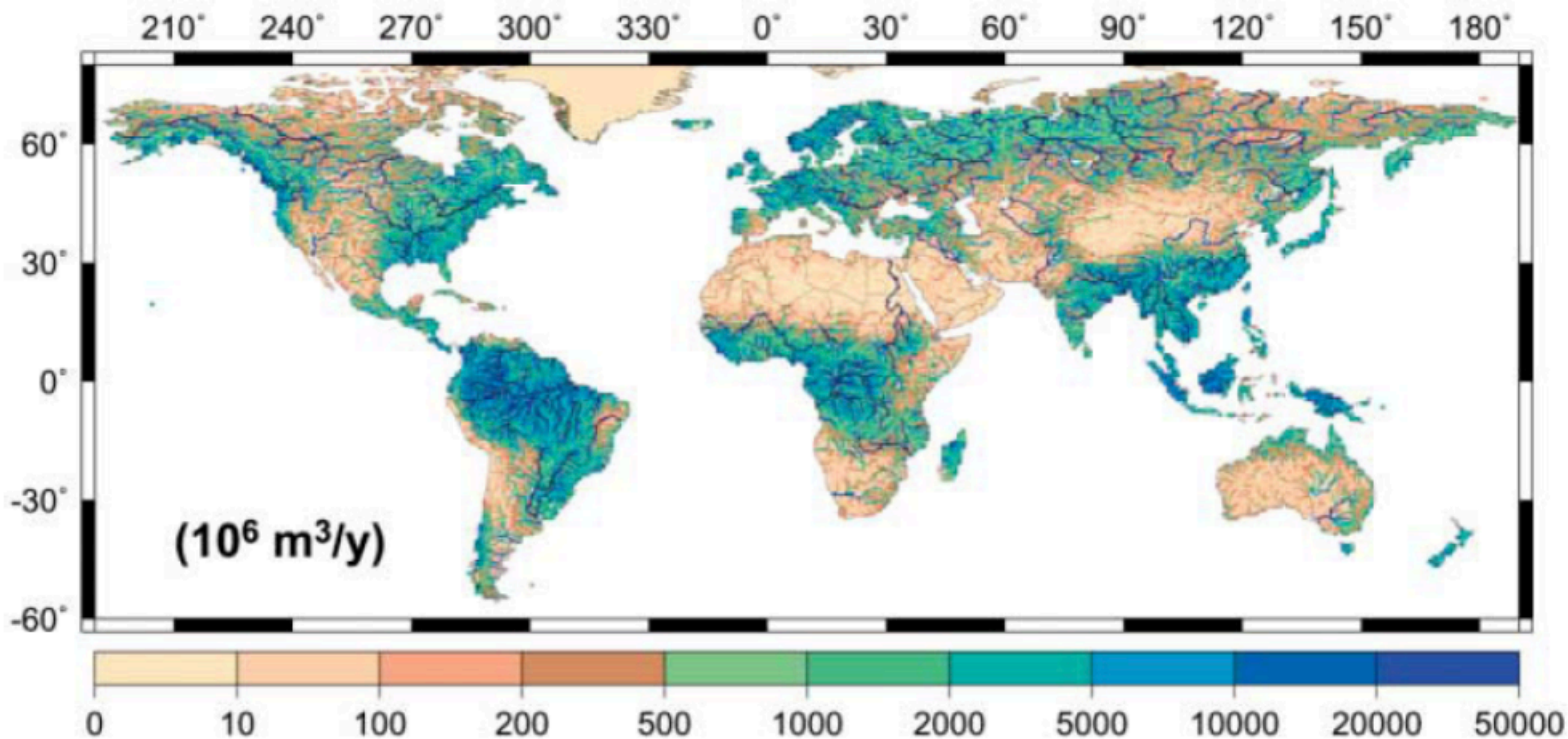
Recap: the terrestrial water balance

p: precipitation
q: surface water outflow
g_{in}: inflow groundwater
g_{out}: outflow groundwater
ET: evapotranspiration
ΔS: change in storage



$$p + g_{in} - (q + g_{out} + ET) = \Delta S$$

Annual River Discharge



› What is the most striking thing about this map?

Land surface hydrology: runoff due to soil saturation/ infiltration capacity exceedance

- Immediate production of surface runoff if the soil is saturated and has no more capacity to absorb water in its matrix. Any additional precipitation, irrespective of intensity, becomes surface flow.
- Soil depth, upstream watershed area, local topography important

- Anthropogenic modification: Problems of water logging near irrigation channels, …

Surface Runoff and Streamflow

<u>Objective</u>:
Understand, measure and predict surface flow over land and in rivers resulting from a rainfall event

<u>Of Practical Interest</u>:

Local / regional flooding

Water resource planning (e.g, droughts)

Hydraulic structure design

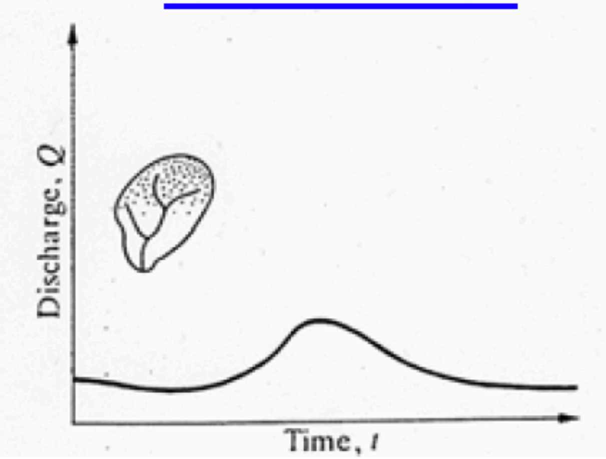
Land use designation

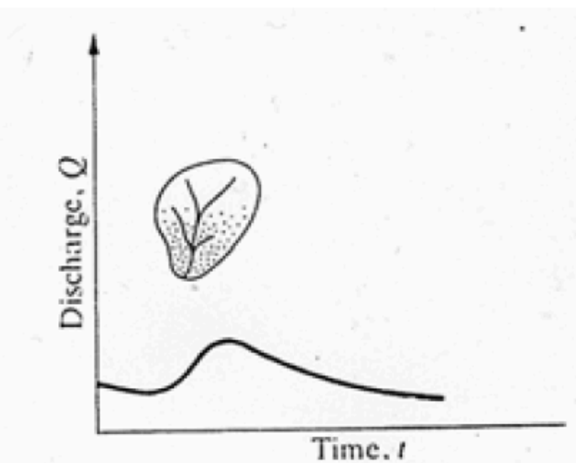
Urban:
Drainage network design
Combined Sewer Overflows

Rural:
Erosion

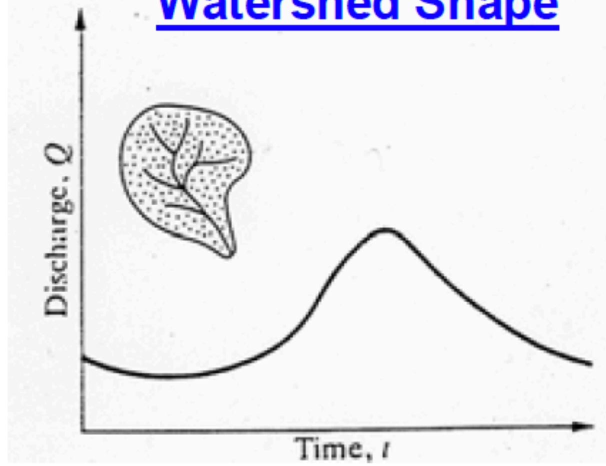
Hydrograph shape varies with:

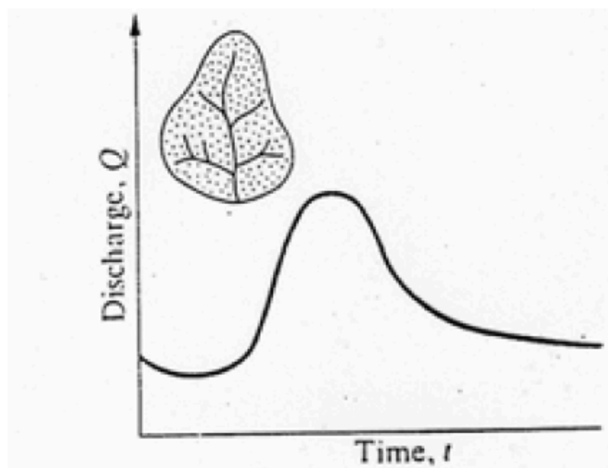
Storm Location



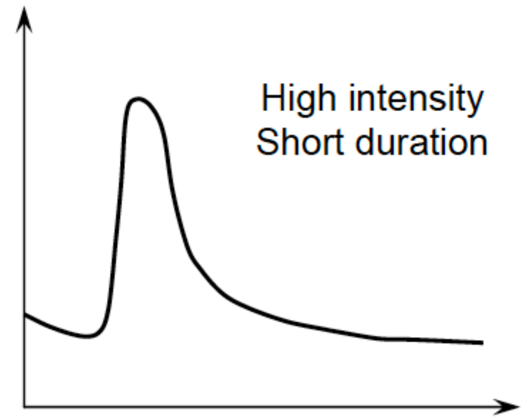


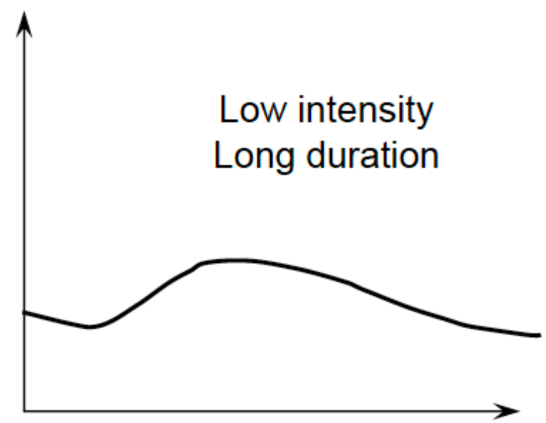
Watershed Shape





Storm Characteristics

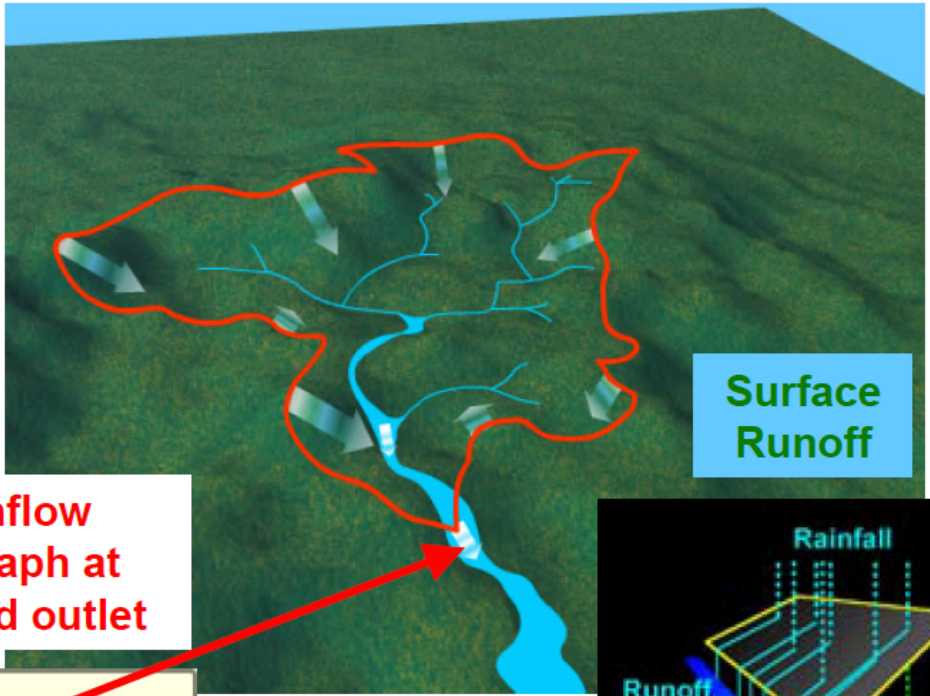


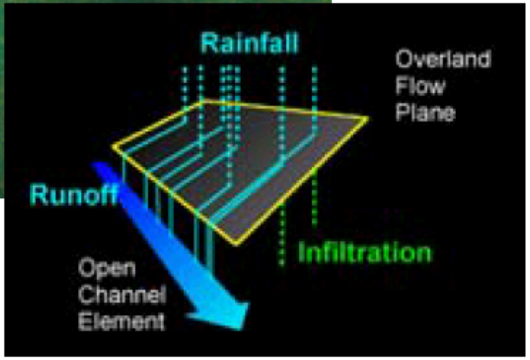


Also varies with soil type and land use

Traditional Hydrology

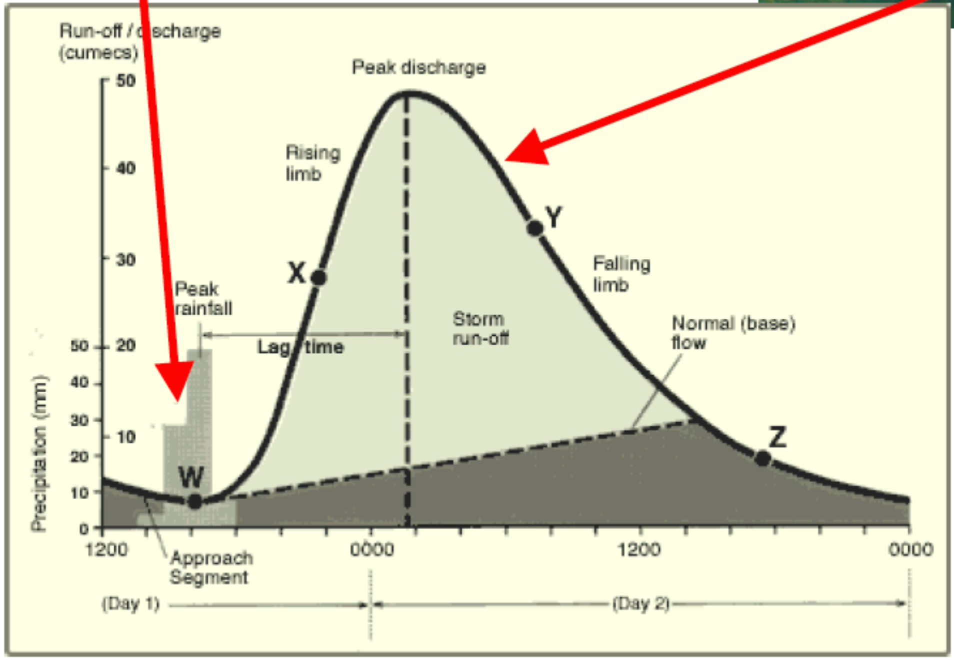
Rainfall →
Surface Runoff →
Elevated Streamflow





Storm over watershed

Streamflow hydrograph at watershed outlet



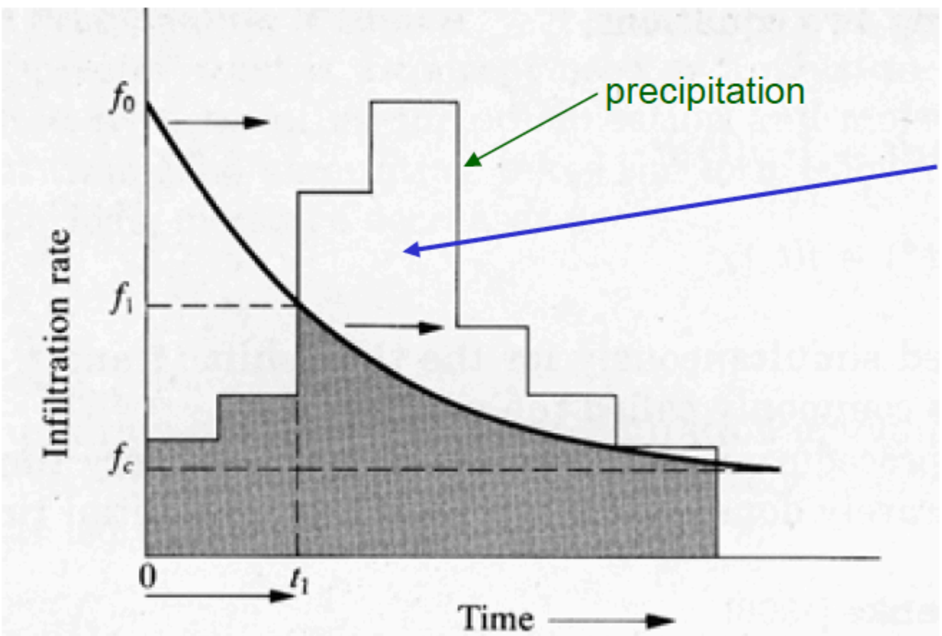
Kinematic Wave: How surface runoff travels down hillslope

How is surface runoff generated in the first place?

What else might contribute to elevated storm streamflow?

Traditional Surface Runoff Processes

<u>Infiltration rate f:</u> Rate at which incident precipitation can be "absorbed" by land surface
Depends on soil properties and antecedent moisture conditions
Generally decreases over time



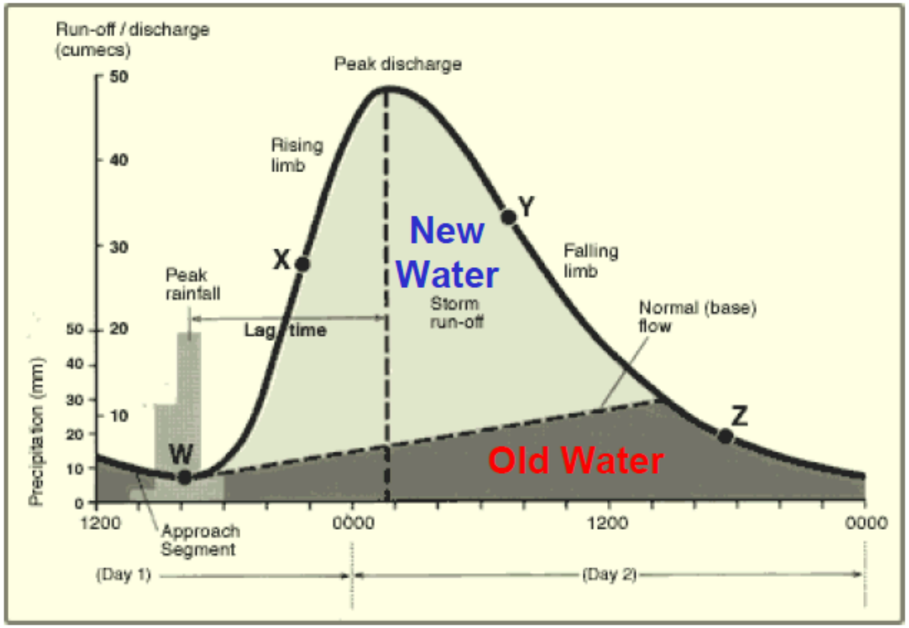
<u>Hortonian Runoff</u>

- Infiltration rate decreases below precipitation rate
- Runoff = precipitation – infiltration
- "Infiltration excess" runoff

Traditional Composition of Elevated Streamflow

Aforementioned Runoff/Streamflow Generation Mechanisms:

Can occur via: Land surface
Stream channels
Deep groundwater aquifers
Shallow subsurface



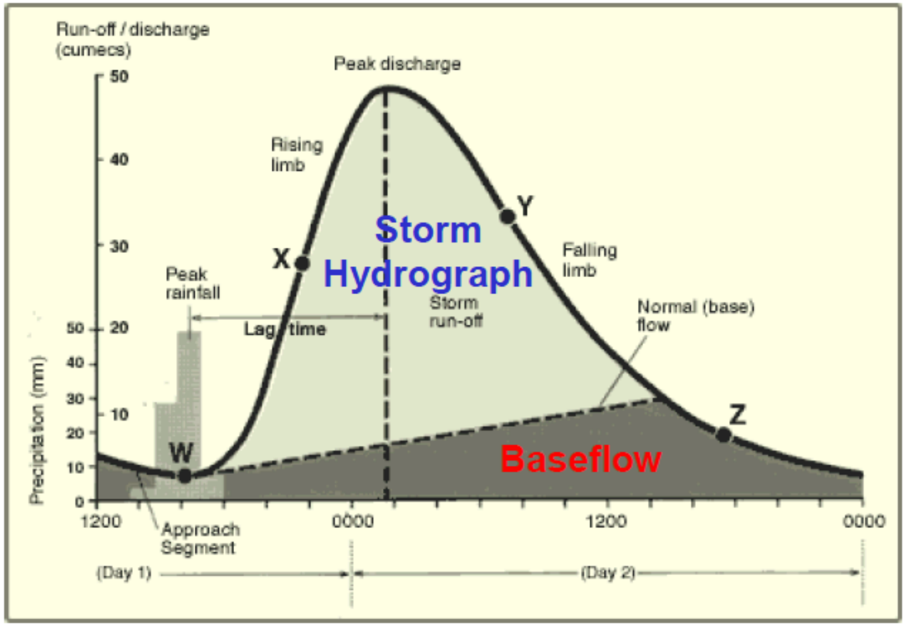
All mechanisms share a common thread:

New Water: Contributors to elevated streamflow all come from precipitated water during storm

Old Water: Ambient water residing within watershed (e.g., groundwater) is a negligible contributor to storm-related streamflow

Traditional Streamflow Hydrograph Separation

Traditional storm streamflow analysis: Strives to separate streamflow hydrograph into storm hydrograph (***new water***) and baseflow (***old water***)



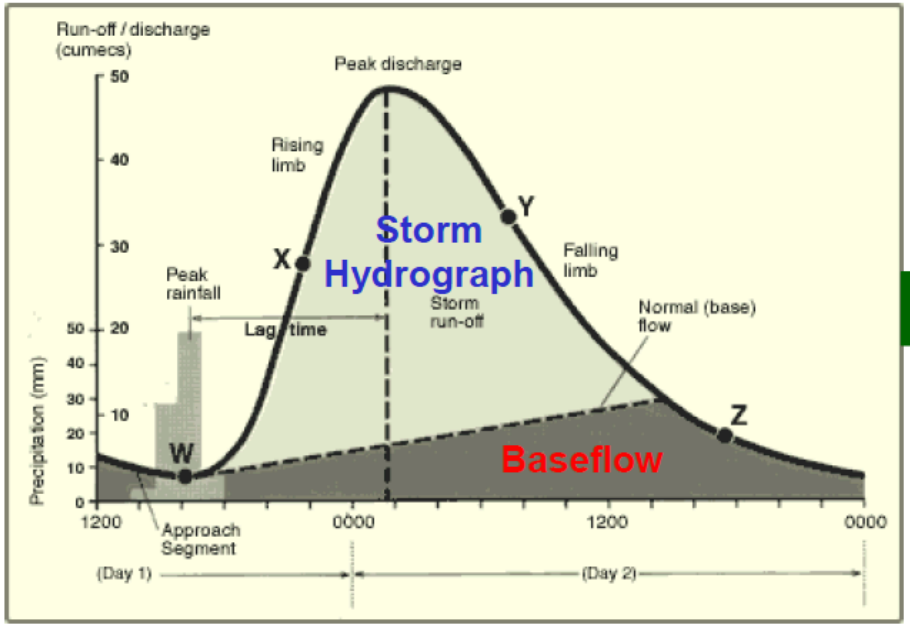
- At a point, precipitation = runoff + infiltration
- Storm hydrograph volume (at outlet) is a subset of the total precipitation volume (over watershed), i.e. runoff volume
- Infiltration enters groundwater and does not contribute to storm hydrograph

➔ ***Plausible theories, but never proven***

Numerous techniques developed to predict storm hydrograph response to point runoff over watershed (e.g., Unit Hydrograph, Linear Reservoir)

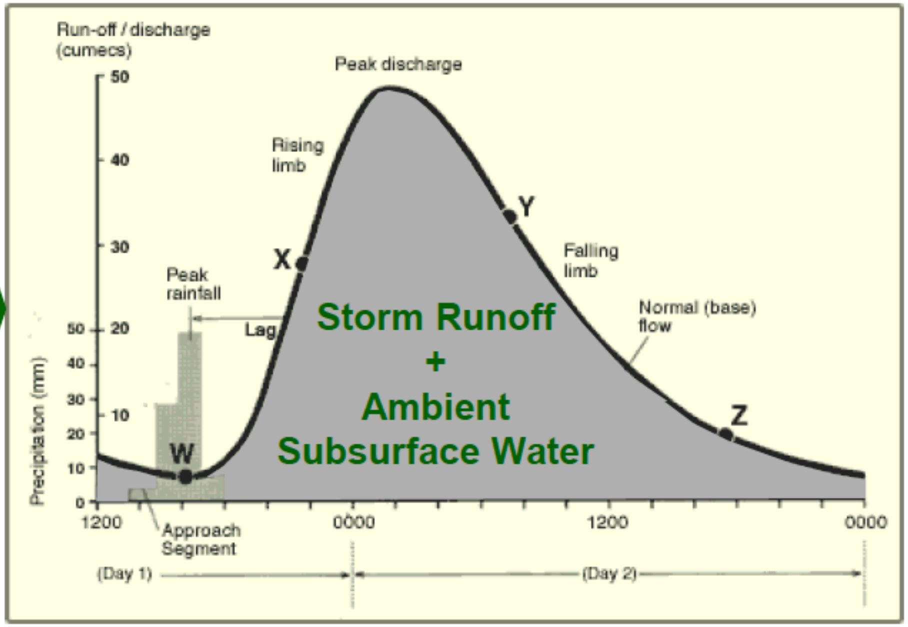
Actual Composition of Elevated Streamflow

Traditional Conceptualization



Isolation of new water for storm streamflow is "convenient fiction"

Alternative Conceptualization

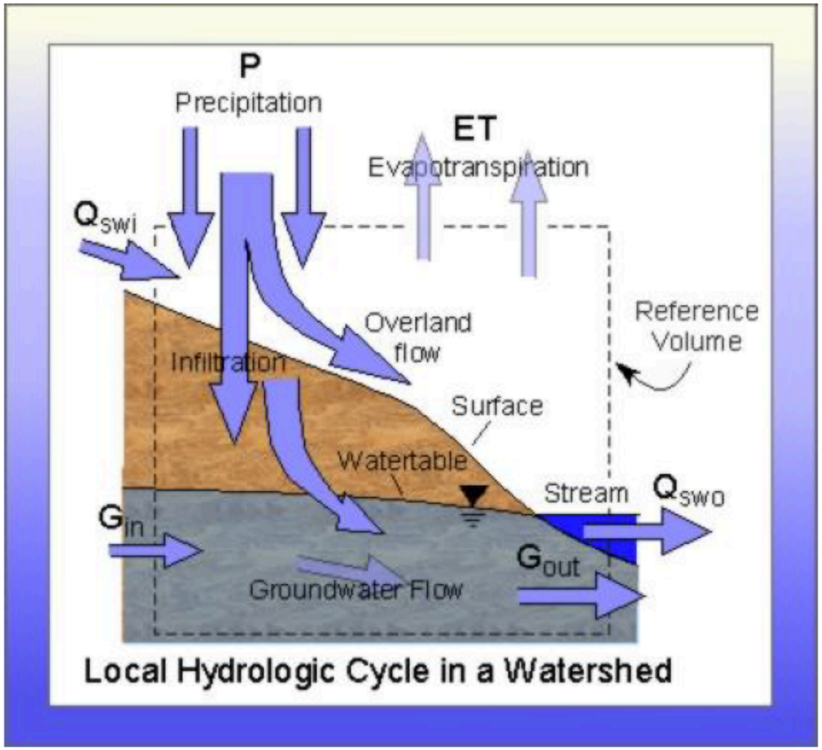


Storm streamflow is a mixture of new water and old water

Storm streamflow analyses should incorporate subsurface flow dynamics rather than remove it

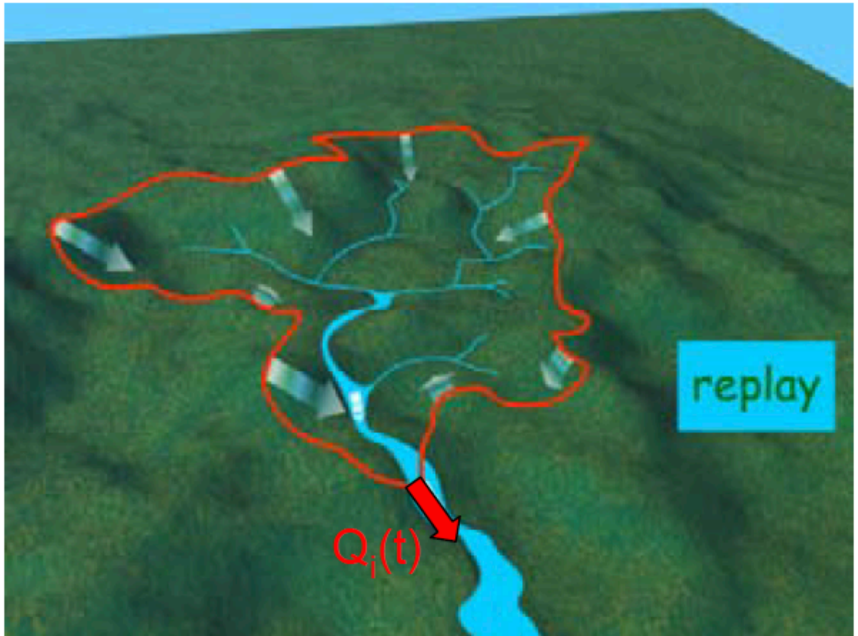
Surface – Subsurface Integration

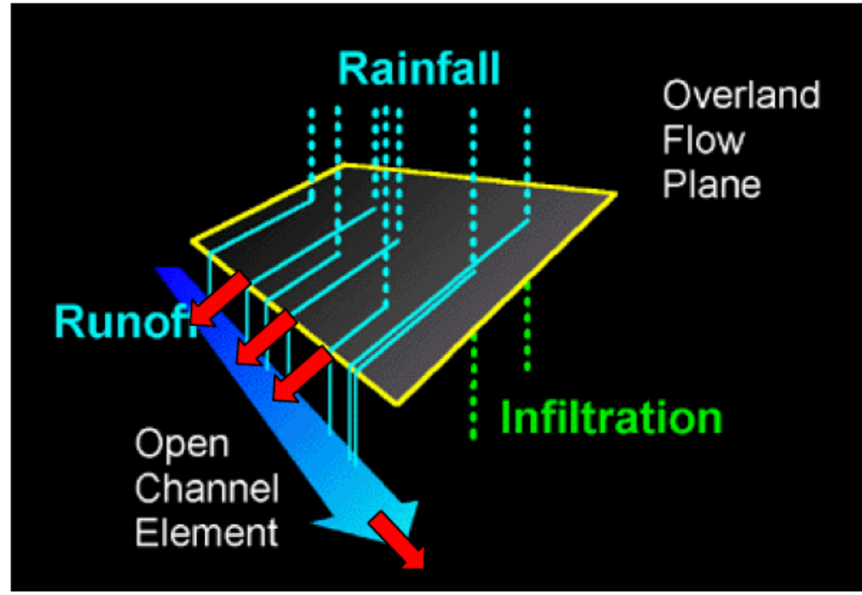
- Extremely difficult to couple surface and subsurface flow within a watershed using established analytical theory
  - Kinematic Wave for surface runoff / streamflow routing
  - Richard's Equation for surface infiltration / unsaturated zone flow
  - Aquifer equations for saturated groundwater flow



Extensive ongoing research on alternative approaches which are computationally efficient yet physically reasonable

Surface Runoff / Kinematic Wave:

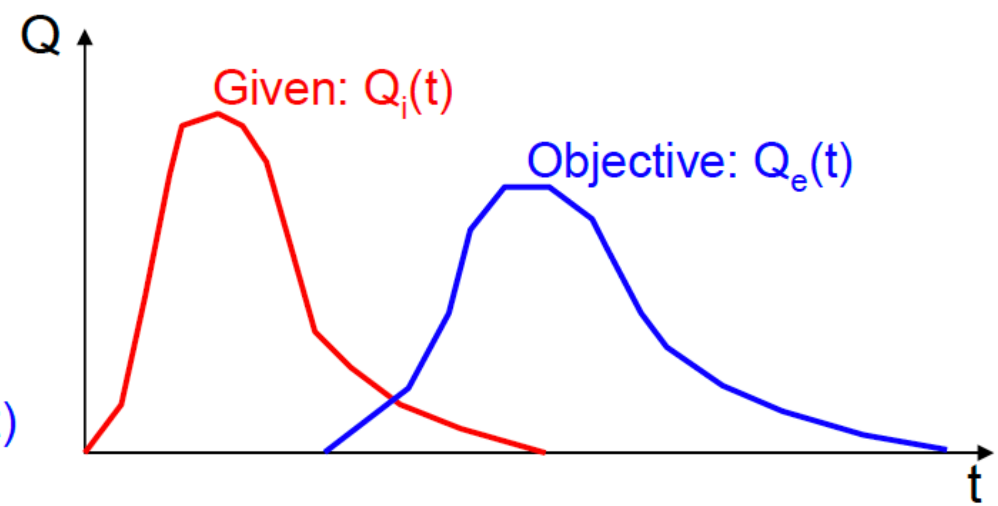




Streamflow Routing

Behavior of a flood wave along a defined open channel

$Q_e(t)$



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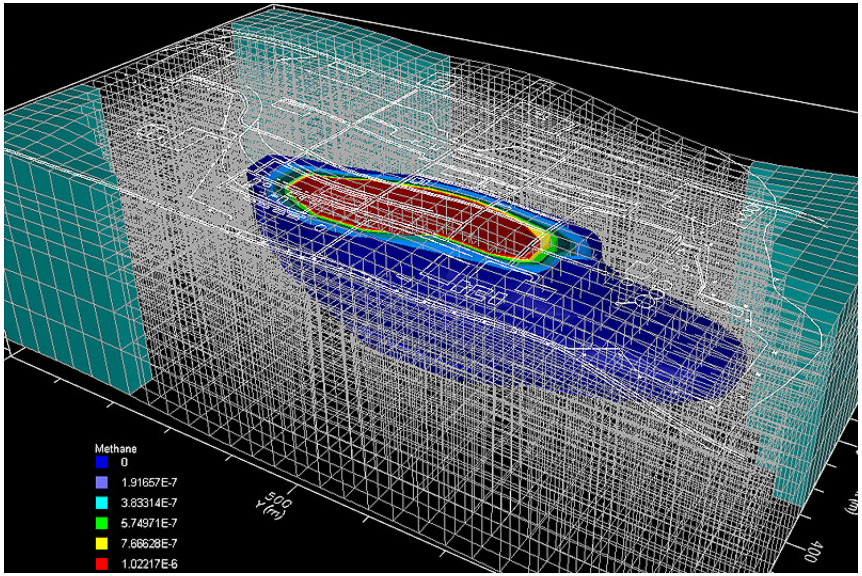
How do we represent all these processes?

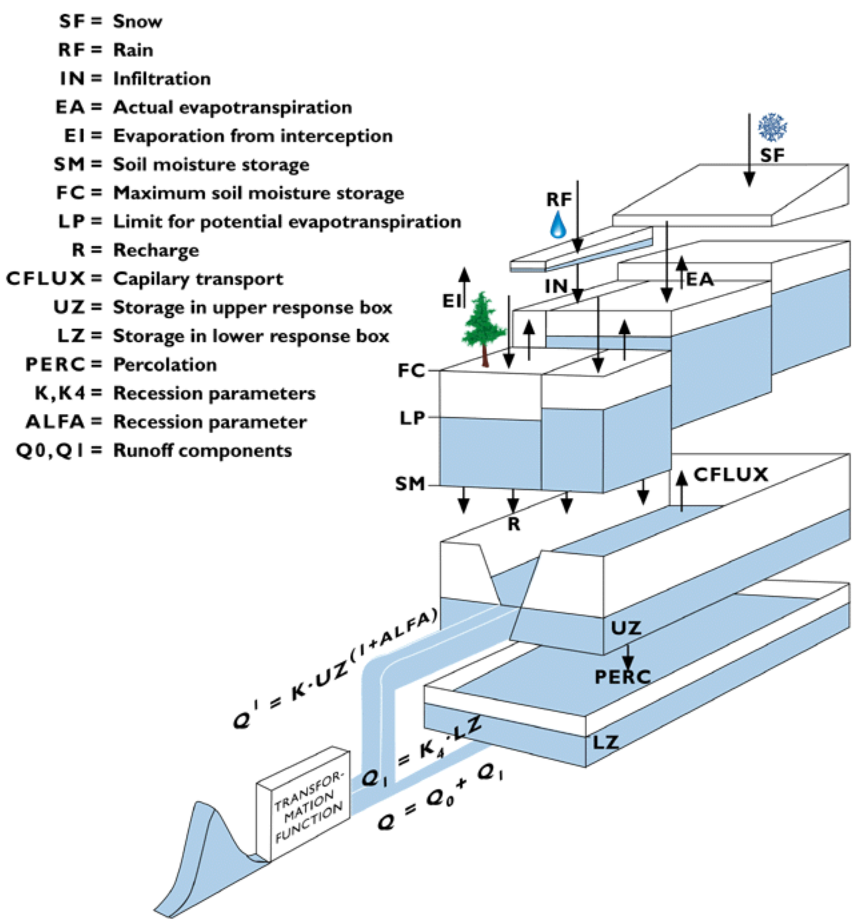
- Three main components
  - 1-D Infiltration/recharge (so-called Darcy flow)
  - 2-D River routing and discharge (flood forecasting)
  - 3-D Saturated subsurface or groundwater flow (critical for water resources evaluation, drought forecasting, etc.)
- Some modeling systems focus on just one of these components
  - MODFLOW(3-D groundwater)
  - TOPMODEL (2-D land surface)
- Some try to incorporate all three and more
  - HBV
  - CLM
  - WRF-Hydro



Contaminant modeling with MODFLOW

Conceptual ”rainfall - runoff” models: The HBV example

- Only requires daily precipitation, temperature & estimates of evapotranspiration
- Uses conceptual numerical descriptions of processes at catchment scale
- Can be run in a semi-distrubuted way by dividing catchments into sub-basins
- Used for operation flood forecasting in the Nordic countries including Norway
- Requires tailoring of input data (geostatistics), assumptions to parameters, good data for calibration



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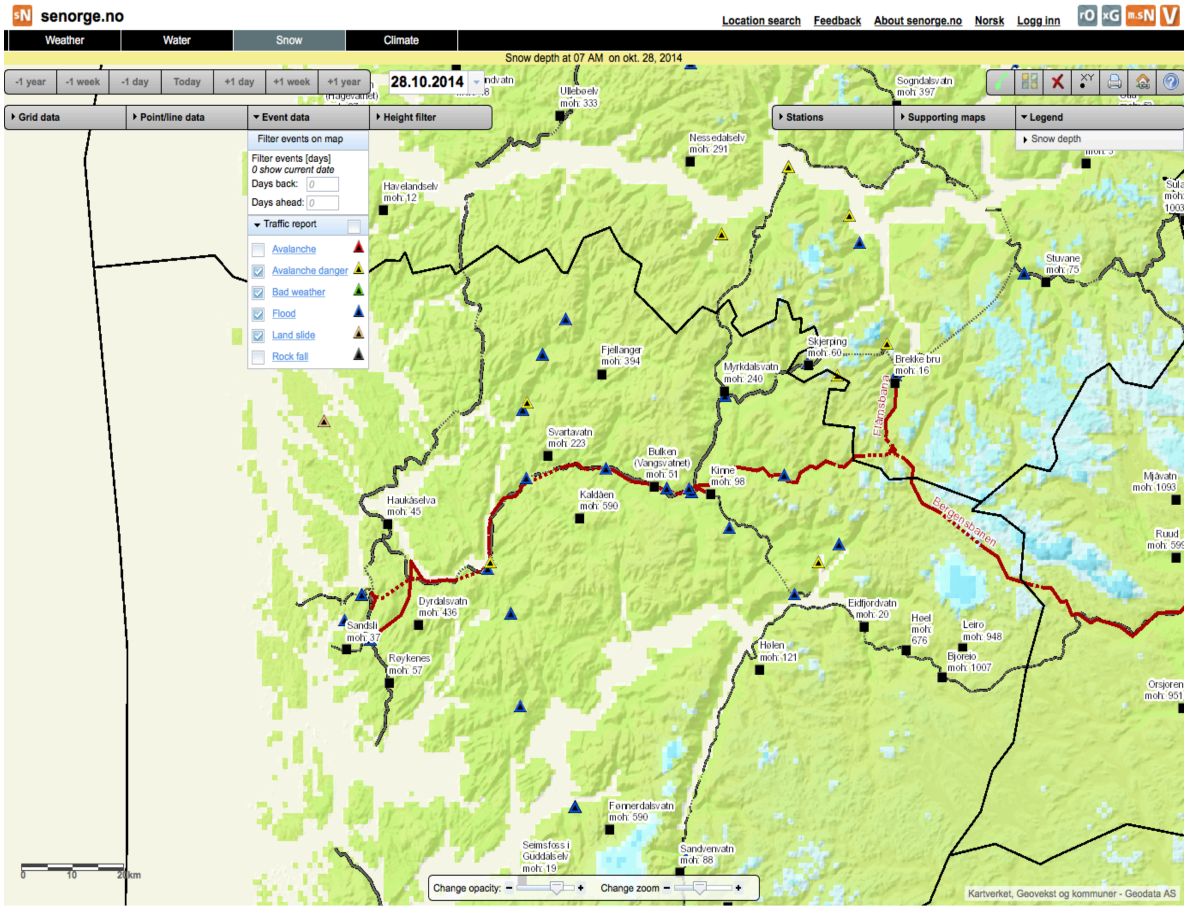
Streamflow and flood forecasts from NVE using HBV

- Point-based Hydrological predictions at catchment-basin scales
- Quite good at identifying events; relatively inexpensive
- See last weekend [flooding in Southern Norway]
- Lack of flood warning on smaller river systems;
- Lack of overbank inundation information, precise details



(from senorge.no)

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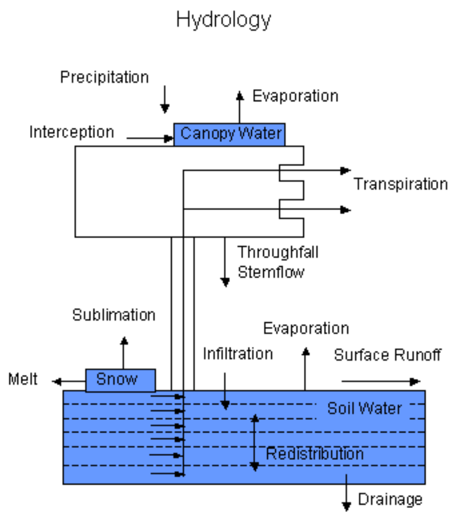
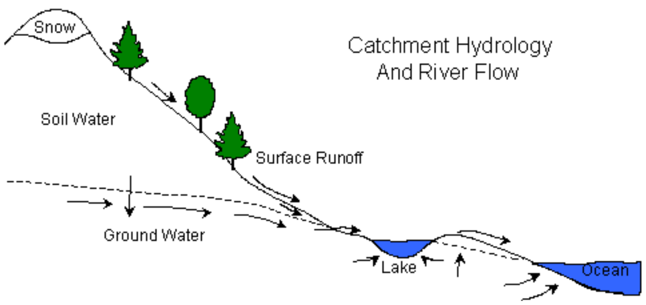
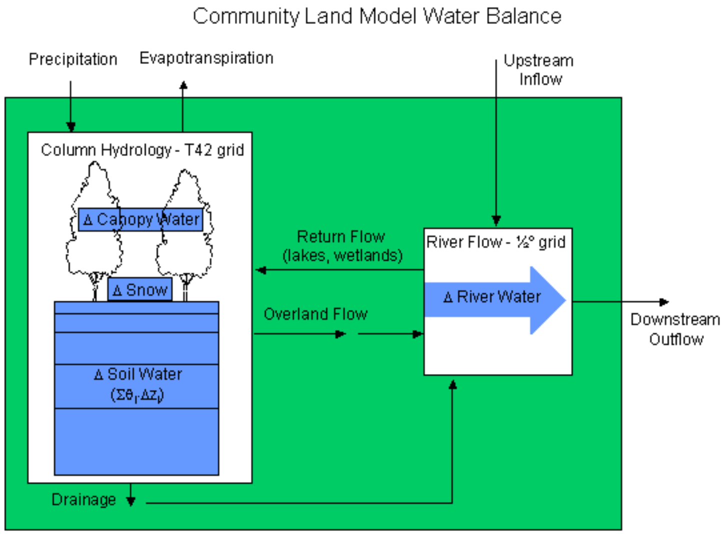
Combined conceptual – physical models: CLM

- CLM incorporates all elements in subgrid calculations; heavily reliant on parameterizations



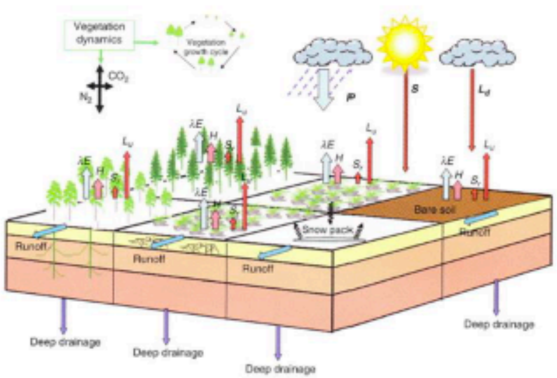




Column (T42): Precipitation + Return - Evapotranspiration - Total Runoff
River (½°): Inflow + Total Runoff - Return - Outflow
Grid Cell (T42): Precipitation + Inflow - Evapotranspiration - Outflow

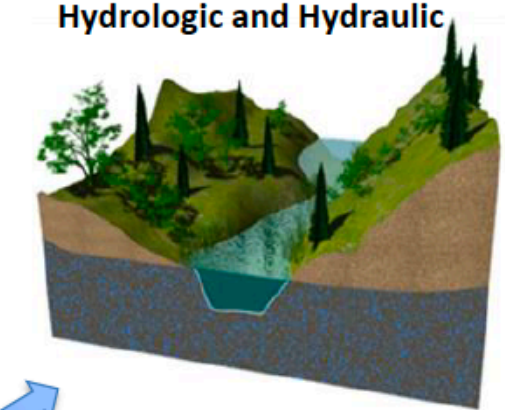
WRF-HYDRO SYSTEM DESCRIPTION

Column Land Surface Models:
Noah/NoahMP/SAC-HTET*

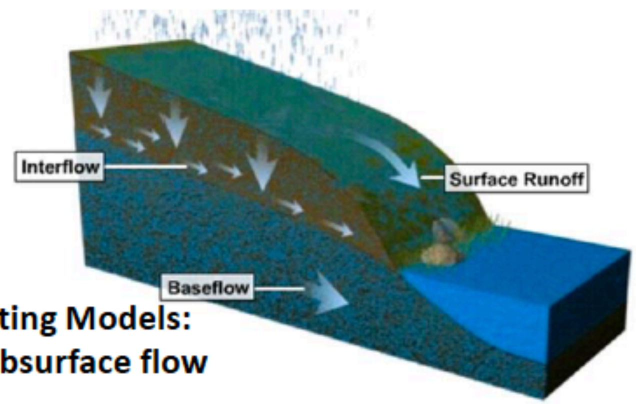


Output Variables:
Evapotranspiration
Soil moisture/Soil Ice
Snowpack/snowmelt
Runoff
Radiation Exchange
Energy Fluxes
Plant Water Stress

Channel & Reservoir Routing Models: Hydrologic and Hydraulic



2-way coupling



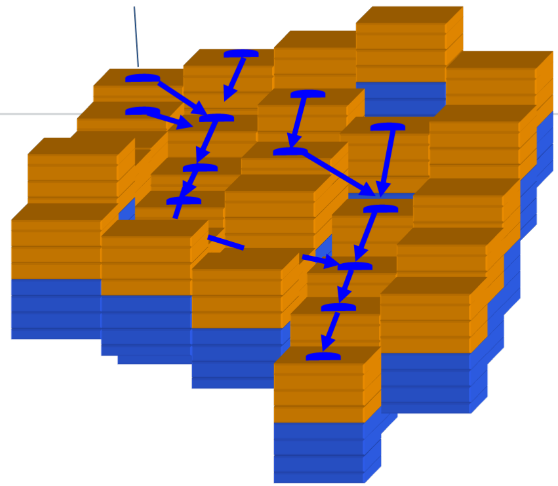
1-way coupling or 2-way coupling

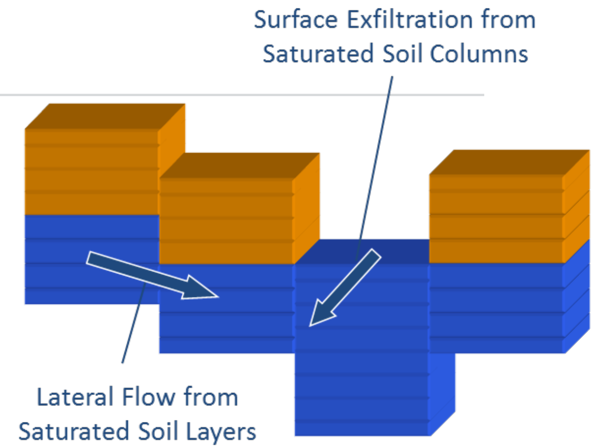
Output Variables:
Streamflow
River Stage
Flow Velocity
Reservoir Storage & Discharge

Terrain Routing Models:
Overland, subsurface flow

Output Variables:
Stream Inflow, Surface Water Depth, Groundwater Depth, Soil Moisture

Routing physics in WRF-Hydro

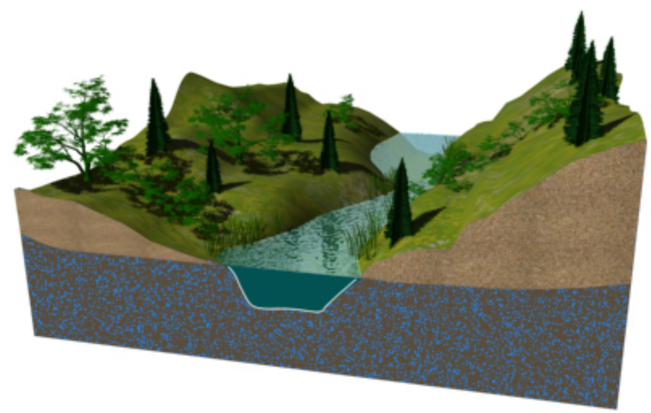




› Surface routing:
- St. Venant equation
- Manning's equation

› Sub-surface routing:
- Saturated overflow
- Darcy equation

› Channel routing:
- 1-d diffusive wave
- one-way overflow into channel;
- no sub-surface loss;
- infinite channel depth



(Gochis et al., 2014 NCAR Tech Notes)

National Water Model (NWM) Version 1.0 Technical Specs

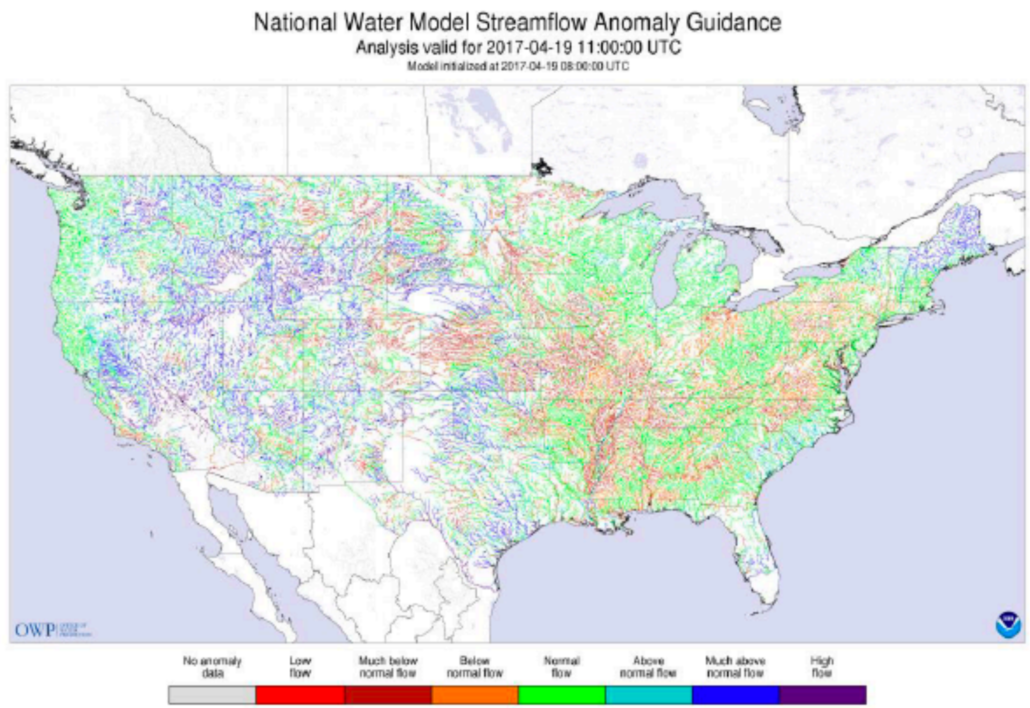
Sponsor	NOAA Office of Water Prediction (OWP)
Development Team	NCAR/RAL, NOAA/OWP/NWC, USGS, CUAHSI, Universities
Software	Built on the NCAR-supported community WRF-Hydro modeling system
Hardware	NCEP Central Operations Weather and Climate Operational Supercomputing System (WCOSS)

Data Throughput:

- Input data per day: 4.45 Terabytes
- Output data per day: 3 Terabytes
- # of river channels: 2.7 million
- # of reservoirs: 1,260
- Total # of computational elements: ~360,000,000

Model Details:

- Number of lines of code: 74,740
- Computer usage: > 100,000 cpu-hours per day



Available online at: *http://water.noaa.gov/tools/nwm-image-viewer*

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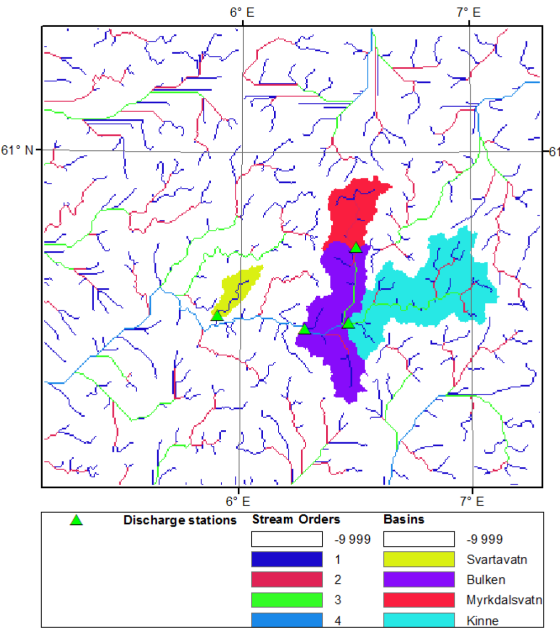
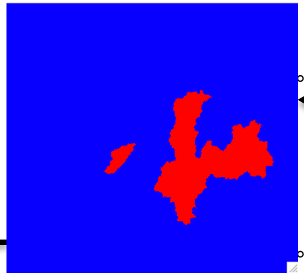
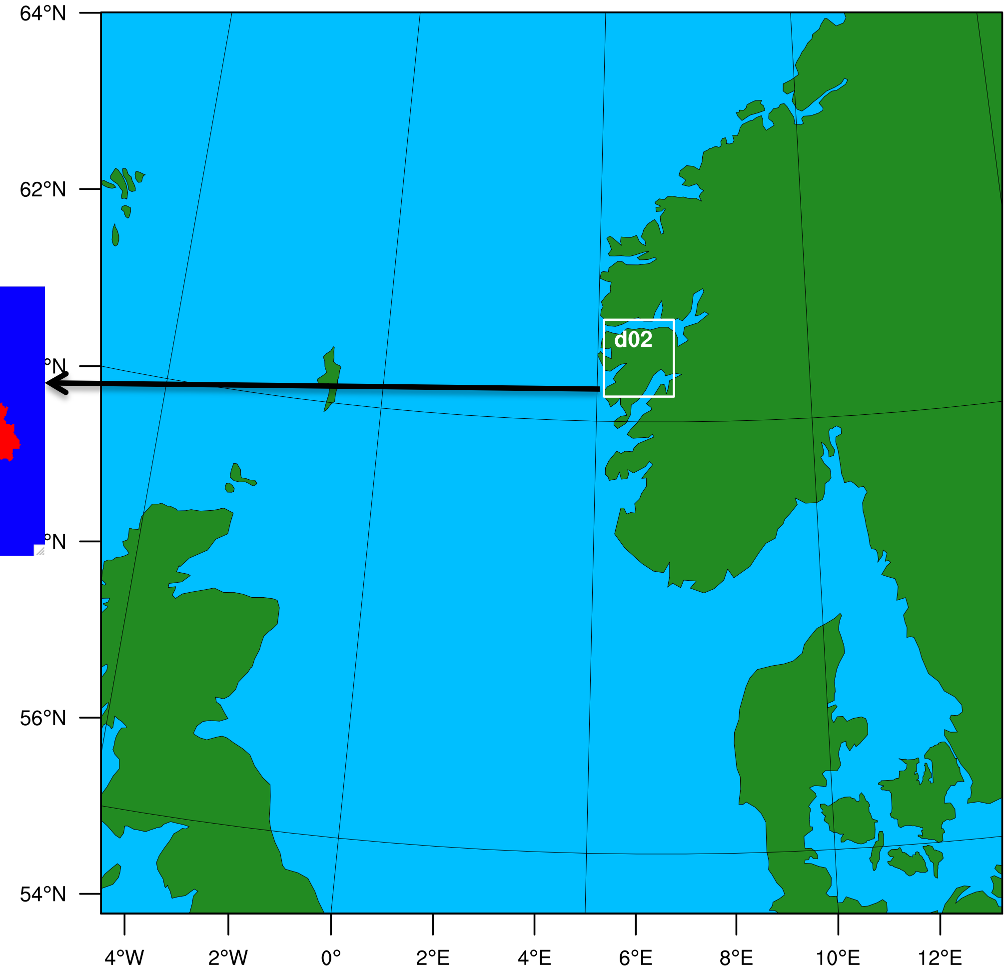
WRF-Hydro Domain design

Catchments in yellow (used for calibration), red, purple and blue





WPS Domain Configuration



(The importance of high grid resolution: Pontoppidan et al., 2017, Tellus A)

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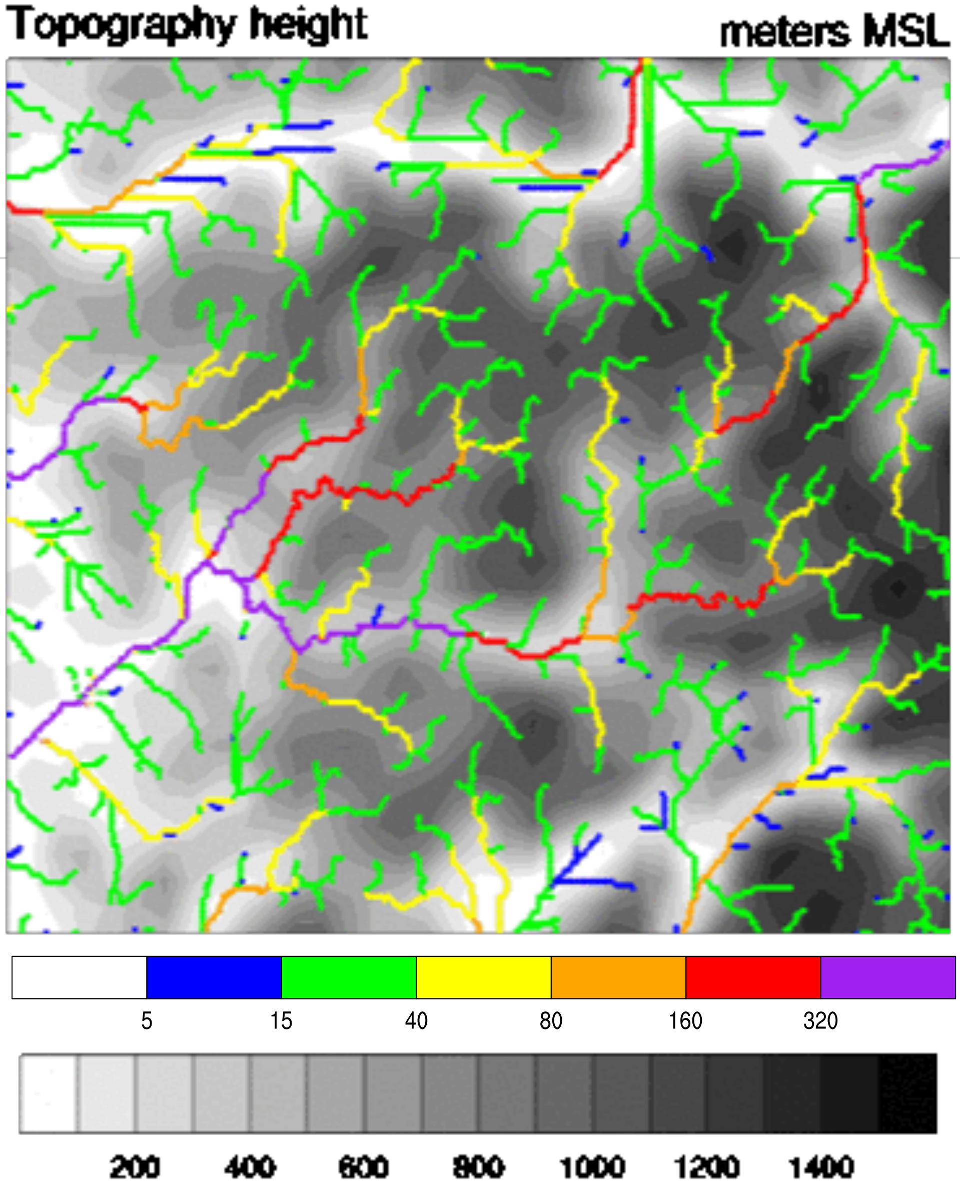
- Unlike conceptual models the physical model provides comprehensive information over the entire stream network
- 2-way coupling, which can capture important feedbacks
- But is expensive, difficult to validate in data poor regions

Streamflow, Oct 20-31, 2014, Voss



Conclusions/outlook

- Hydrology is outrageously complicated; simplifications should be scientifically based
- Scales matter! Is the time scale one of minutes, hours, days, months or years? Are the spatial scales isolated ecosystems, catchments or major continental basins?
  - The appropriate tool depends on this
  - For continents/major basins: CLM
  - For watersheds: Conceptual models (HBV)
  - For detailed, continuous information: WRF-Hydro
- *All* approaches to modeling the hydrological system involve trade-offs
  - Physical models are expensive but provide exceptional detail and costs are dropping exponentially
  - Conceptual models are cheap and probably good enough for many purposes but require many assumptions and data massaging

Figure: Photo from the flooding in Voss, fall 2015. This camping area with many permanent trailer homes is right on the flood plain.

THANK YOU!

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