The Ultimate Hydrologic Sponge:

how the plumbing system of the Cascades controls streamflow, geomorphology, and response to disturbance

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C.Tague, *University of California Santa Barbara*
A.Jefferson, *Kent State University*
S.Lewis & M.Safeeq, *Oregon State University*

- The Cascades: a peculiar landscape
- The hydrologic plumbing system of the Oregon Cascades
- Implications for geomorphic processes and water quality
- How might this apply to Battle Creek and environs?

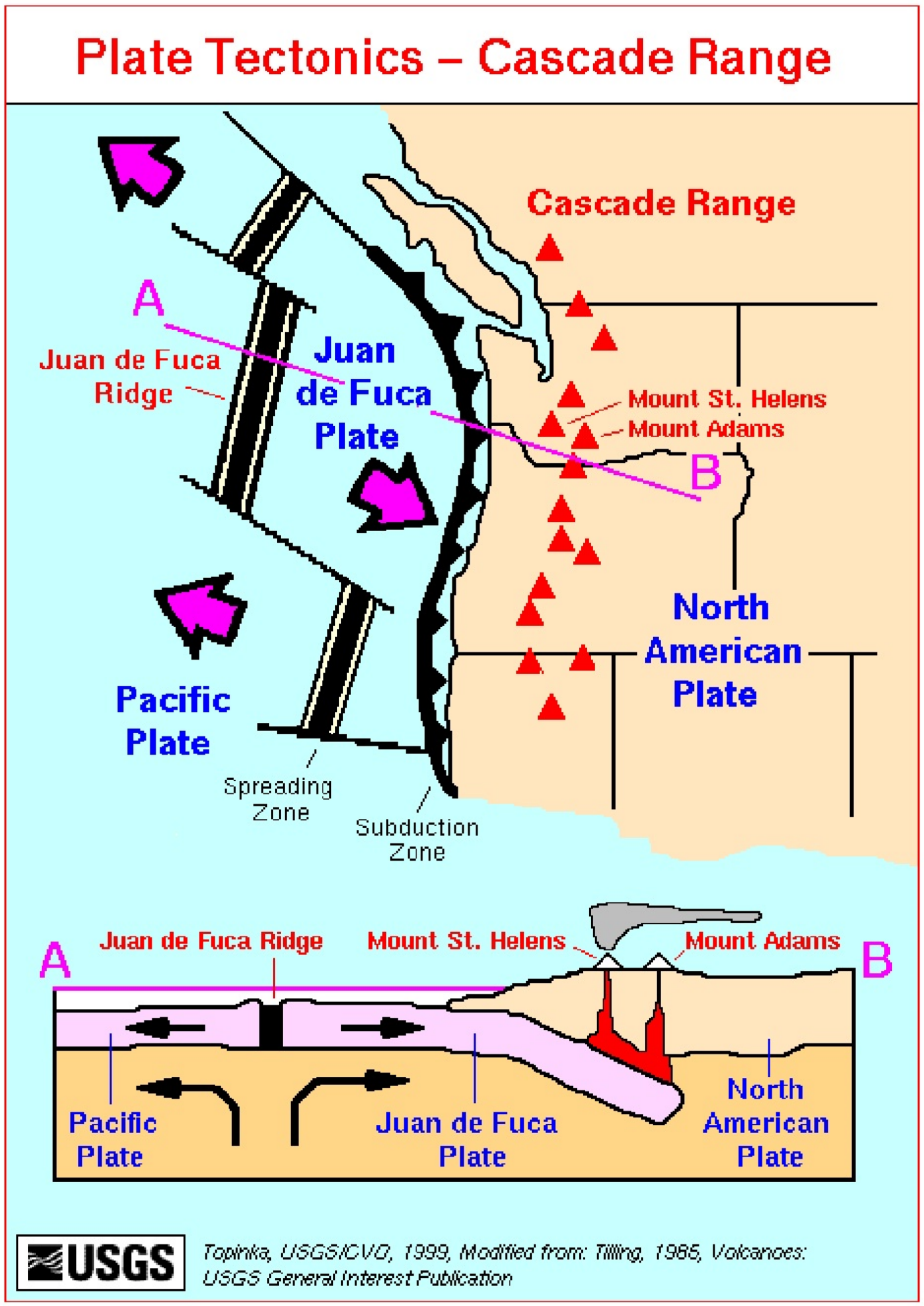
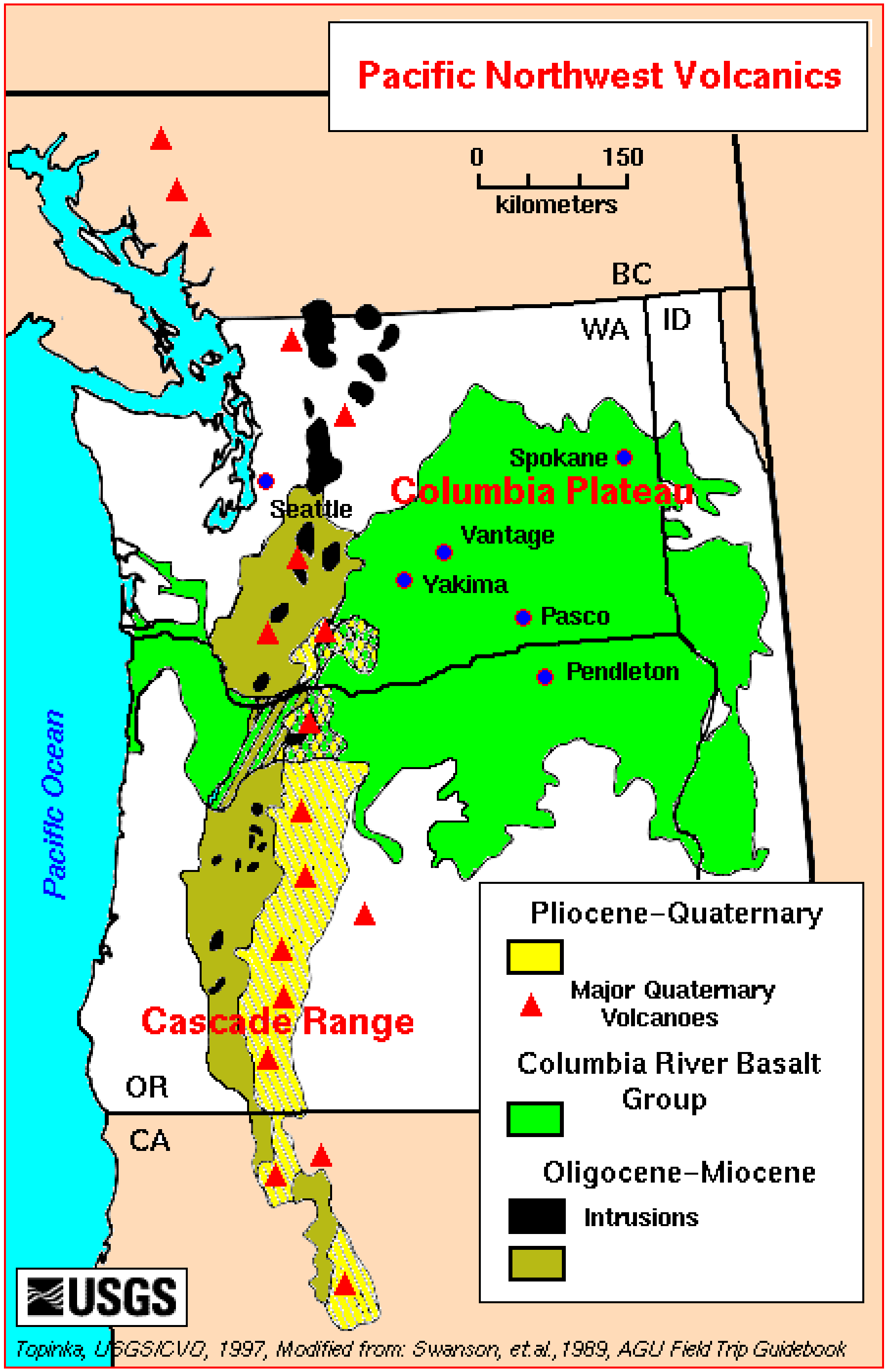
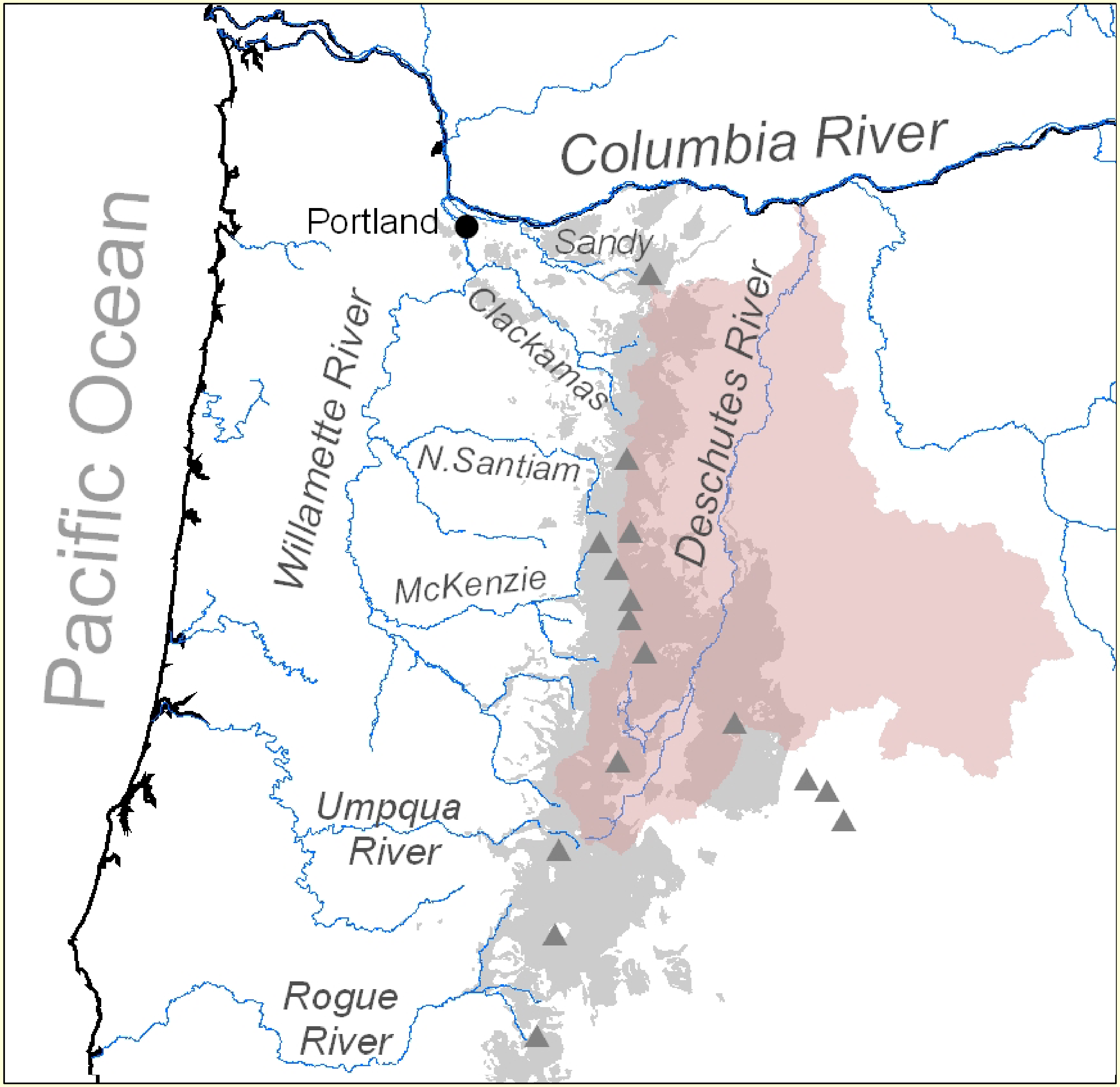
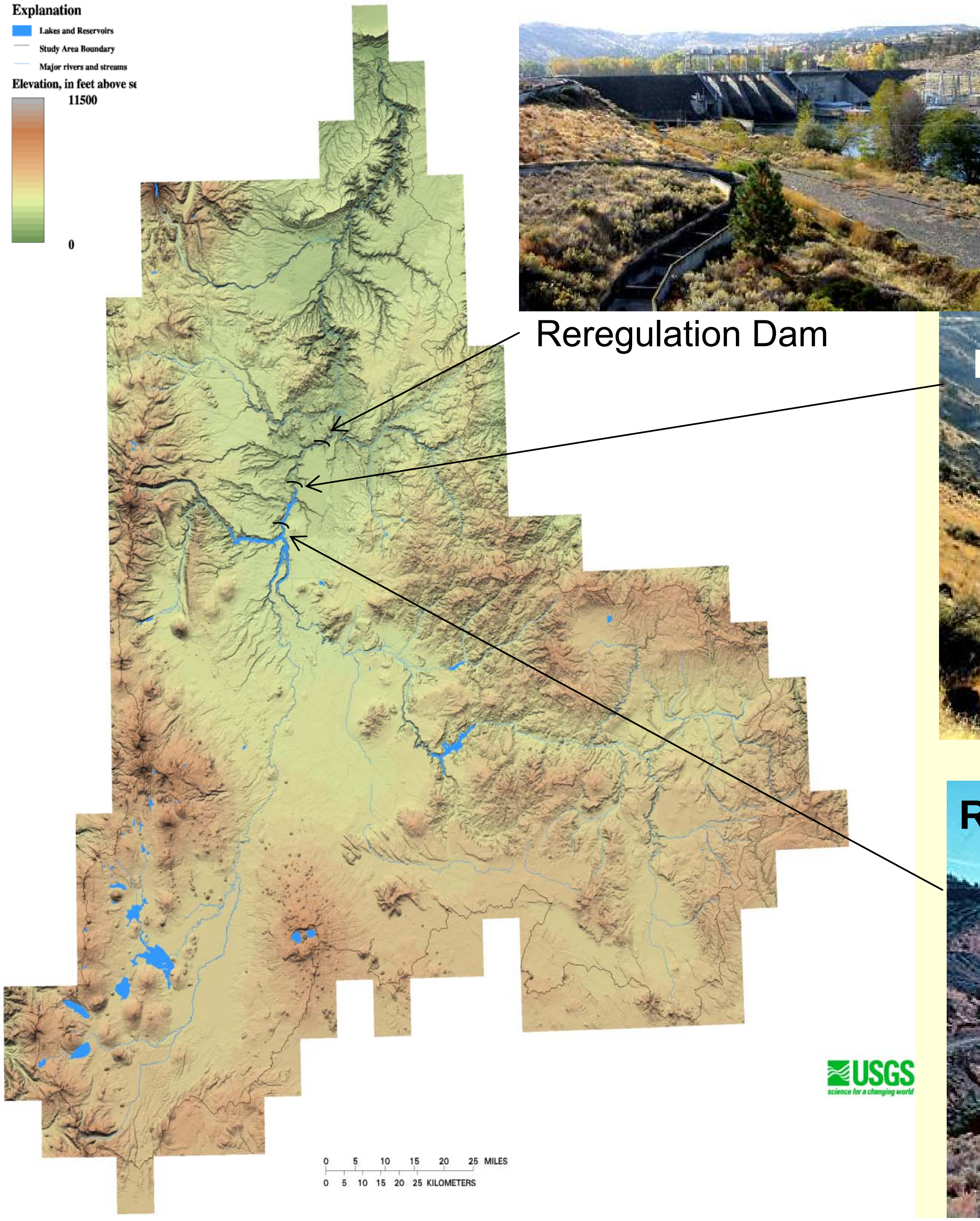


Plate Tectonics – Cascade Range
Cascade Range
Juan de Fuca Ridge
Juan de Fuca Plate
Mount St. Helens
Mount Adams
A
B
North American Plate
Pacific Plate
Spreading Zone
Subduction Zone
Juan de Fuca Ridge
Mount St. Helens
Mount Adams
Pacific Plate
Juan de Fuca Plate
North American Plate
USGS
Topinka, USGS/CVO, 1999, Modified from: Tilling, 1985, Volcanoes: USGS General Interest Publication

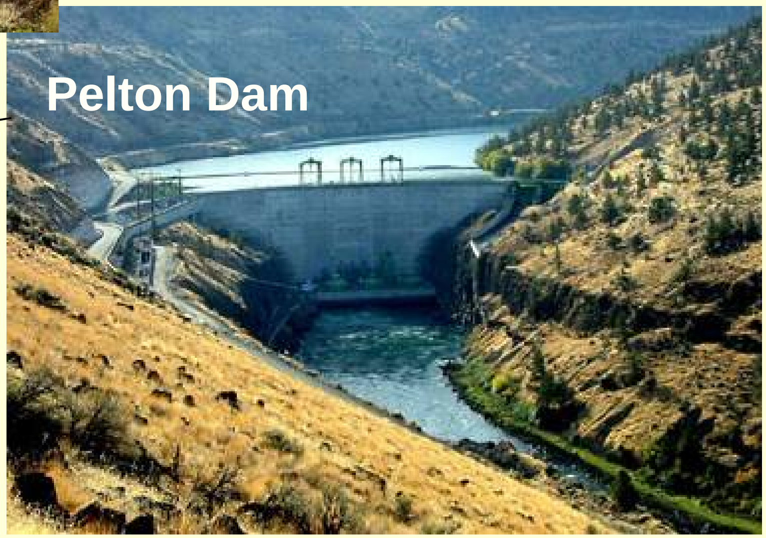

Pacific Northwest Volcanics
0 150
kilometers
BC
WA
ID
Spokane
Columbia Plateau
Seattle
Vantage
Yakima
Pasco
Pendleton
Pacific Ocean
Cascade Range
OR
CA
Pliocene–Quaternary
Major Quaternary Volcanoes
Columbia River Basalt Group
Oligocene–Miocene
Intrusions
USGS
Topinka, USGS/CVO, 1997, Modified from: Swanson, et.al., 1989, AGU Field Trip Guidebook

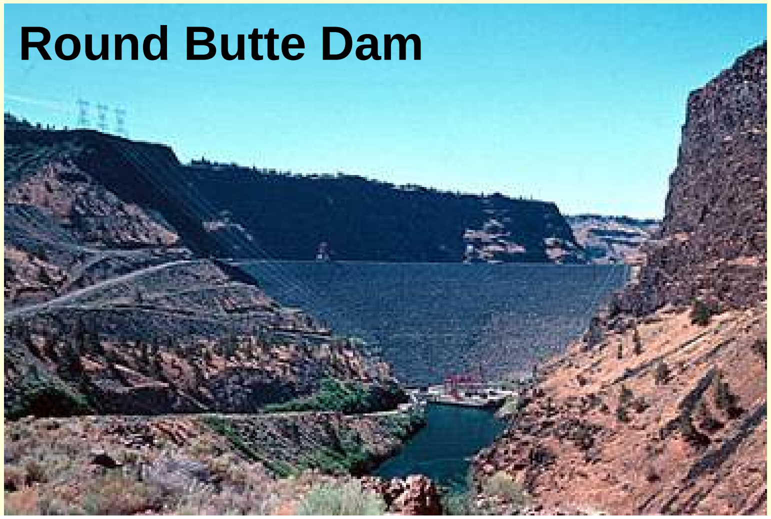

Columbia River
Pacific Ocean
Portland
Sandy
Clackamas
Willamette River
Deschutes River
N.Santiam
McKenzie
Umpqua
River
Rogue
River

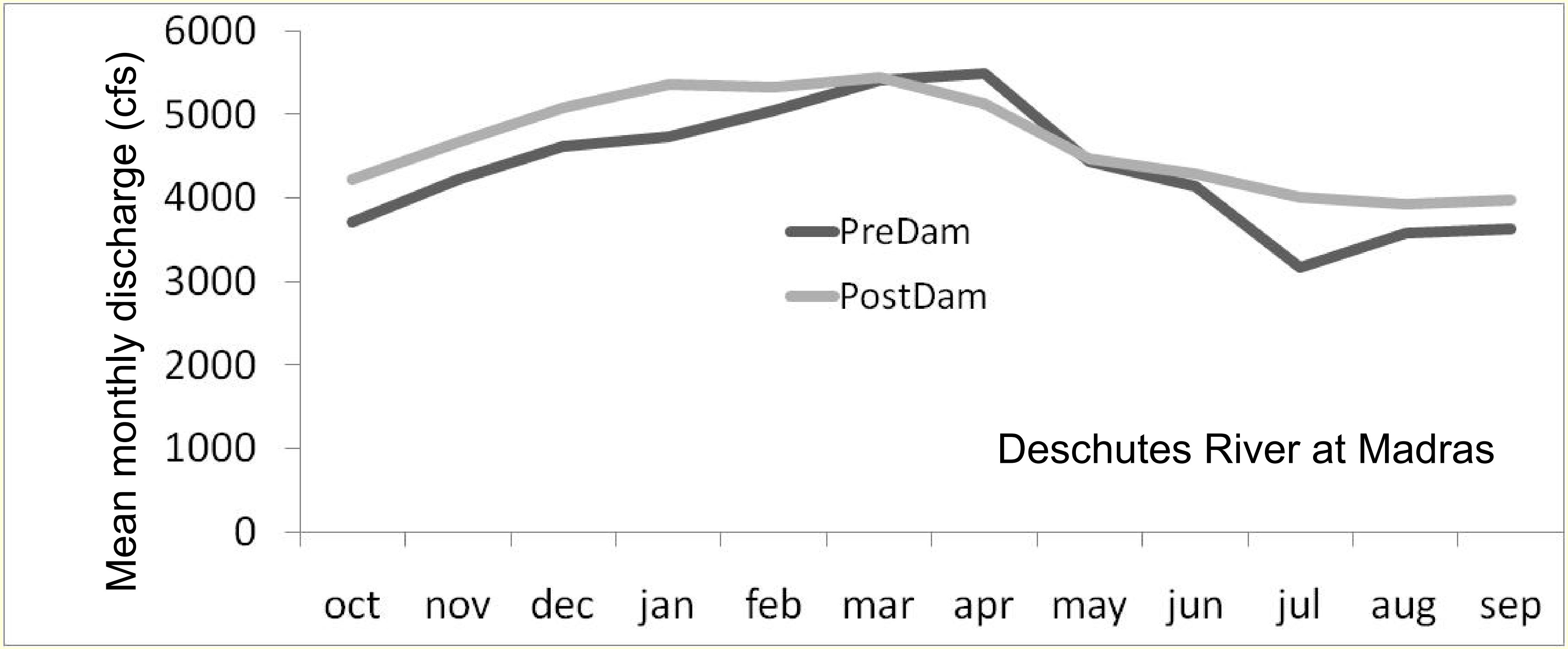
Deschutes Basin
Oregon



Reregulation Dam






Mean monthly discharge (cfs)
6000
5000
4000
3000
2000
1000
0
PreDam
PostDam
Deschutes River at Madras
oct
nov
dec
jan
feb
mar
apr
may
jun
jul
aug
sep


Opal Springs


Metolius River

Nature's chisel

The Flood of '96 resculpts the Deschutes and Clackamas rivers

Rivers: Torrents destroy and create in the same moment

■ Continued from Page One

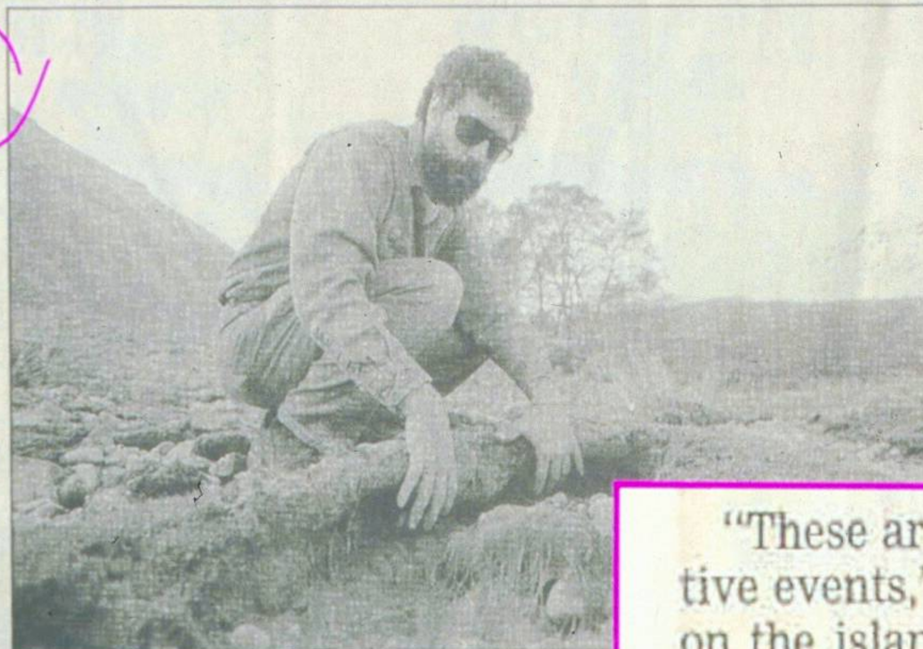
"These are the geologically formative events," said Grant, as he stood on the island's newly revealed rock core. "It is patterns of renewal and patterns of destruction simultaneously."

The Flood of '96 caused tremendous human misery. In the lonely Deschutes basin, homes were inundted, roads washed out. But underneath the headlines is the latest chapter in a story as old as the basalt that formed the canyon 16 million years ago.

As wildfire is to the forest, so floods are to the river. These destructive events belong to long cycles that reinvigorate forests and rivers. Islands are formed and destroyed. Gravel bars are washed away and rebuilt downstream. New channels are cut as the river recreates its path with cobble, sand and debris. Sharp contrasts in climate and geology guided the different marks left on the Deschutes and Clackamas rivers.

Although the Clackamas drains an area only 6 percent the size of the Deschutes basin, the river west of the Cascades pumped more water during the flood. A huge difference in rainfall makes westside rivers more likely to flood. The lower Clackamas also snakes through a wider valley, home now to astounding changes.

The volatile Clackamas jumped course as it roamed its floodplain. Near Barton Park, the river sliced a new channel through a gravel-



Springs Rapid, which was created by a Fourth of July flash flood, survived Febru-

The Oregonian

— just four miles from his riverside home.

gravel operation to mine rock where the river once spilled.

During the flood, the river severely eroded Shoe Island, a boot-shaped

and the company's office sloshed under 5 feet of water.

When the water went down, the office dangled over the relocated Clackamas.

"I was totally awed by the magnitude and power of Mother Nature," said Bob D. Traverso of River Island.

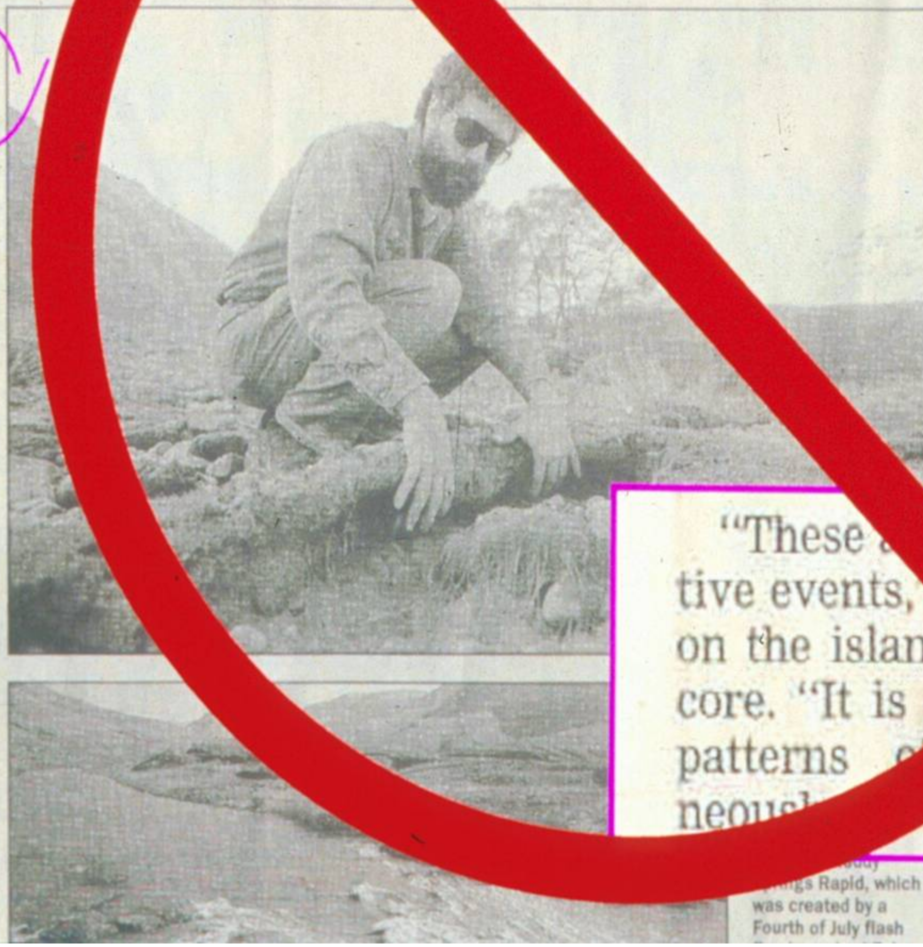
He said the company, which has been given a green light by Clackamas County to expand, has not decided what to do.

The course change nearly shut off water to the east-bank channel, where generations of salmon angle-rs have fished popular holes such as Clark's Eddy.

For fishing guides such as Toman, the lower Clackamas is vastly changed. It deepened the Dog Hole,

Clackamas endures. Change is the strongest current in the life of the river.

"These are the geologically formative events," said Grant, as he stood on the island's newly revealed rock core. "It is patterns of renewal and patterns of destruction simultaneously."



Nature's chisel — The Flood of '96 resculpts the Deschutes and Clackamas rivers

A8 2M METRO/NORTHWEST THE OREGONIAN, MONDAY, FEBRUARY 26, 1996

Rivers: Torrents destroy and create in the same moment

Continued from Page One

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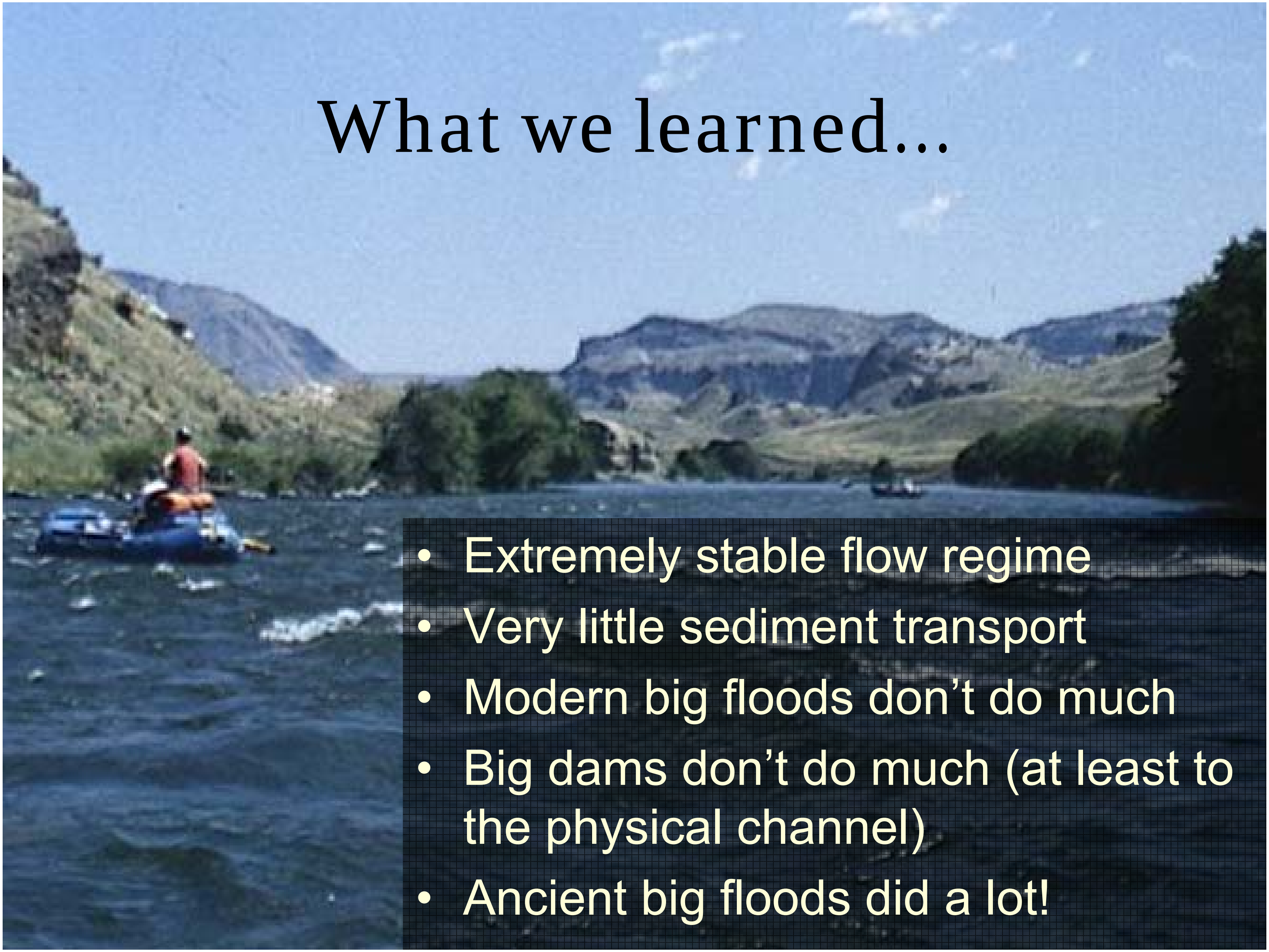
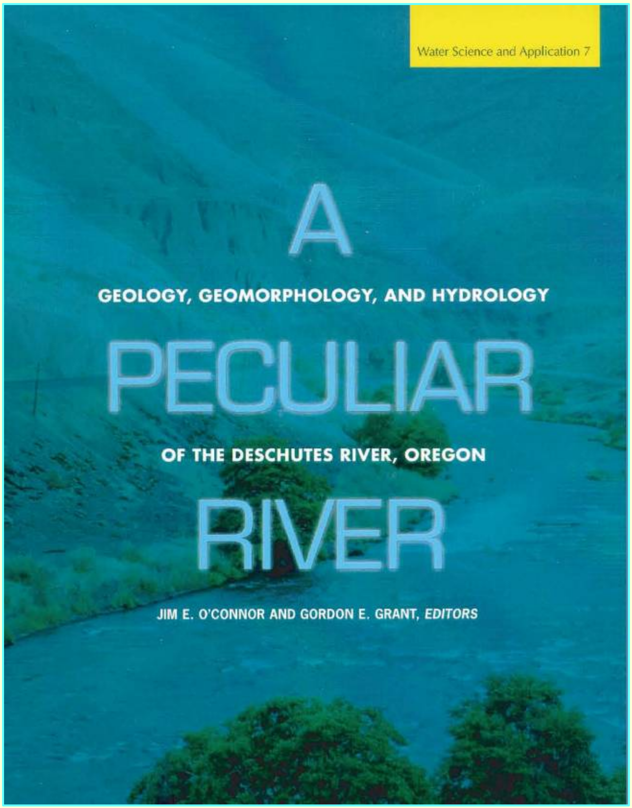


What we learned…

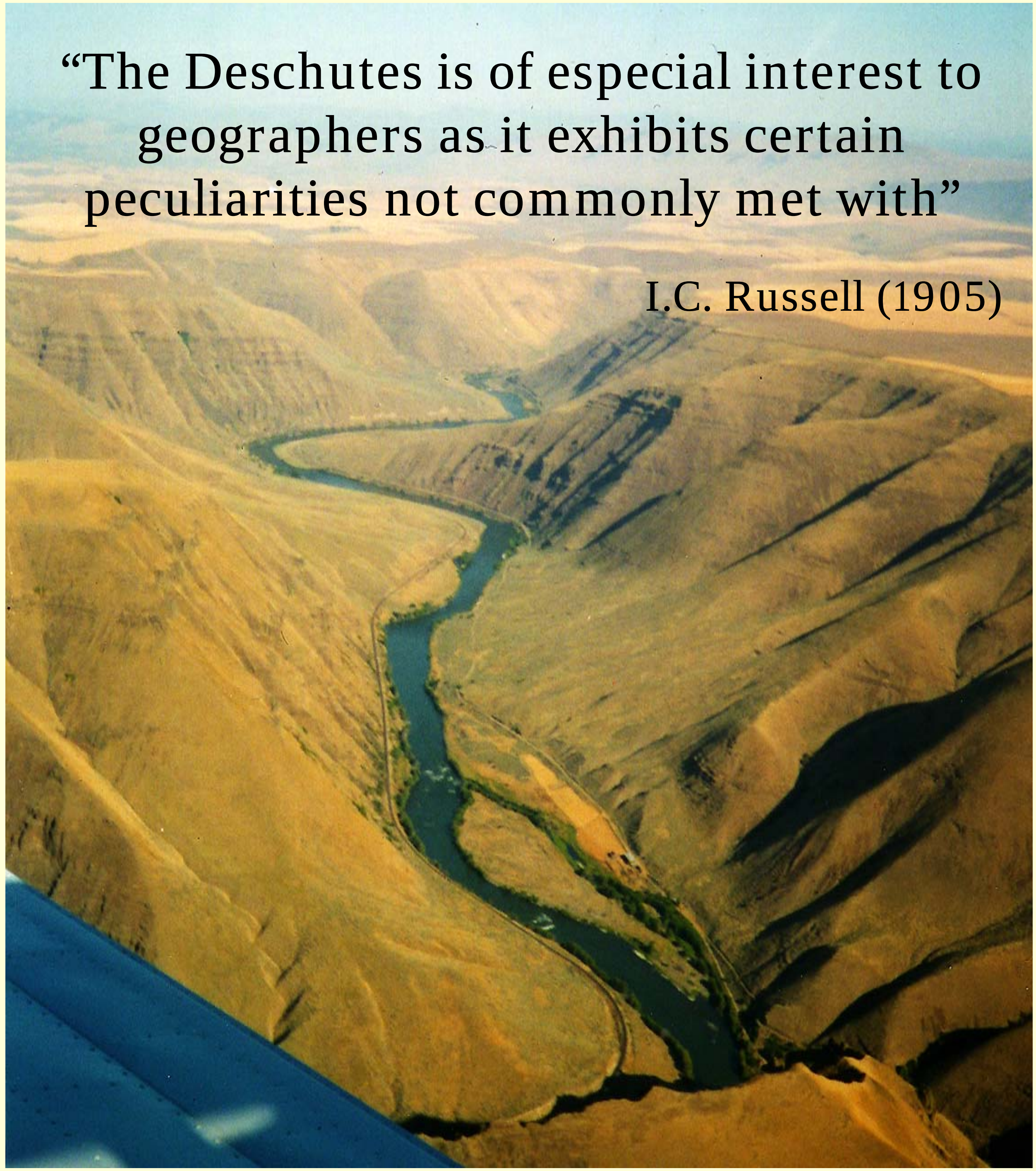
- Extremely stable flow regime
- Very little sediment transport
- Modern big floods don't do much
- Big dams don't do much (at least to the physical channel)
- Ancient big floods did a lot!



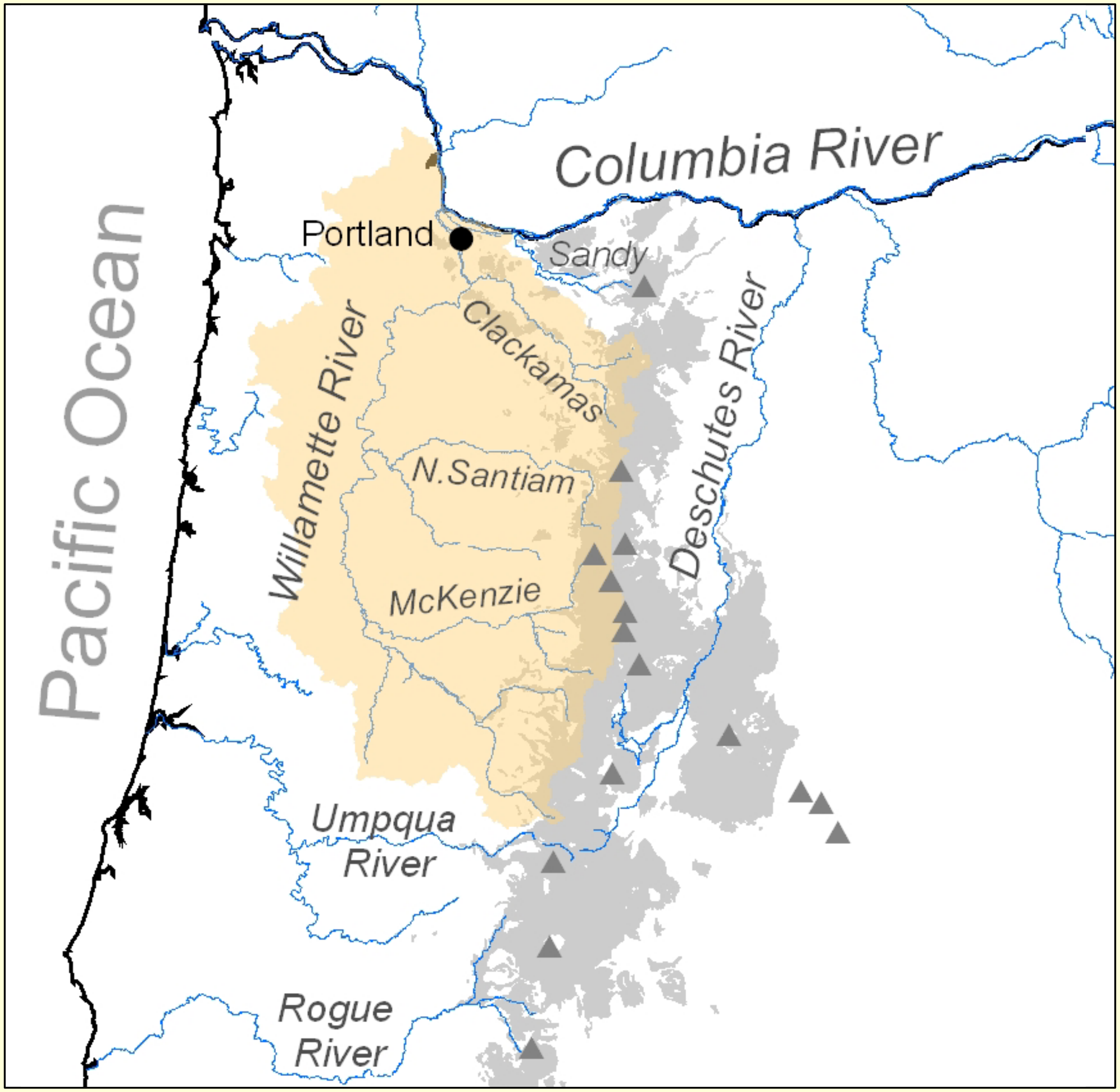
O'Connor & Grant, 2003

"The Deschutes is of especial interest to geographers as it exhibits certain peculiarities not commonly met with"

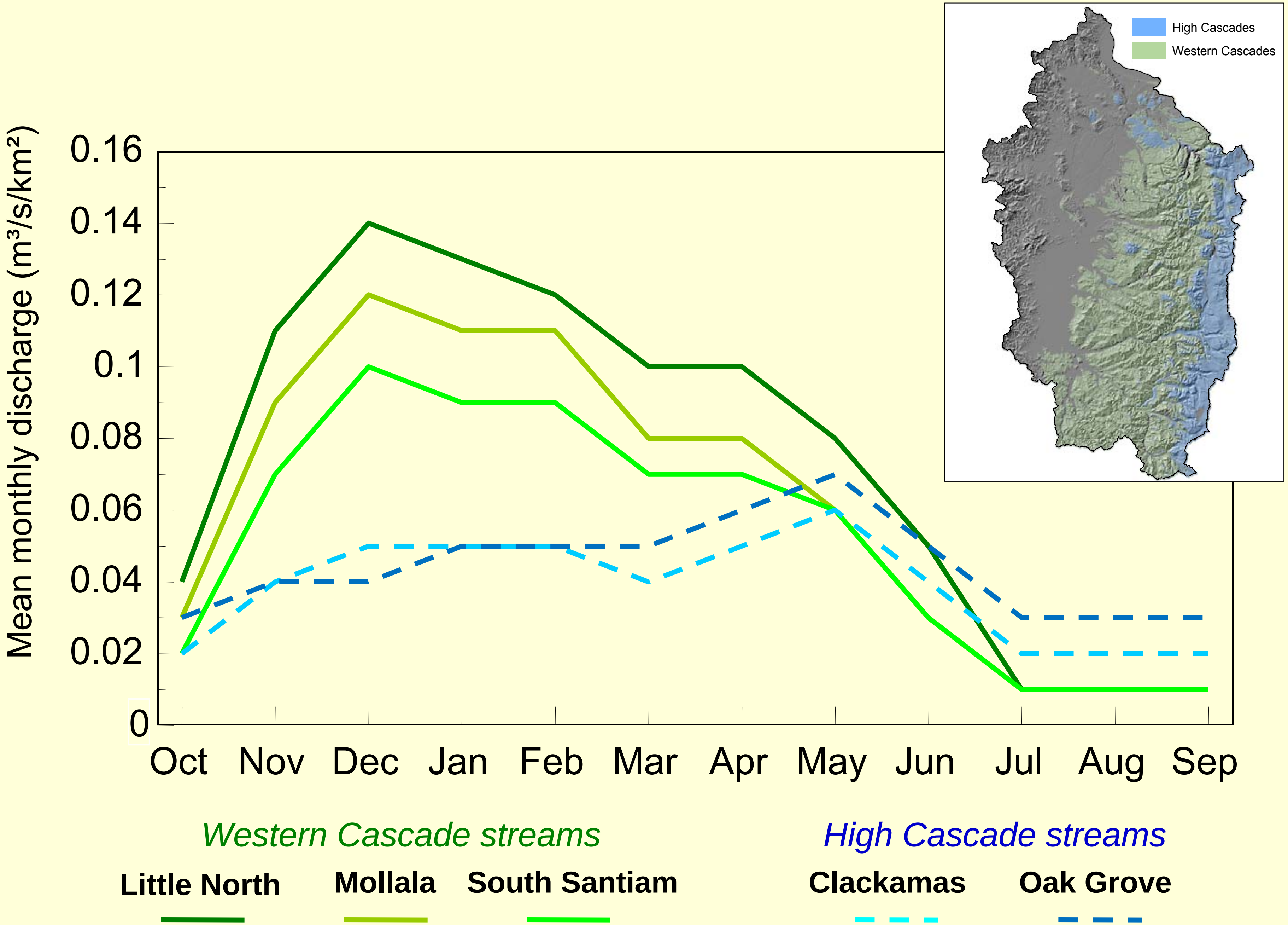
I.C. Russell (1905)



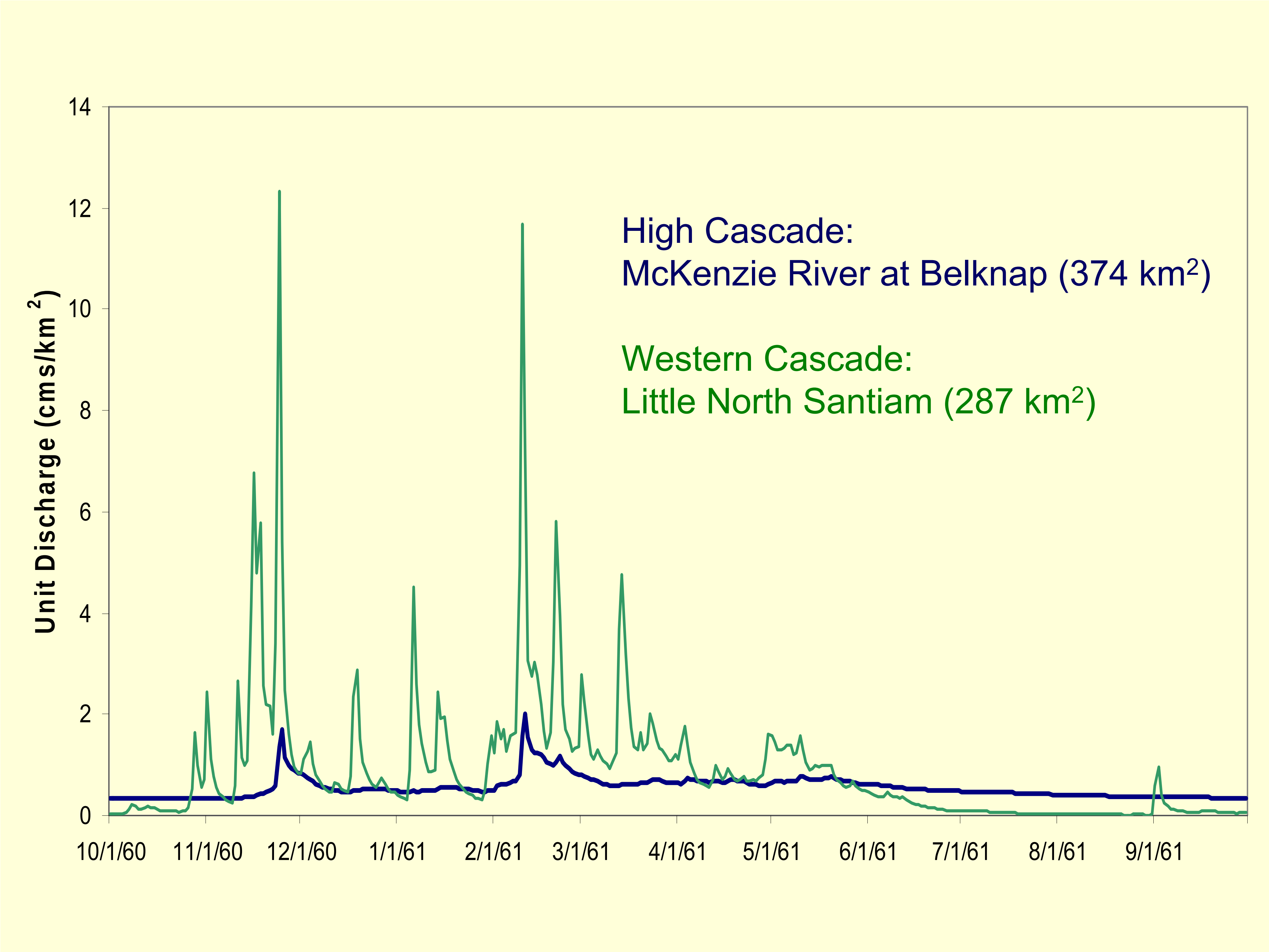
Are there other peculiar places?



- Drains an **uplifted, young volcanic arc**,
- squarely in the path of **westerly prevailing winds**,
- at a **temperate latitude**,
- near a **source of marine moisture**.



From Ingebritsen, Sherrod, and Mariner, 1991


High Cascade:
McKenzie River at Belknap (374 km^2)
Western Cascade:
Little North Santiam (287 km^2)
Unit Discharge (cms/km^2)
0
2
4
6
8
10
12
14
10/1/60
11/1/60
12/1/60
1/1/61
2/1/61
3/1/61
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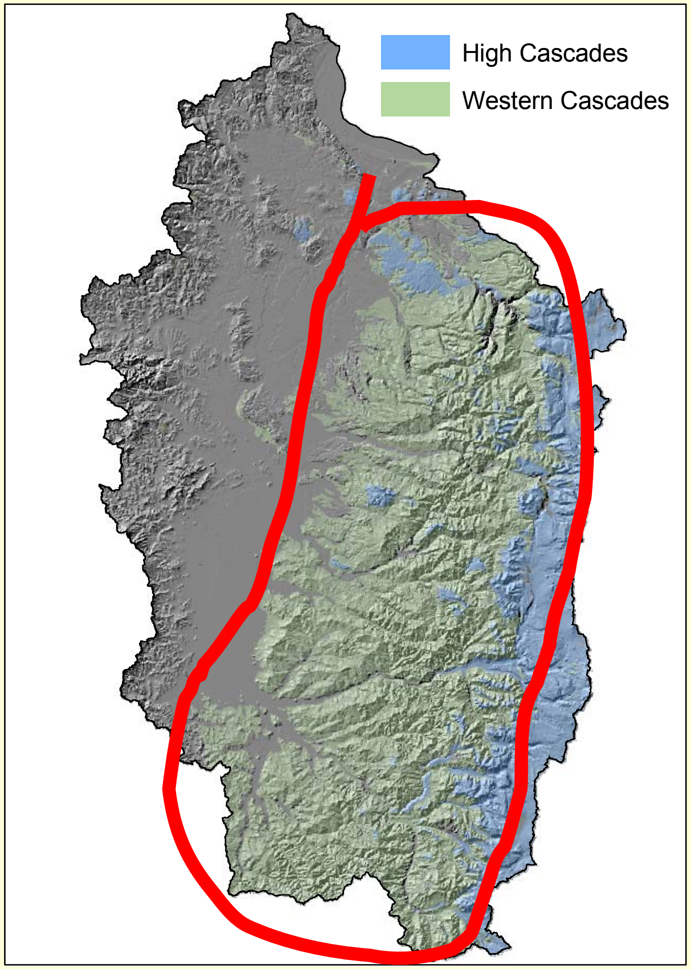
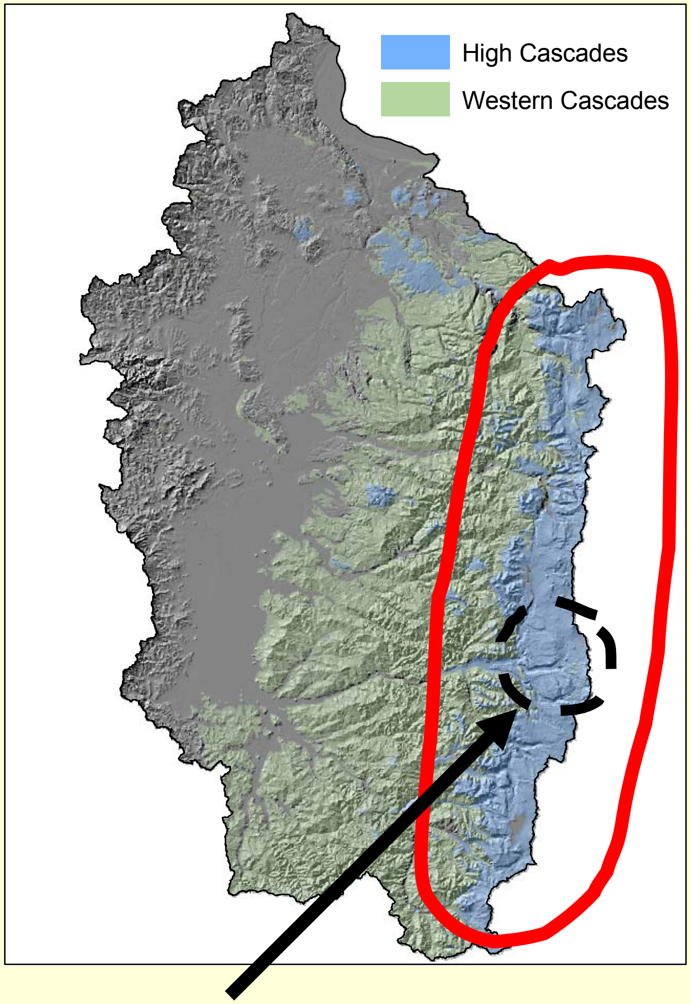
8/1/61
9/1/61



Western Cascades

Older (7-30 million year old) volcaniclastic rocks and basaltic lava flows



Youngest McKenzie Pass lava flows (≤ 1600 years old)

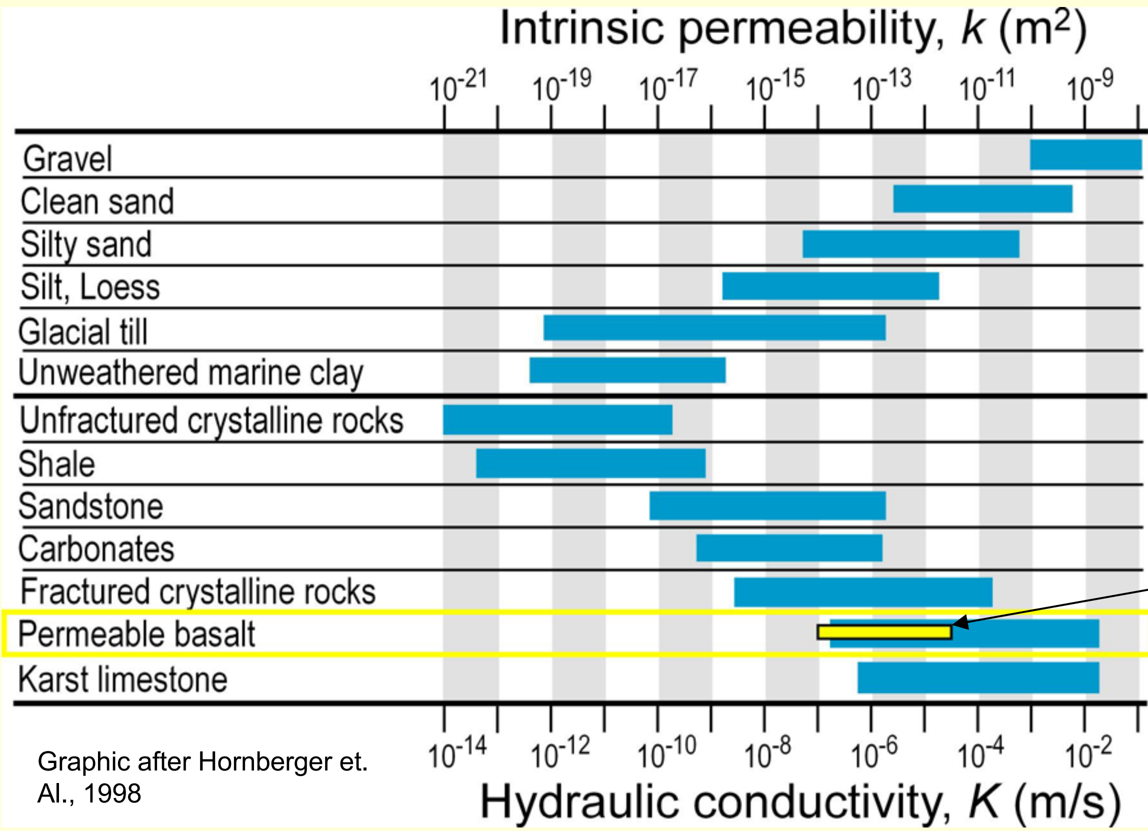
High Cascades

Young basalts, basaltic andesites, andesites, pumice, and ash < 7 million years old


2. 9. 2003

What determines the permeability of lava flows?

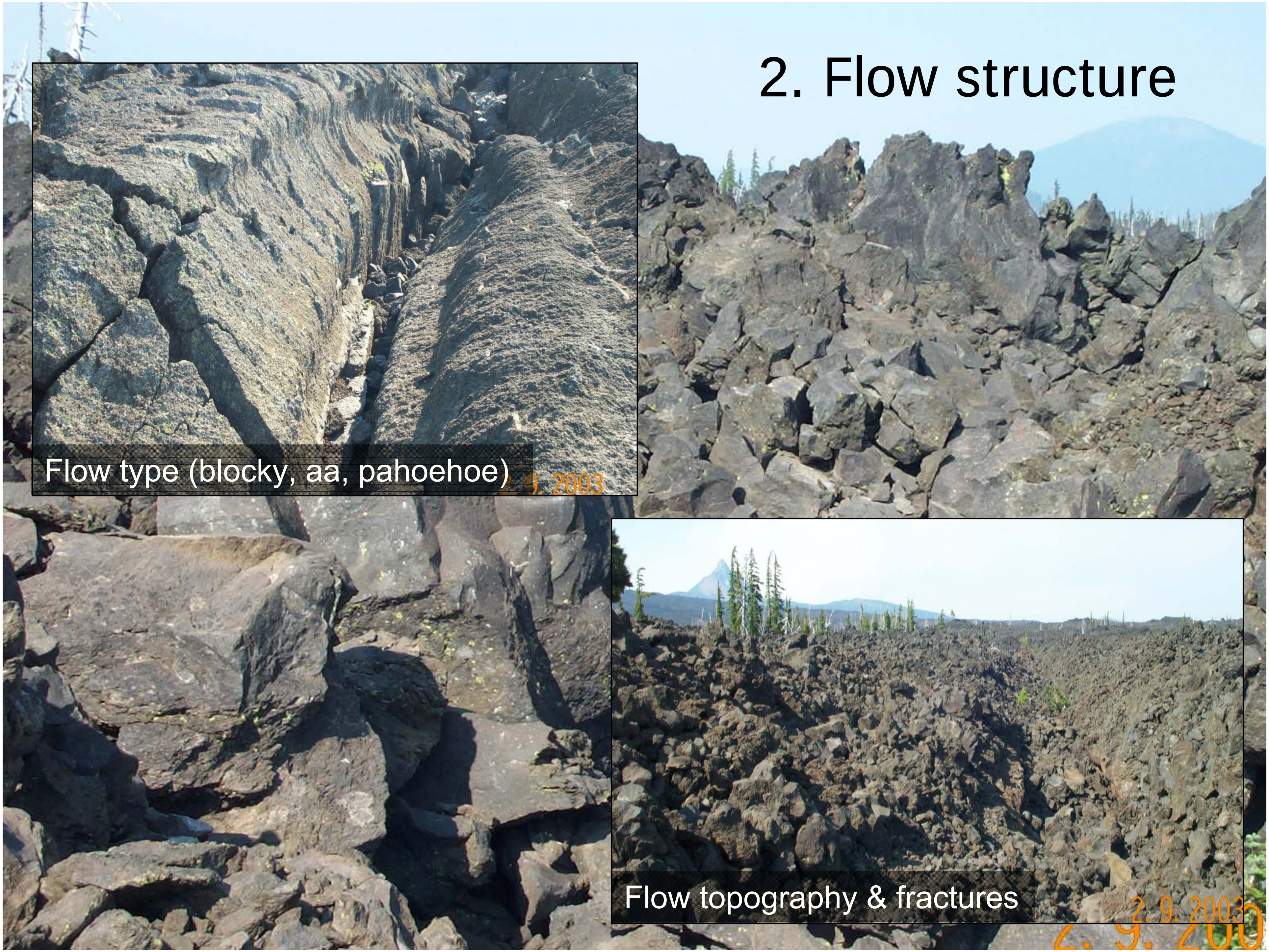
1. Rock lithology

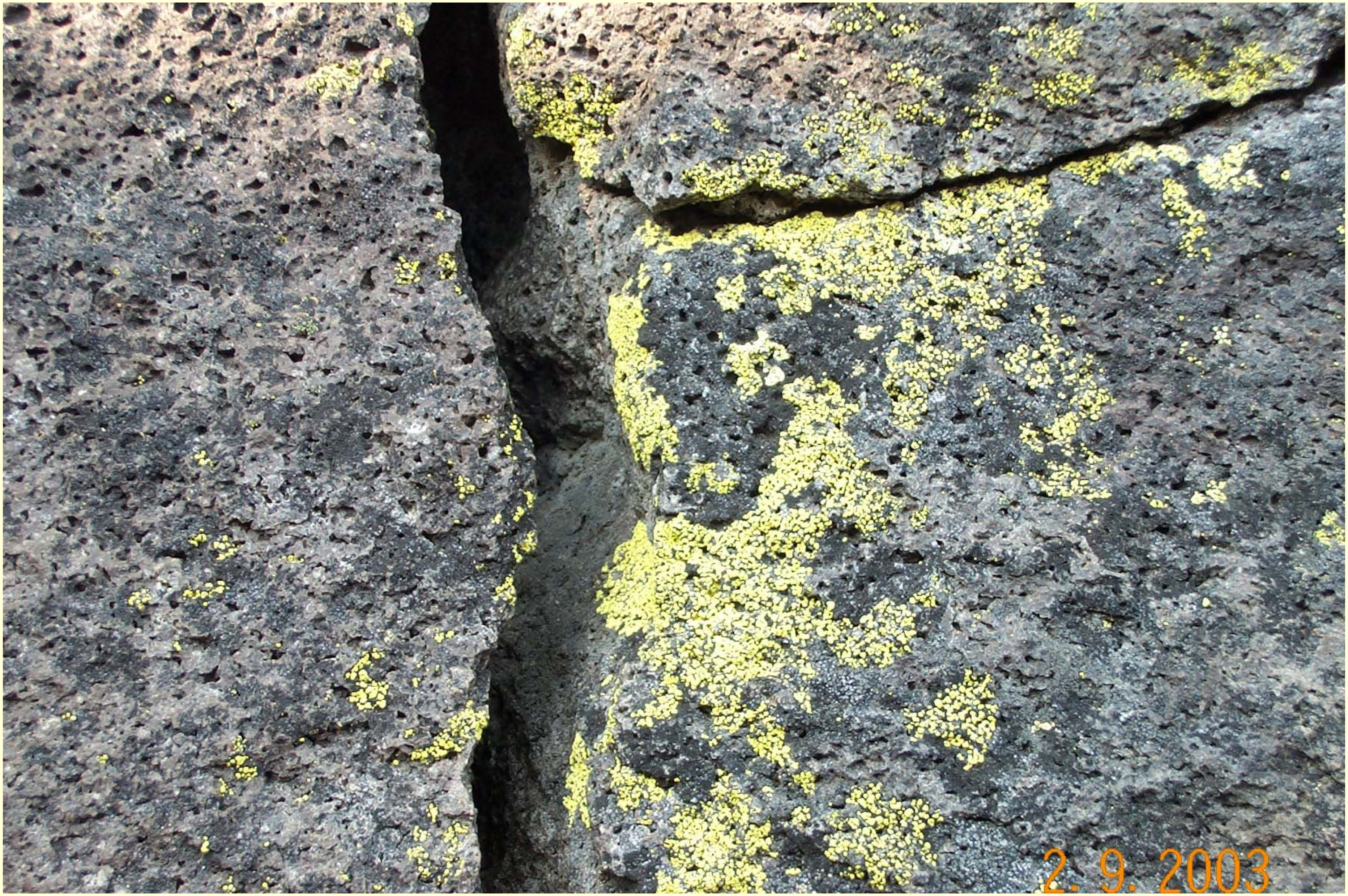


Graphic after Hornberger et. Al., 1998

Cascade basalts
(Saar & Manga, 1999)

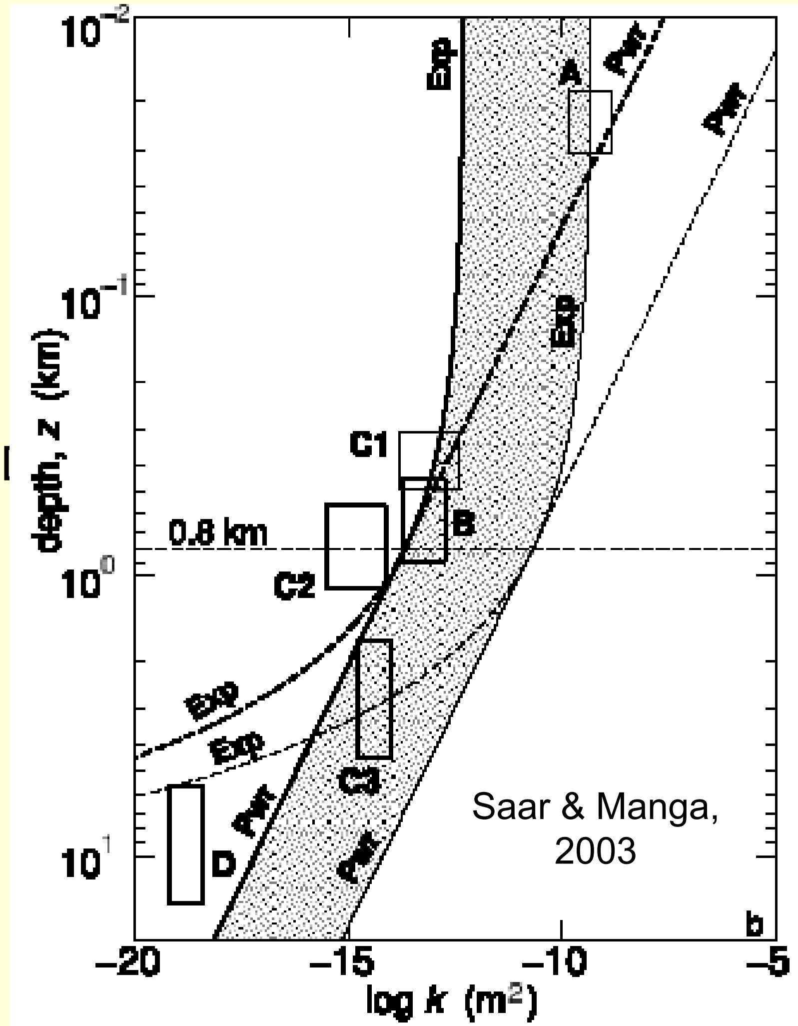
2. Flow structure

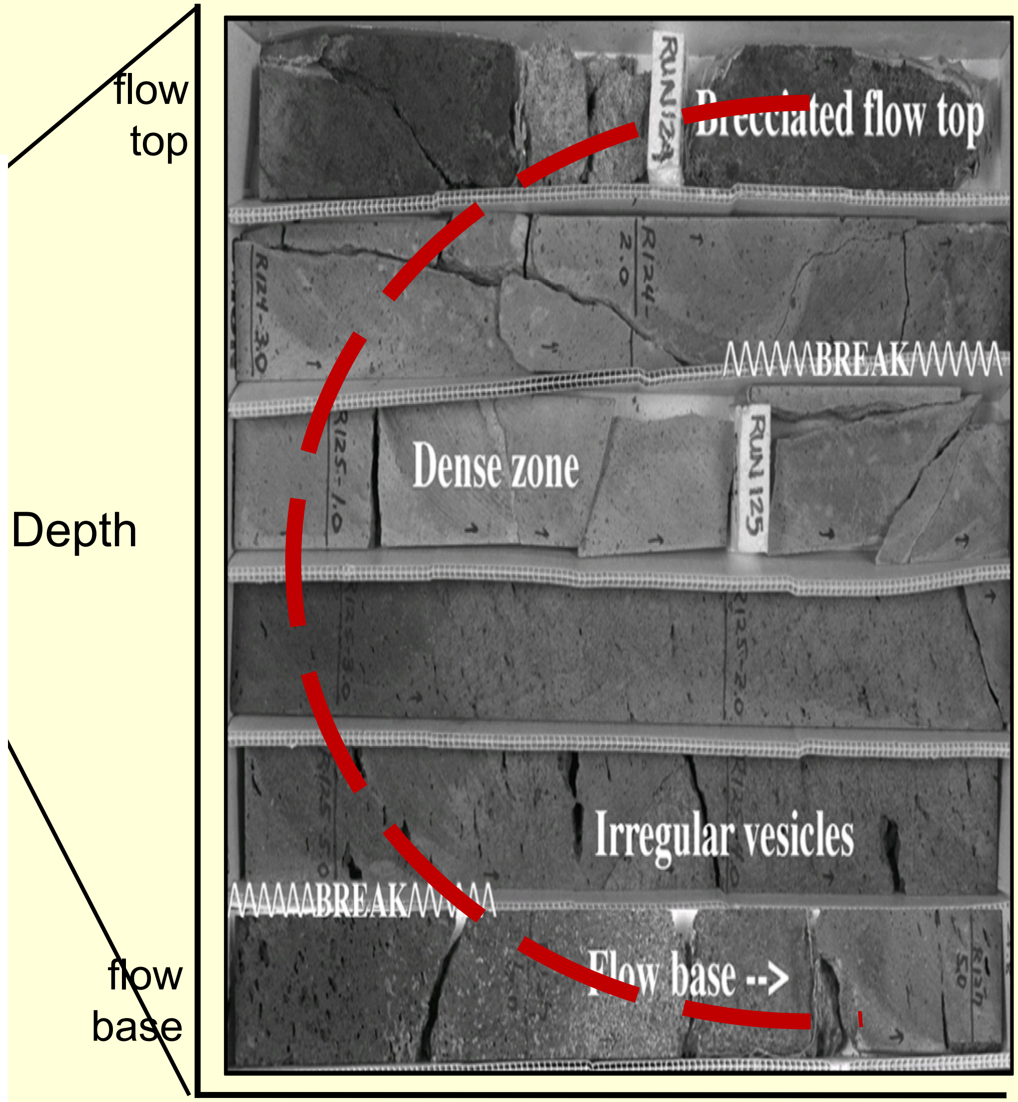



2. 9. 2003

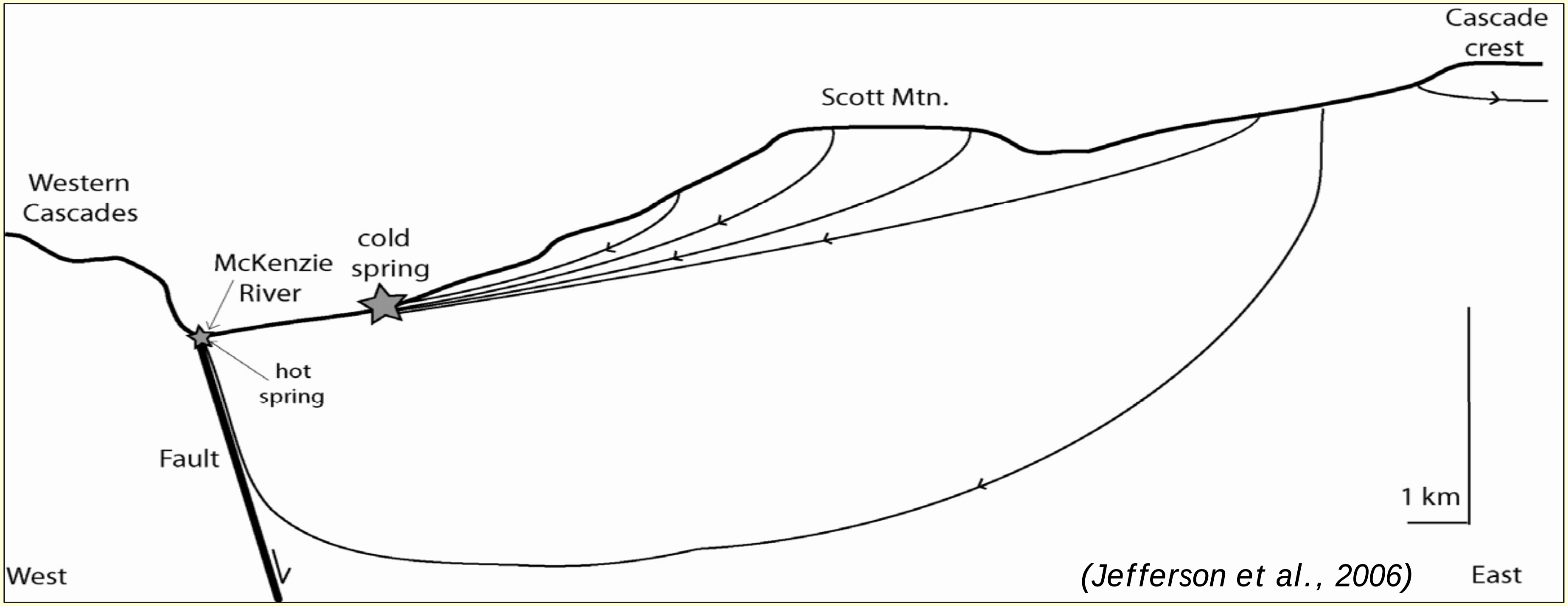
3. Layering within flows and multiple flows

(after Katz and Cashman)



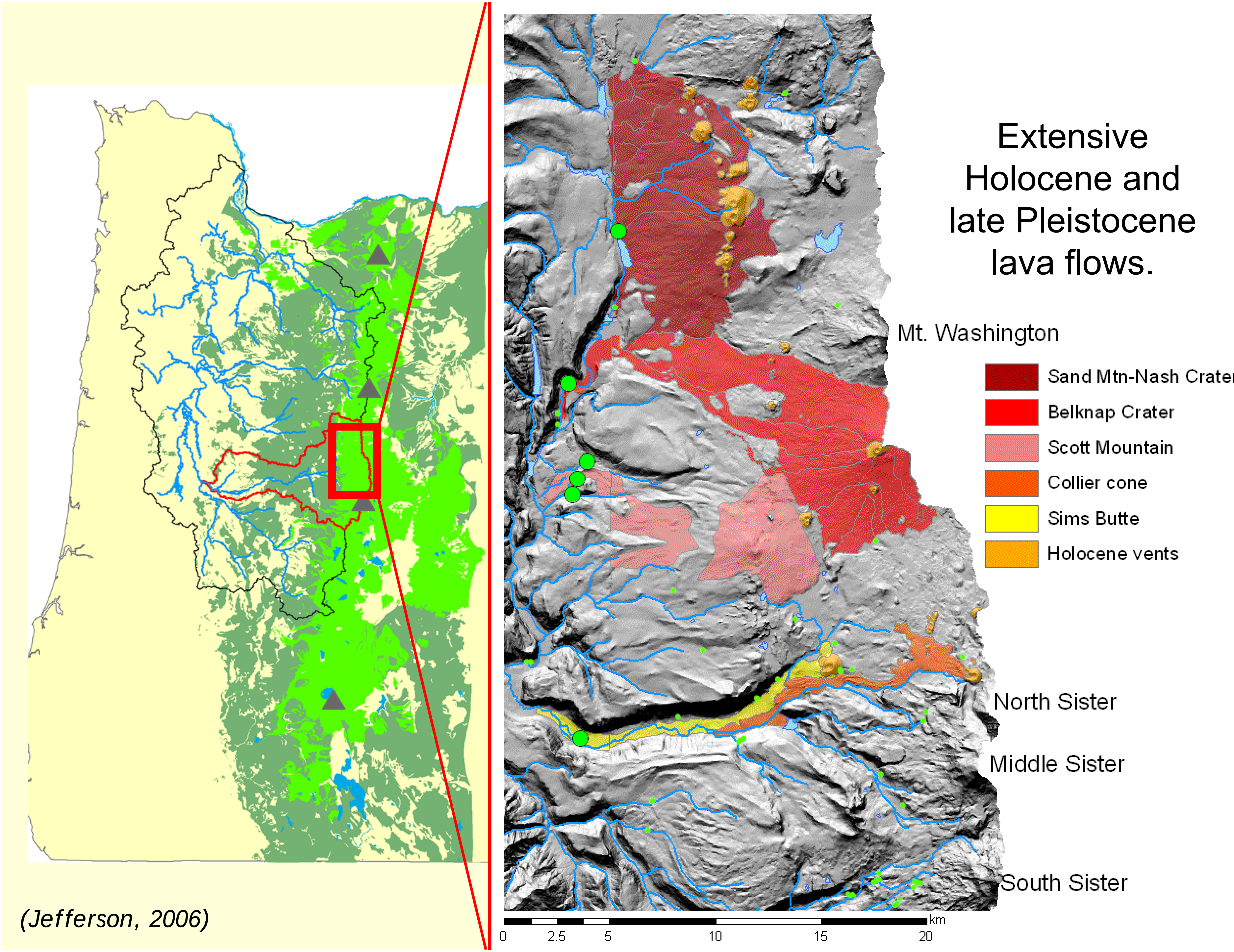


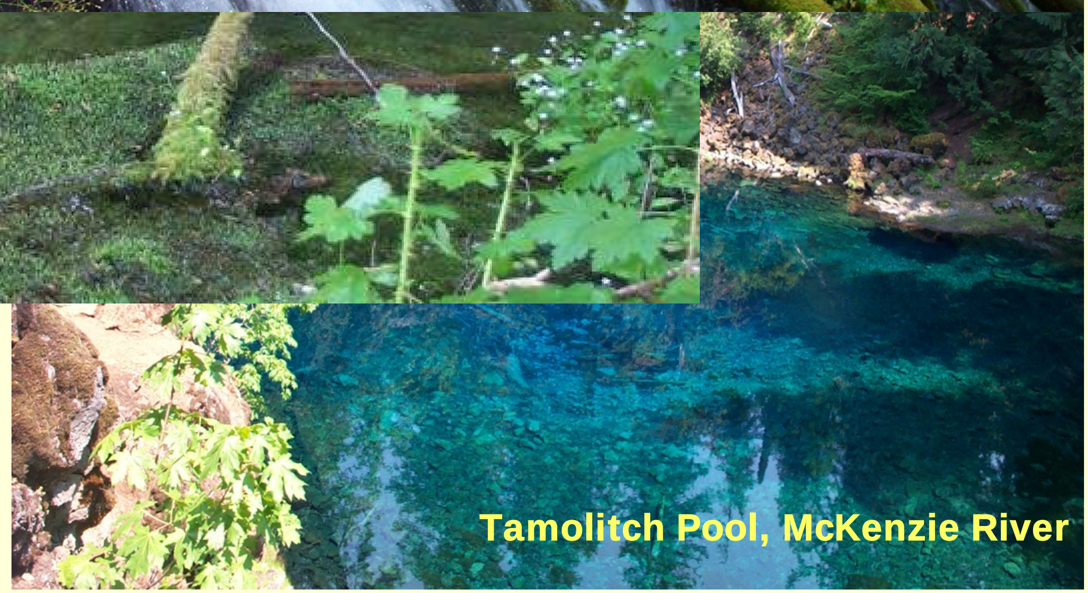
Groundwater flowpaths and geologic history



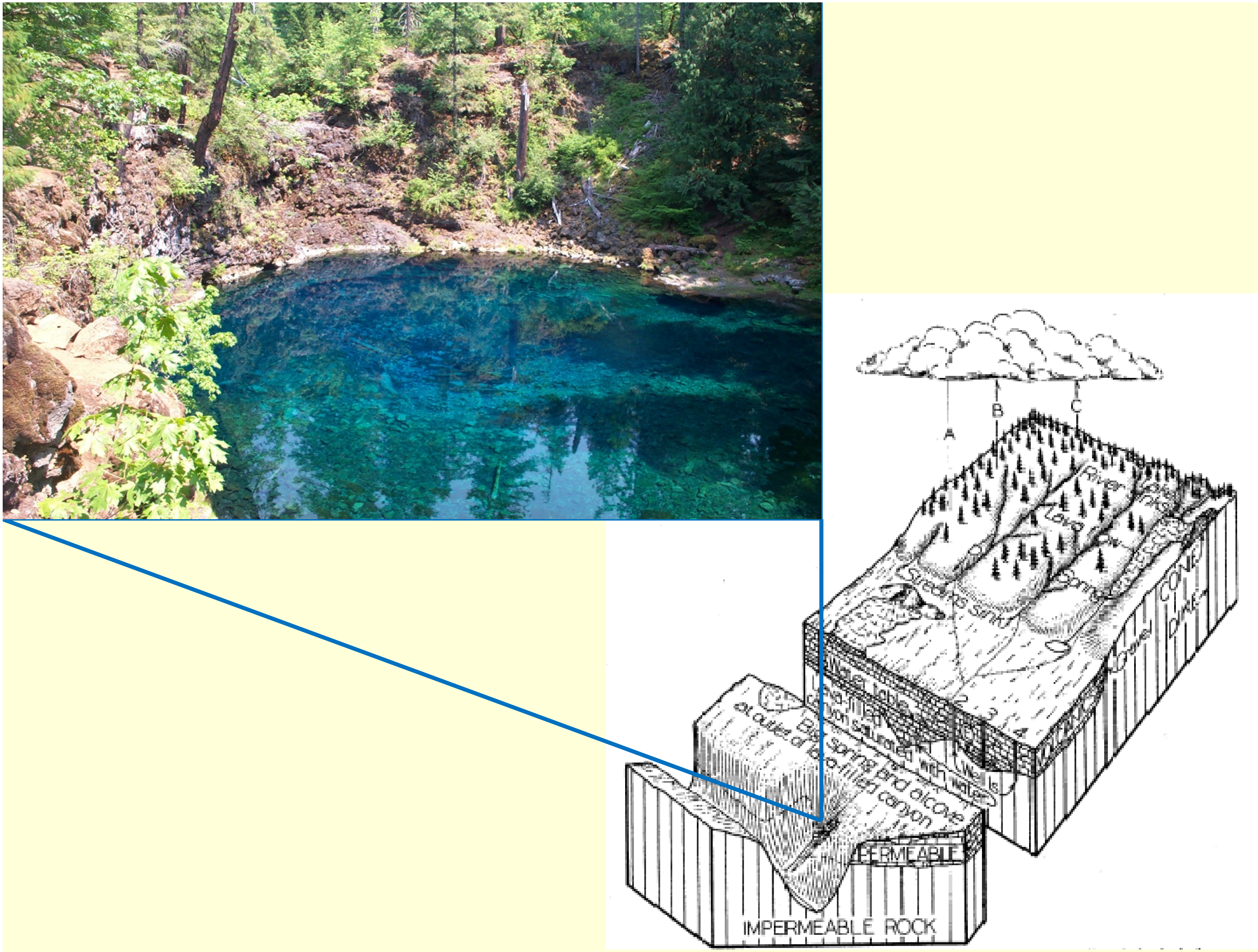
(Jefferson et al., 2006)

- Aquifers constrained by lava flow geometry not always by topography
- Flowpaths are shallow with geothermal influence at fault zones


Extensive Holocene and late Pleistocene lava flows.
Mt. Washington
Sand Mtn-Nash Crater
Belknap Crater
Scott Mountain
Collier cone
Sims Butte
Holocene vents
North Sister
Middle Sister
South Sister
0
2.5
5
10
15
20
km
(Jefferson, 2006)

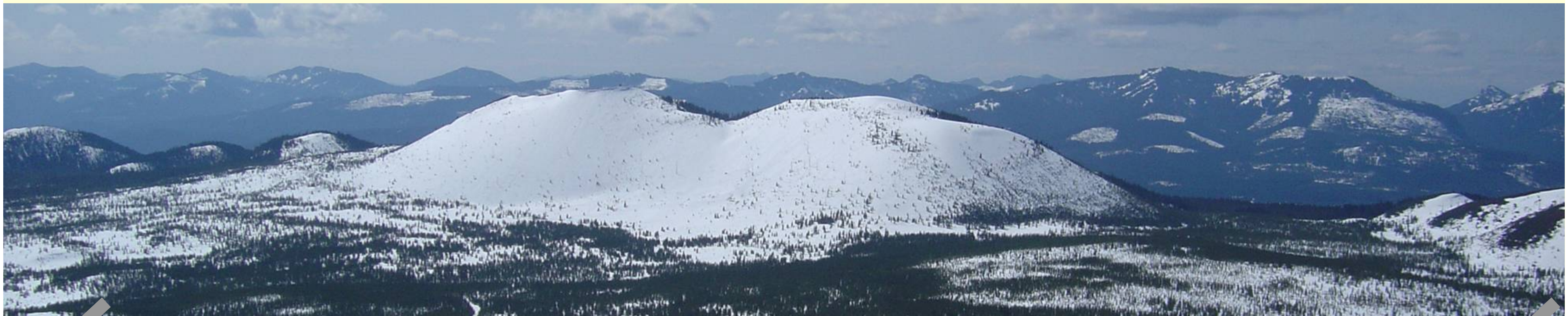


Cascade Springs


A
B
C
River
Lava
Streams sink
Springs
CONE
DIKE
Gravel
Wells
Big spring and alcove at outlet of lava-filled canyon
IMPERMEABLE ROCK

[redacted]

How old is the water coming out of the springs?

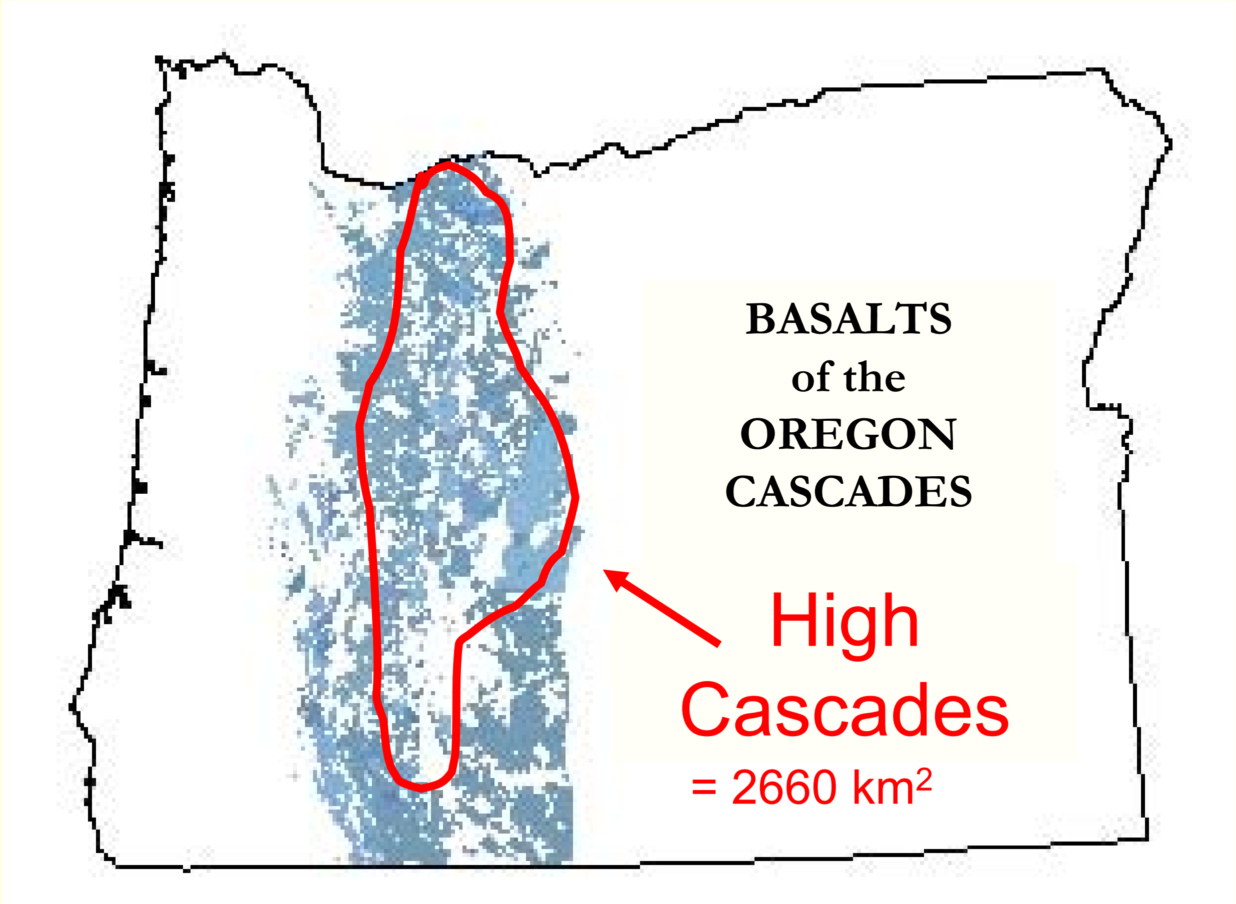


Transit times derived from $^{3}H/^{3}He$ using exponential and gamma distributions

Ages range from 3-14 years

Flow-weighted average = 7.2 years

How big is the sponge?



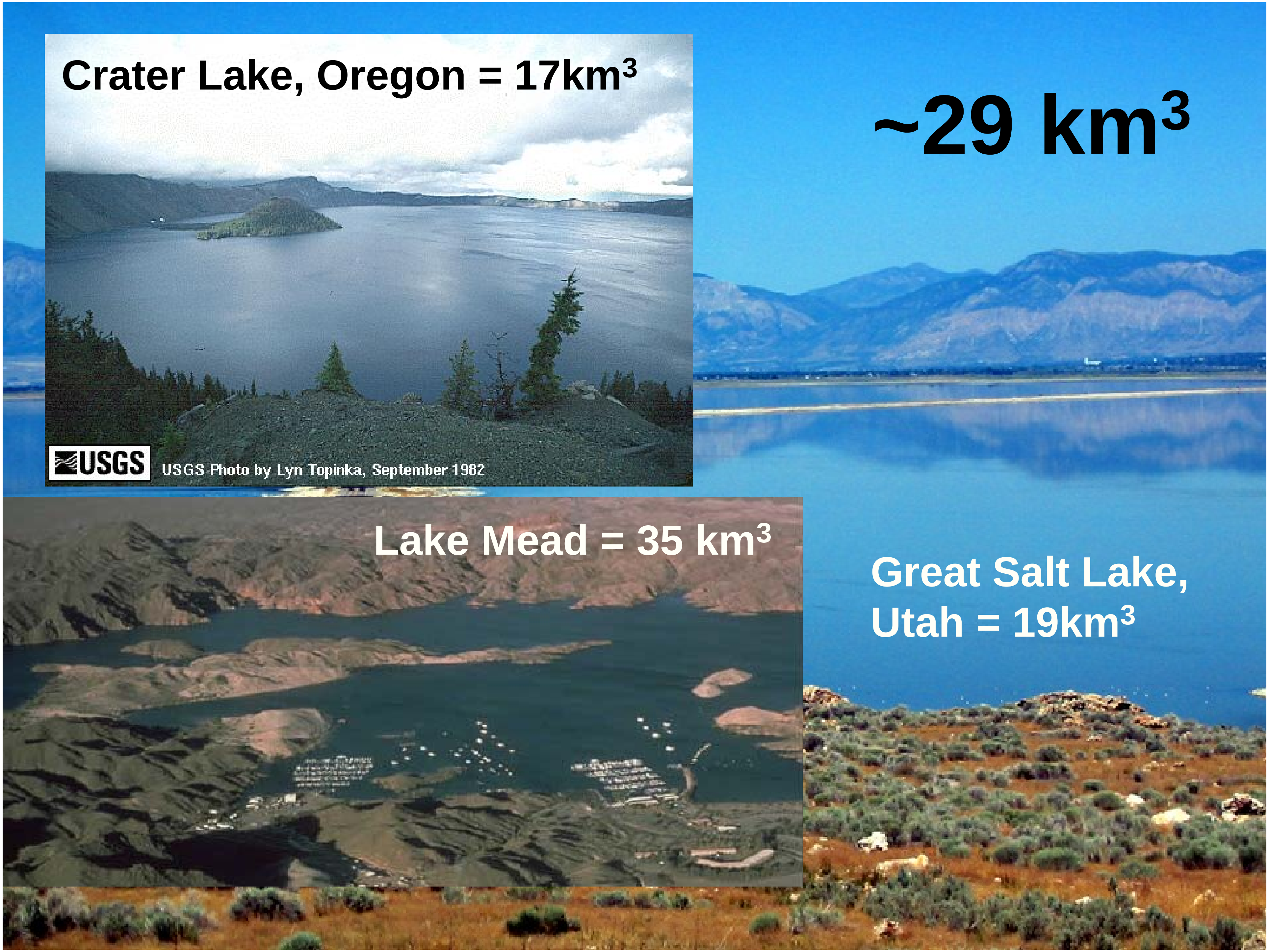
How much water does the sponge hold?

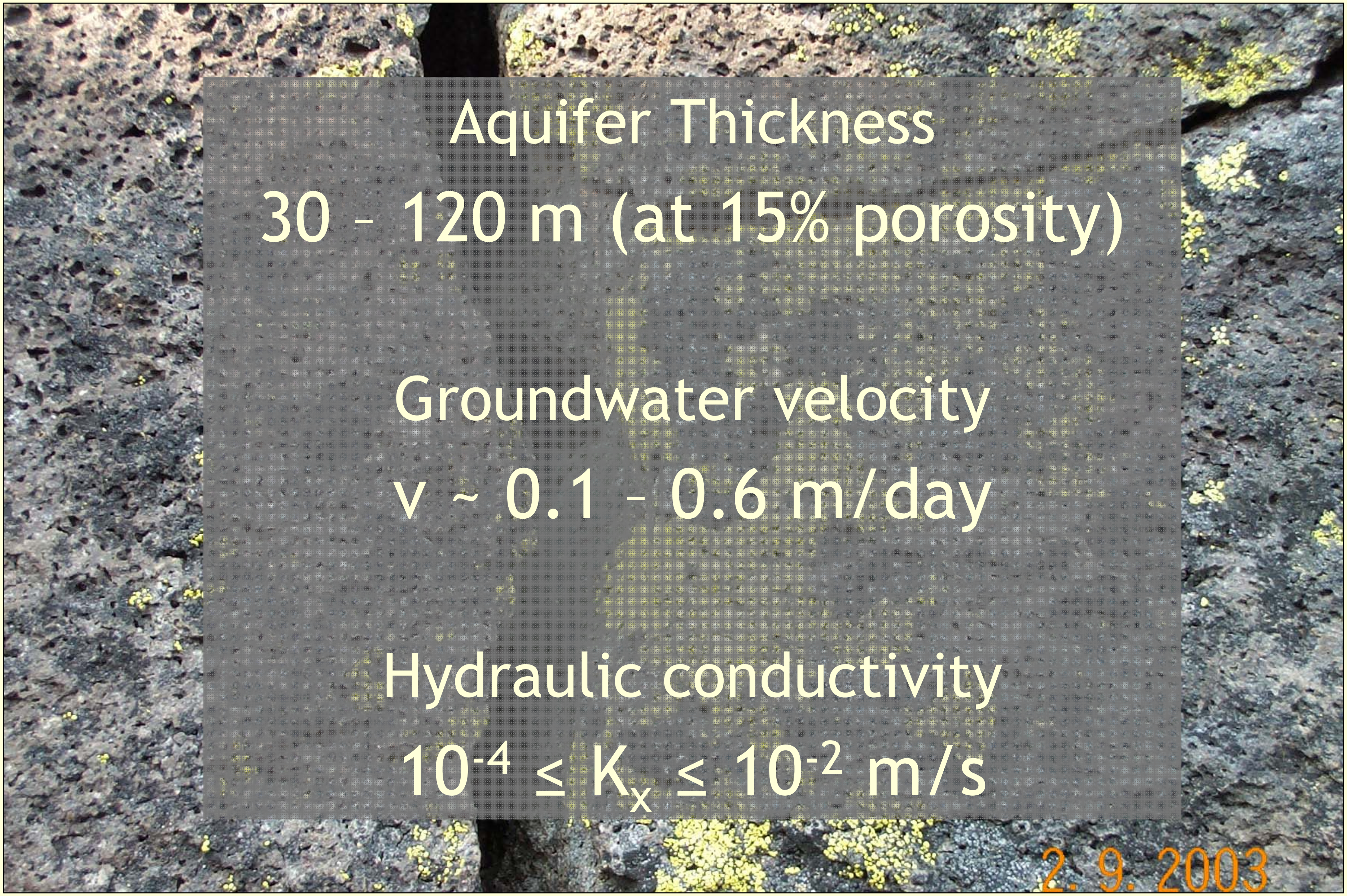
1500 mm/yr

x 2660 km^2

x 7.2 year average residence time

~29 km^3


Crater Lake, Oregon = 17km3
USGS
USGS Photo by Lyn Topinka, September 1982
~29 km3
Lake Mead = 35 km3
Great Salt Lake, Utah = 19km3



Aquifer Thickness

30 – 120 m (at 15% porosity)

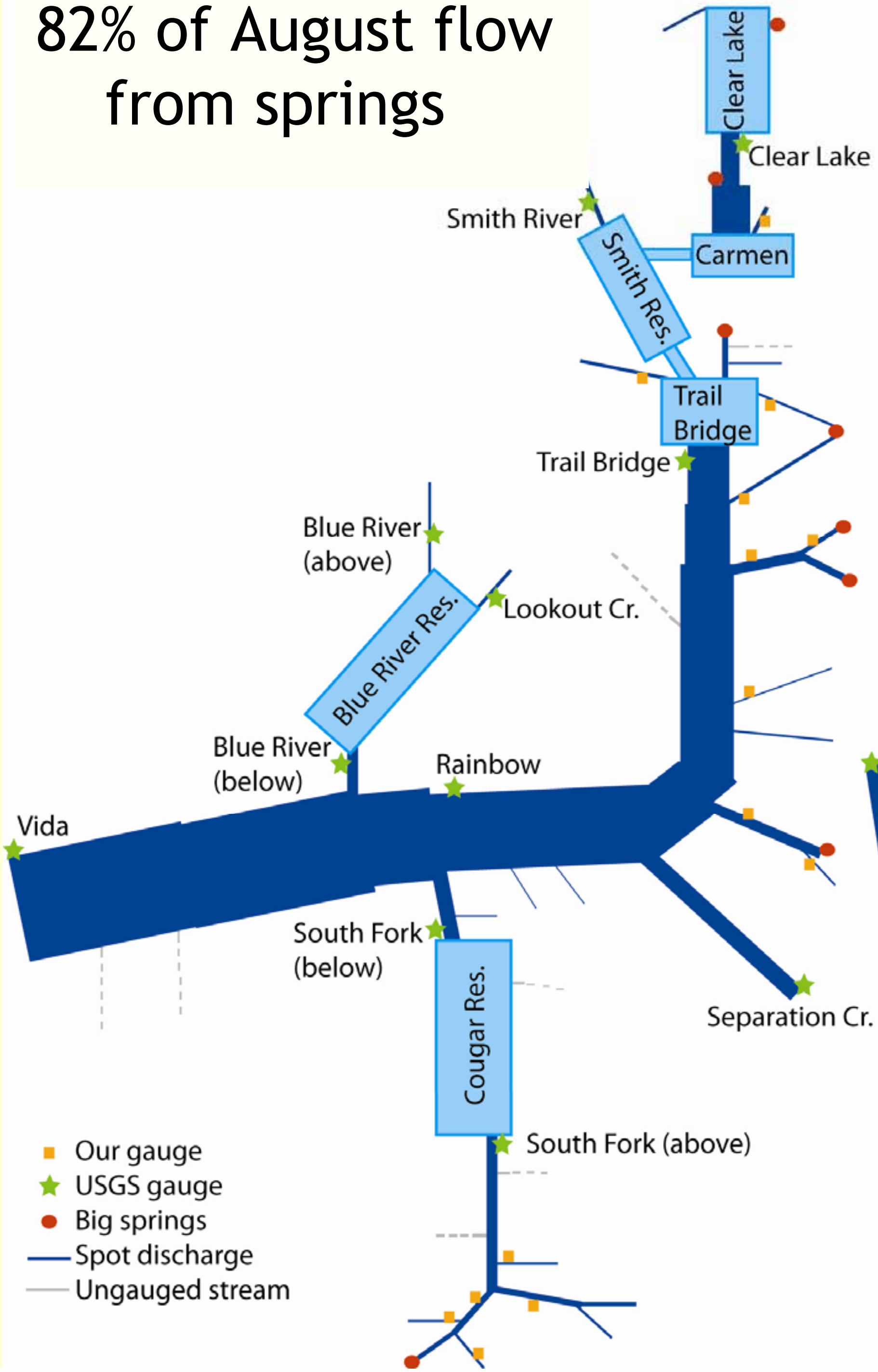
Groundwater velocity

v ~ 0.1 – 0.6 m/day

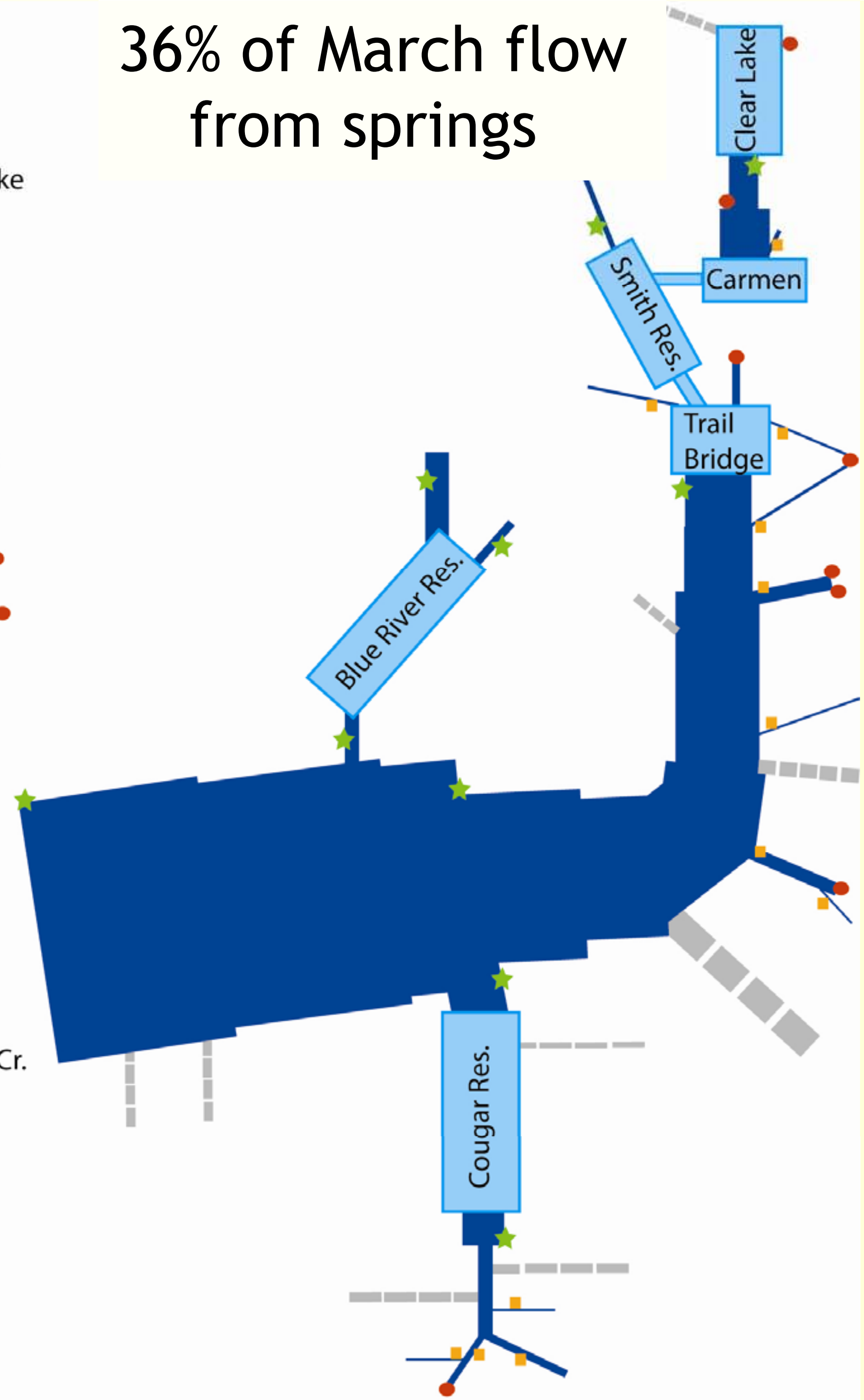
Hydraulic conductivity

$10^{-4} \le K_x \le 10^{-2}$ m/s

82% of August flow from springs

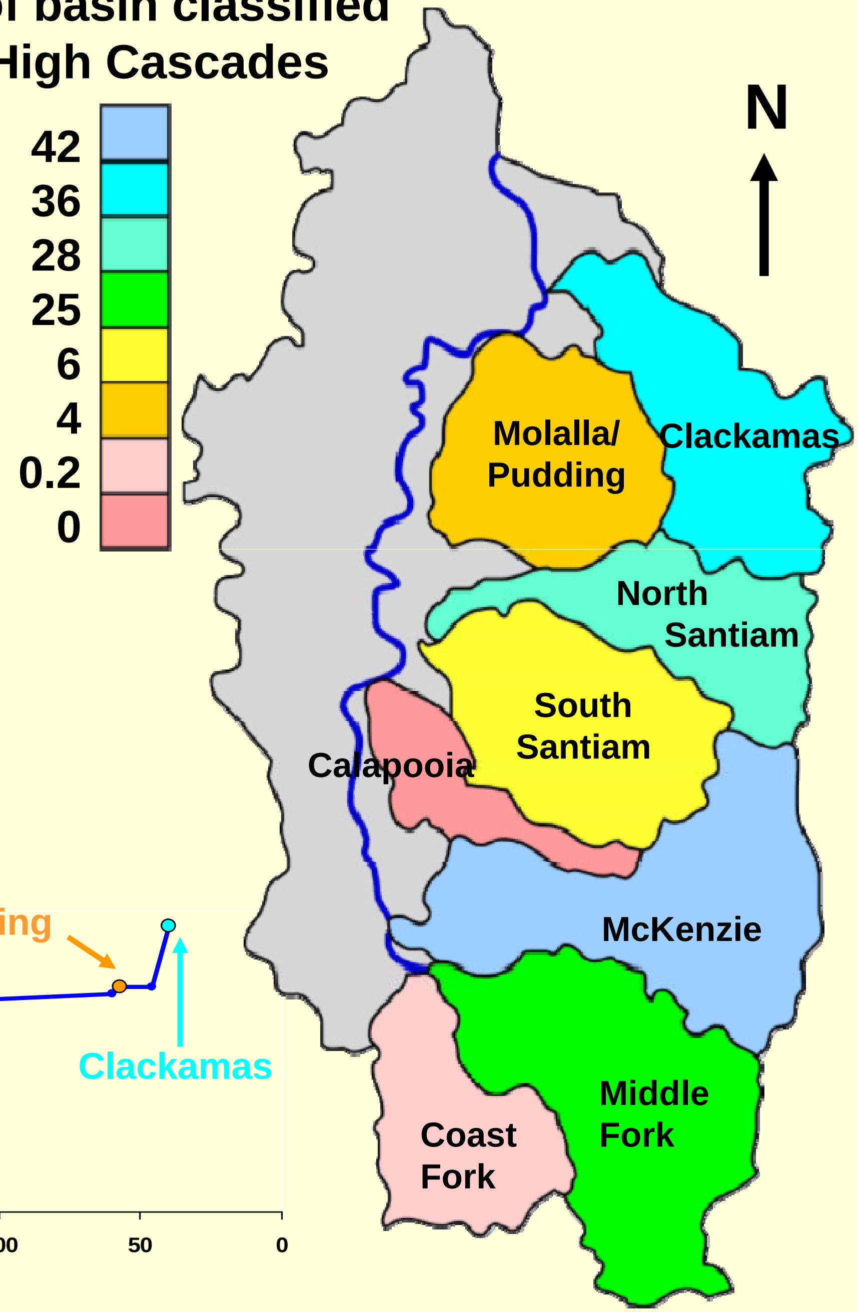


36% of March flow from springs

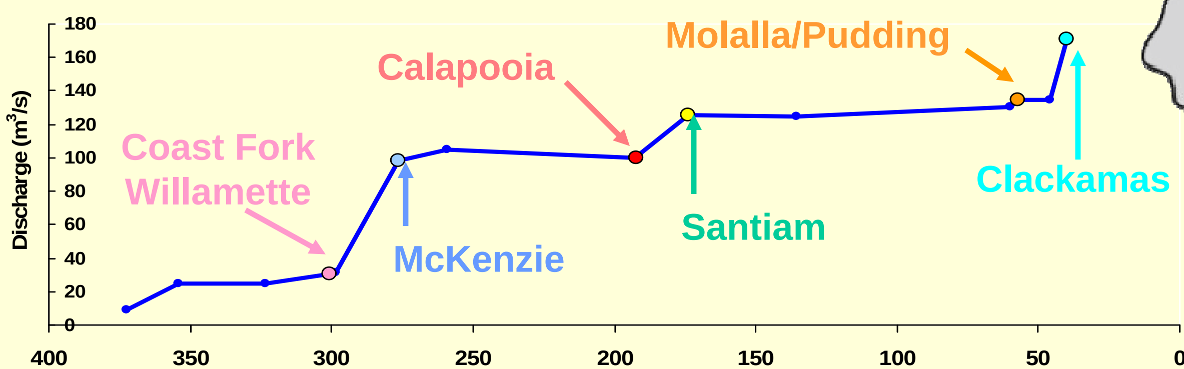


Willamette River at Portland

% of basin classified as High Cascades



1950 Low Flow

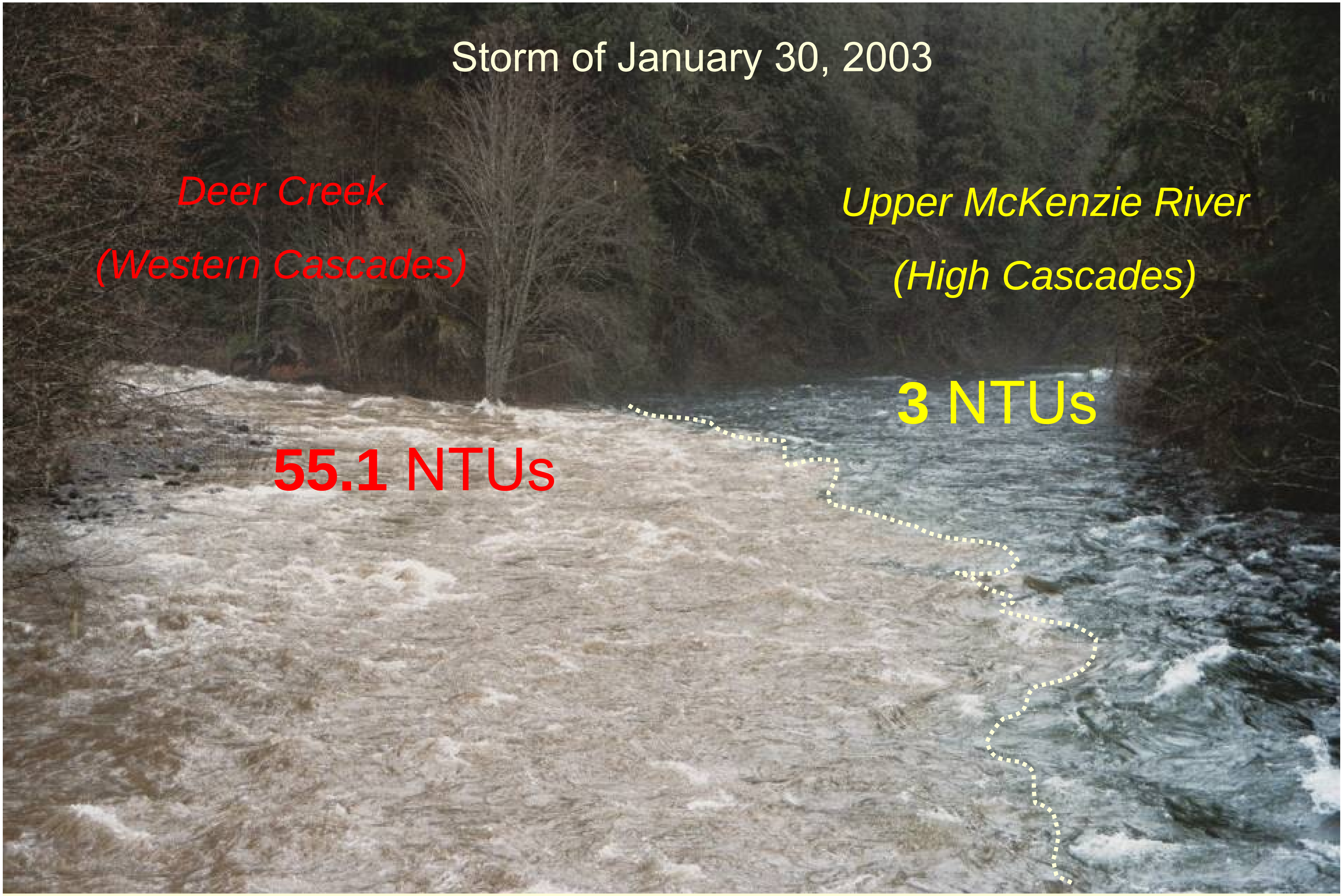


Western Cascades

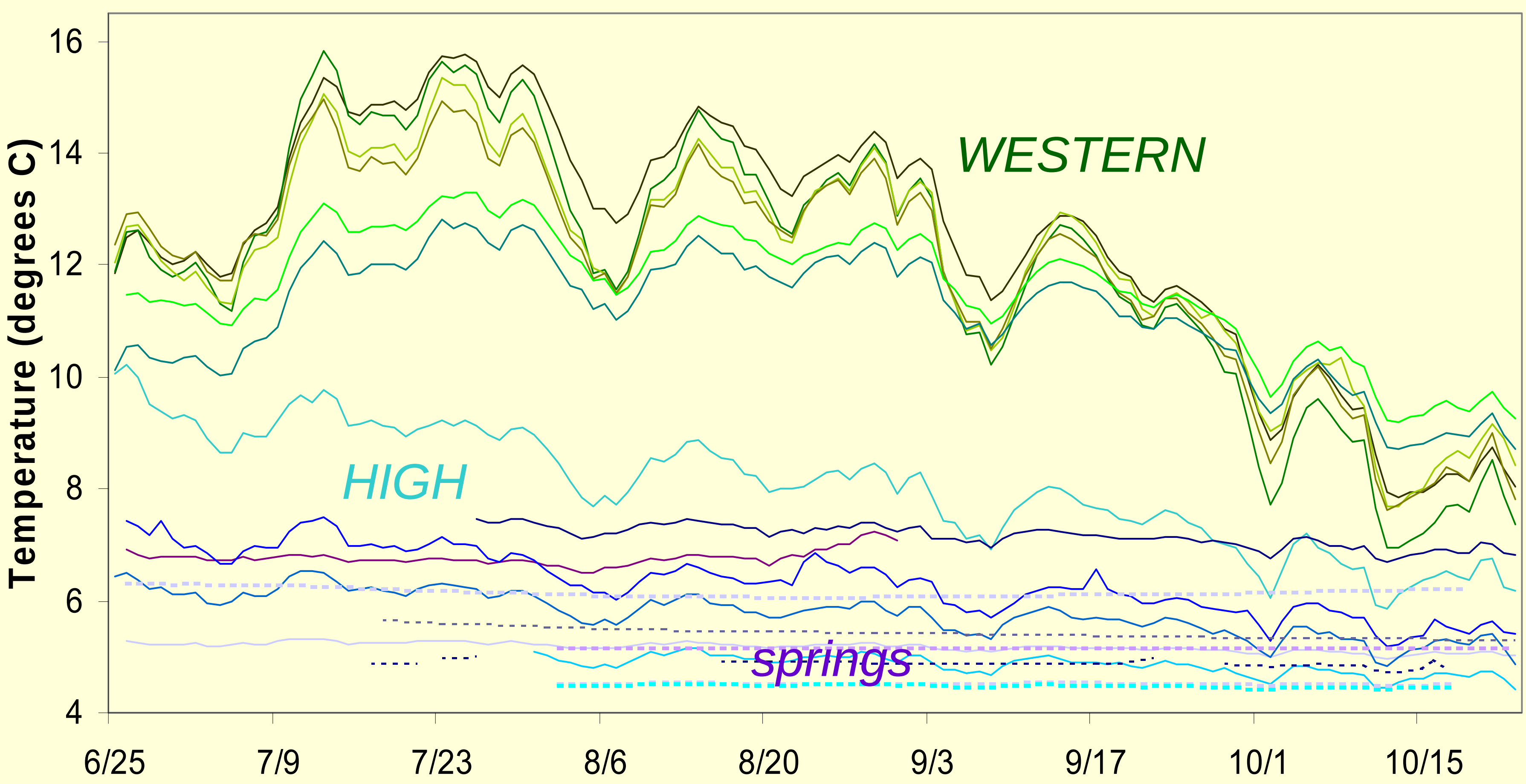
- Mobile wood
- Coarse floodplains & boulder bars
- Rain-on-snow floods
- Flow varies seasonally
- Step-pool organization

High Cascades

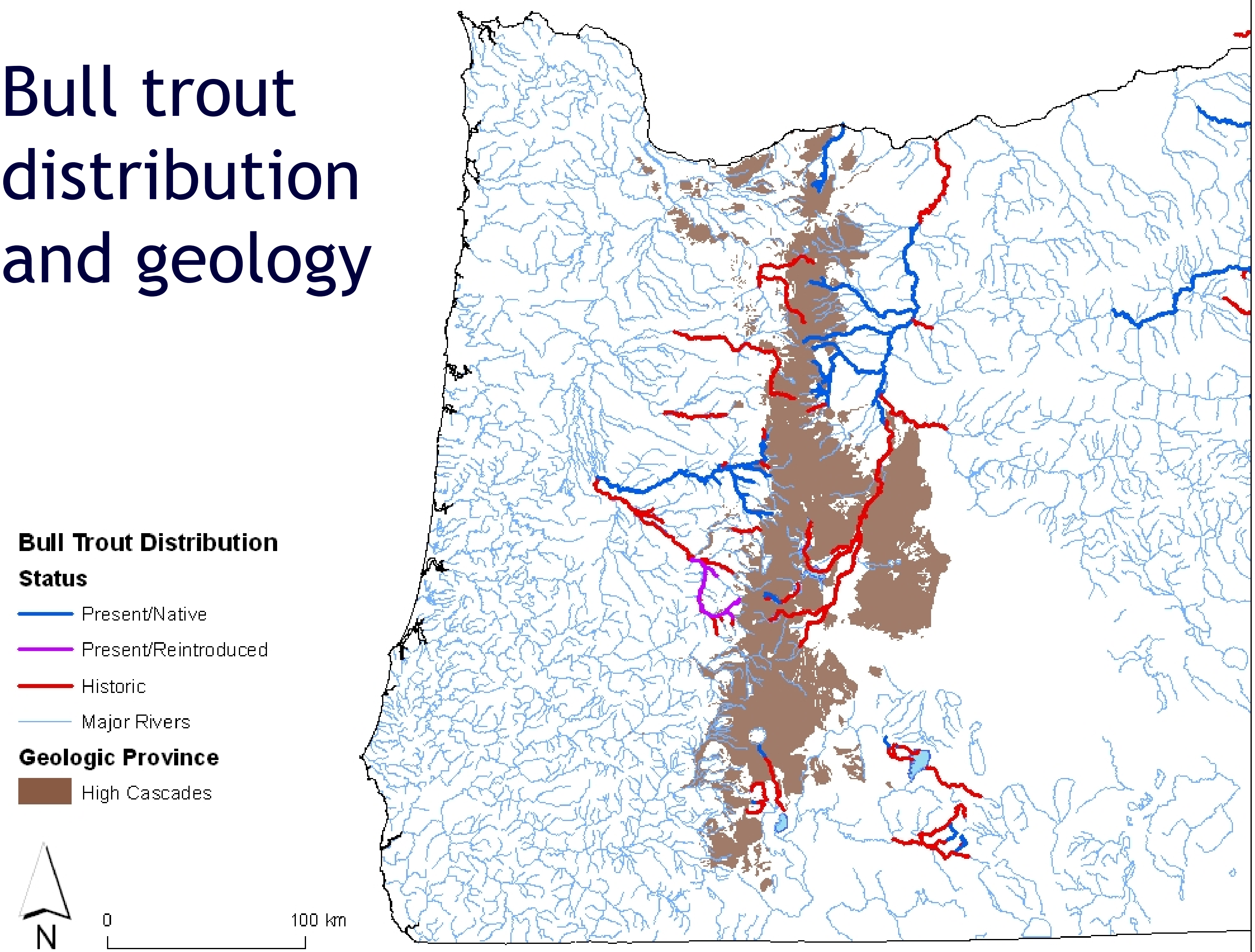
- Stable wood accumulations
- Lack developed floodplain
- Rare floods
- Sustained flow year-round
- Disorganized bed structures

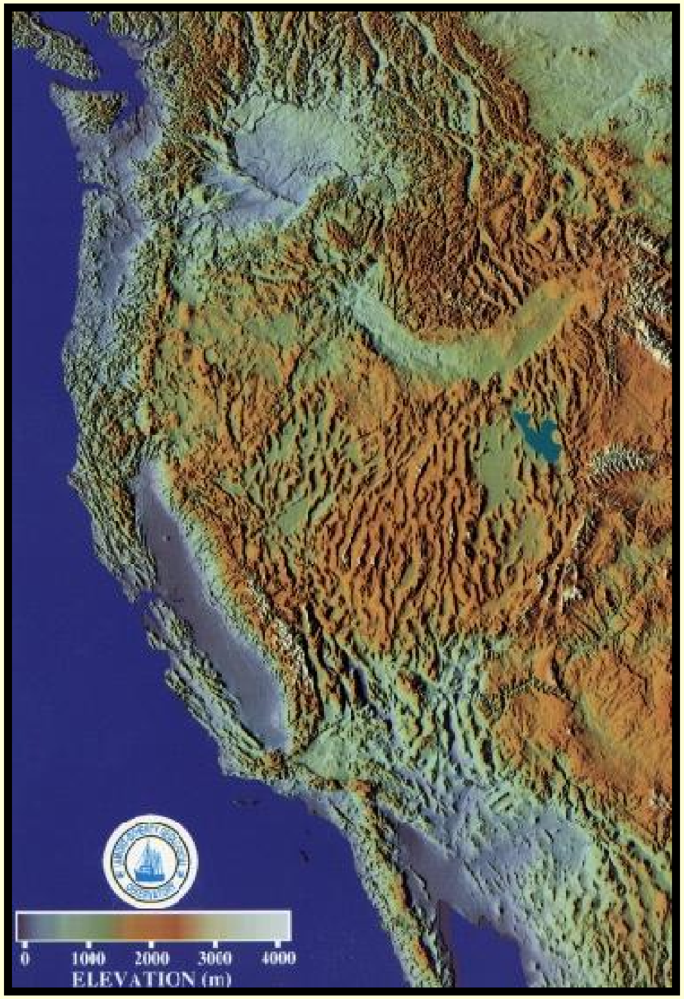

Storm of January 30, 2003
Deer Creek
(Western Cascades)
Upper McKenzie River
(High Cascades)
55.1 NTUs
3 NTUs

Stream Temperatures Summer 2002

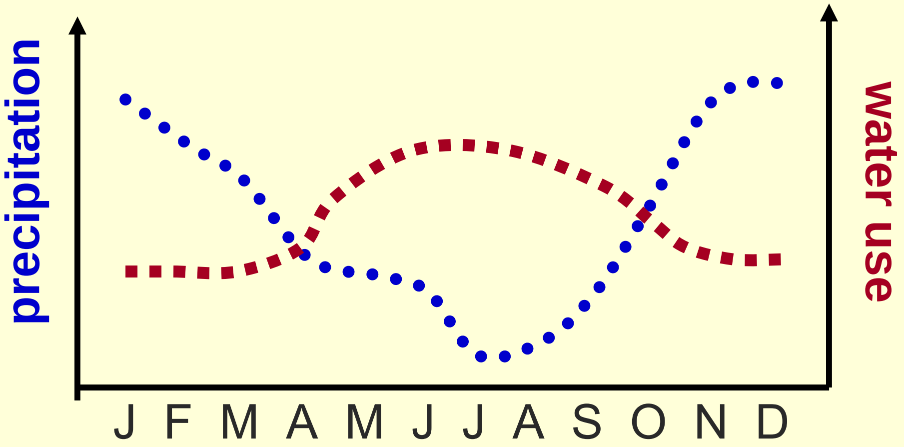


Bull trout distribution and geology





The Paradox of Water in the West…



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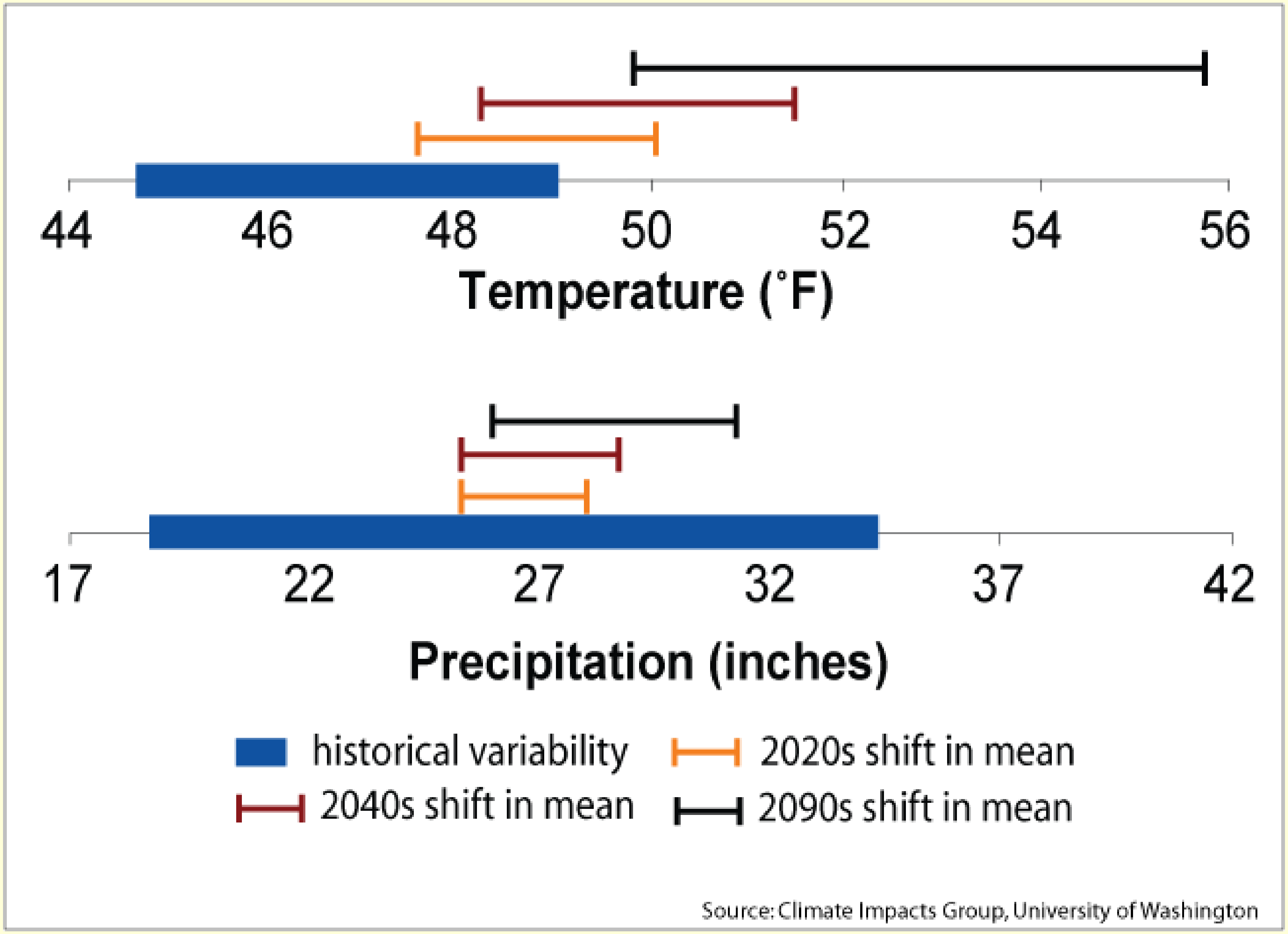
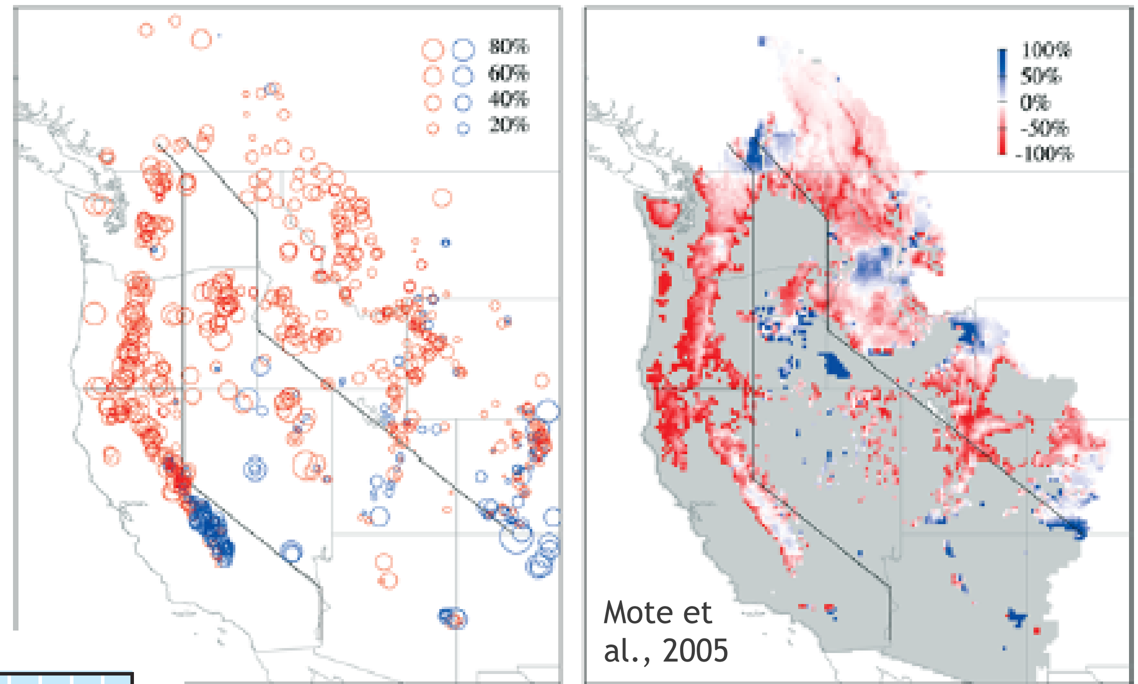


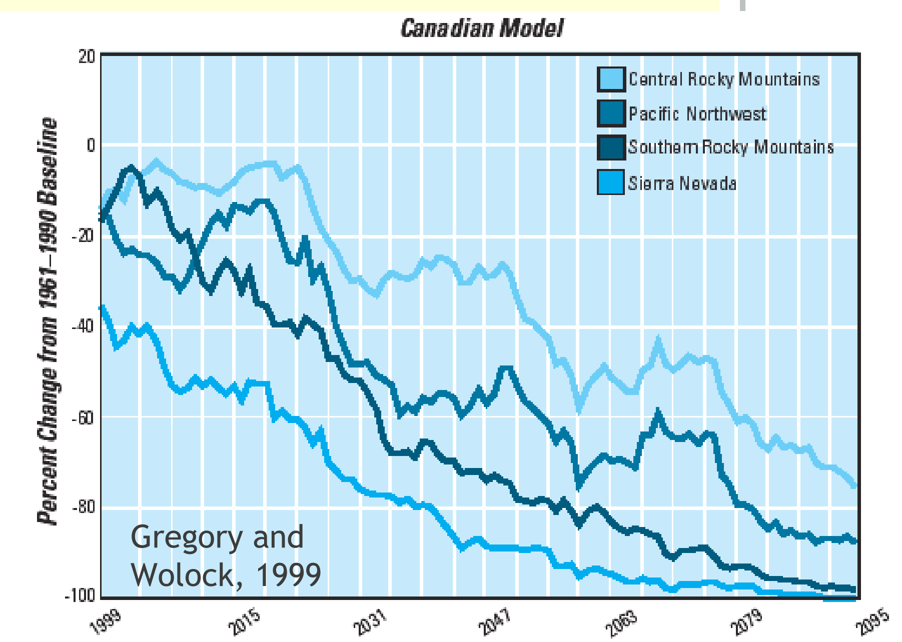
average annual for Pacific Northwest

Snowpacks have gotten smaller, are melting earlier…

Historic linear trends in April 1 Snow Water Equivalent

a. Observed 1950-1997 b. Modeled





…and are projected to continue to diminish.

Snow at risk in a warming climate

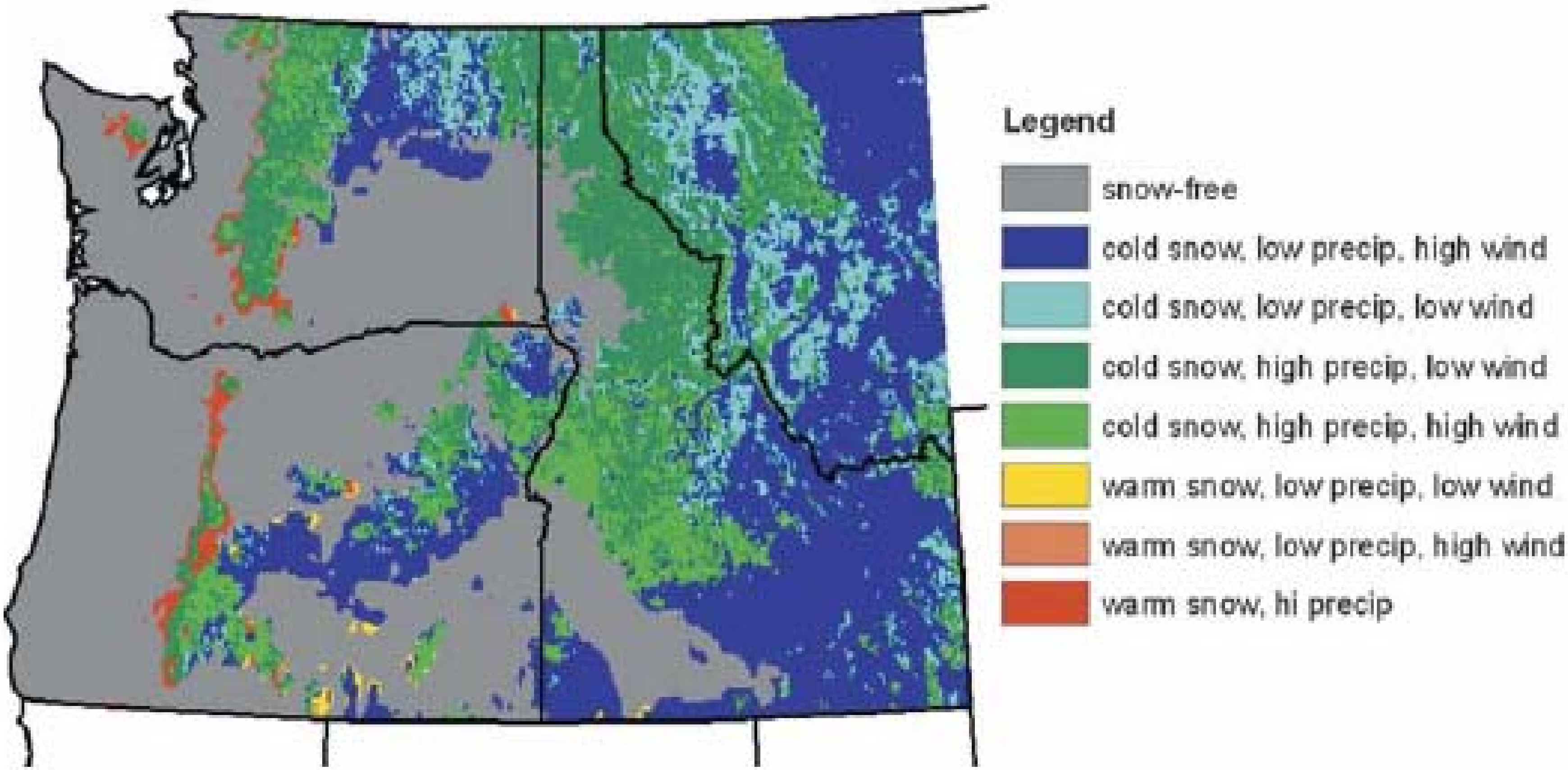
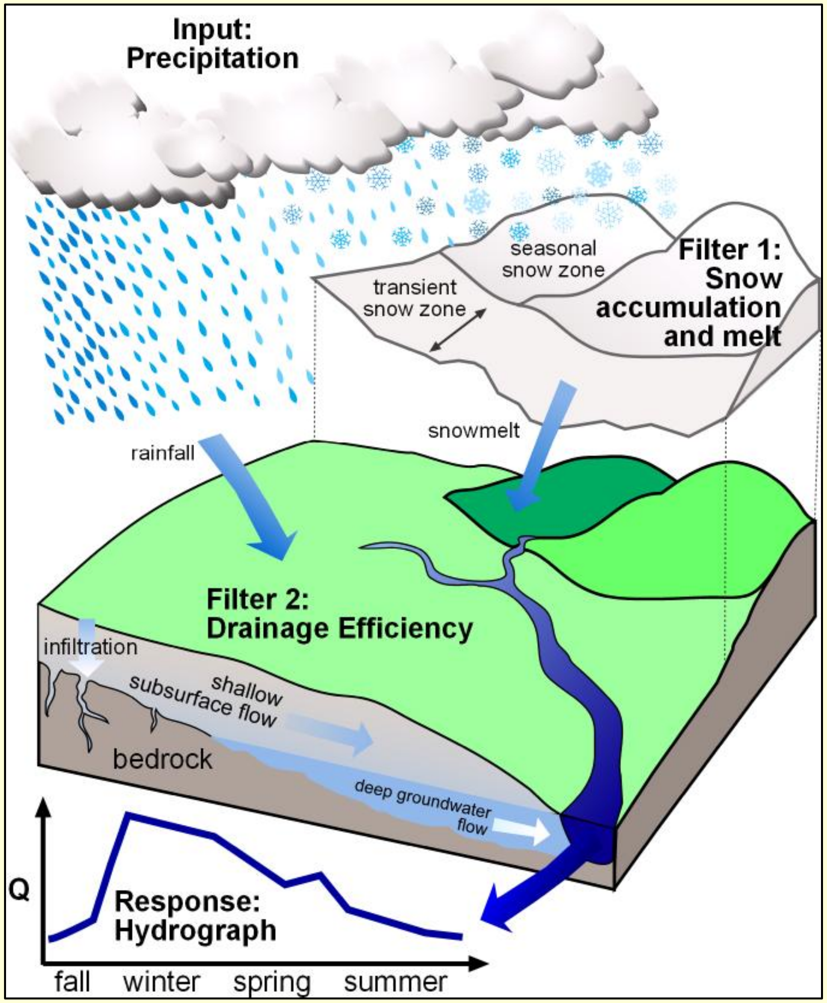


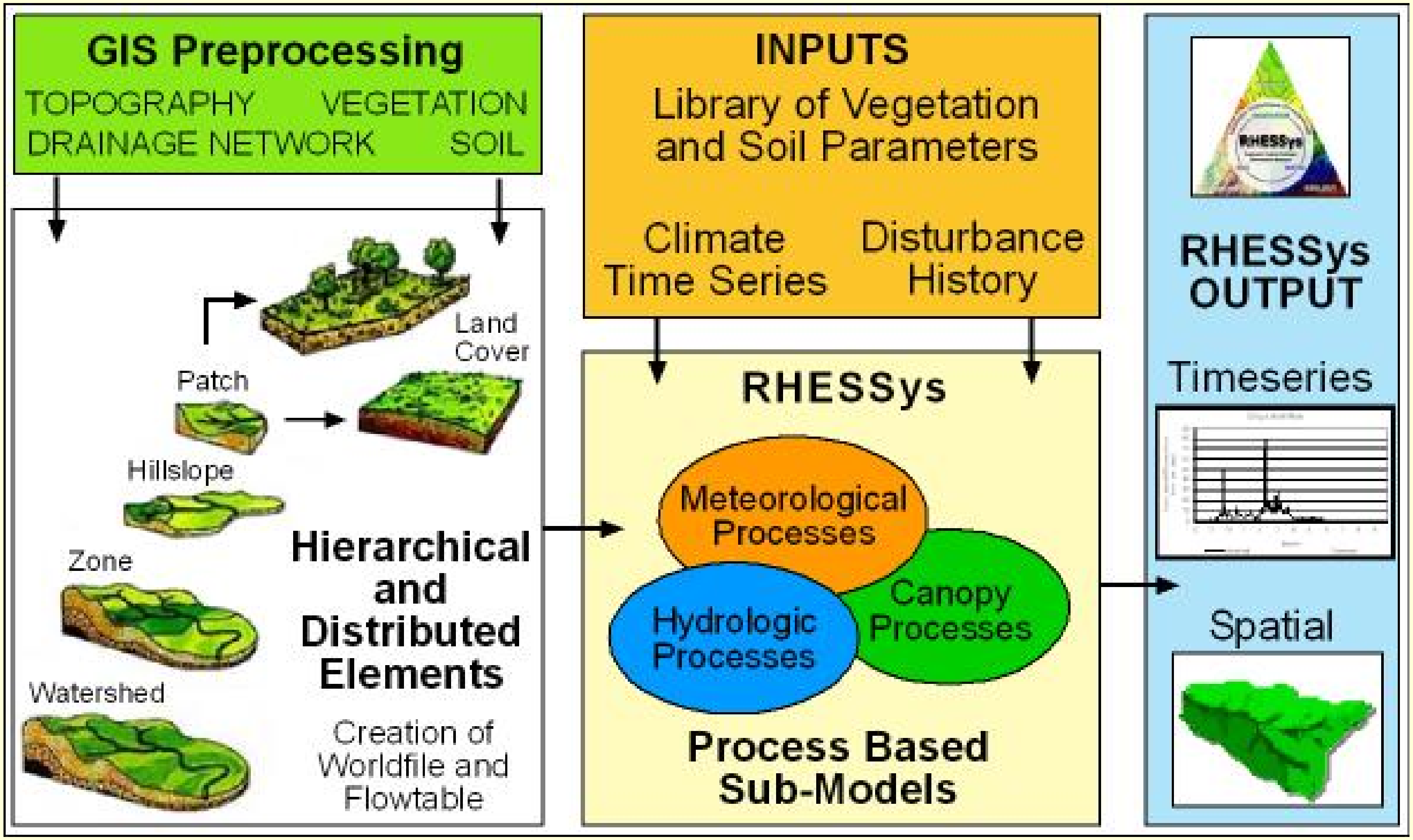
FIG. 3. Snow cover classification using a rain–snow threshold of 0°C. At-risk snow is shown in red.

(Nolin and Daly, 2006)

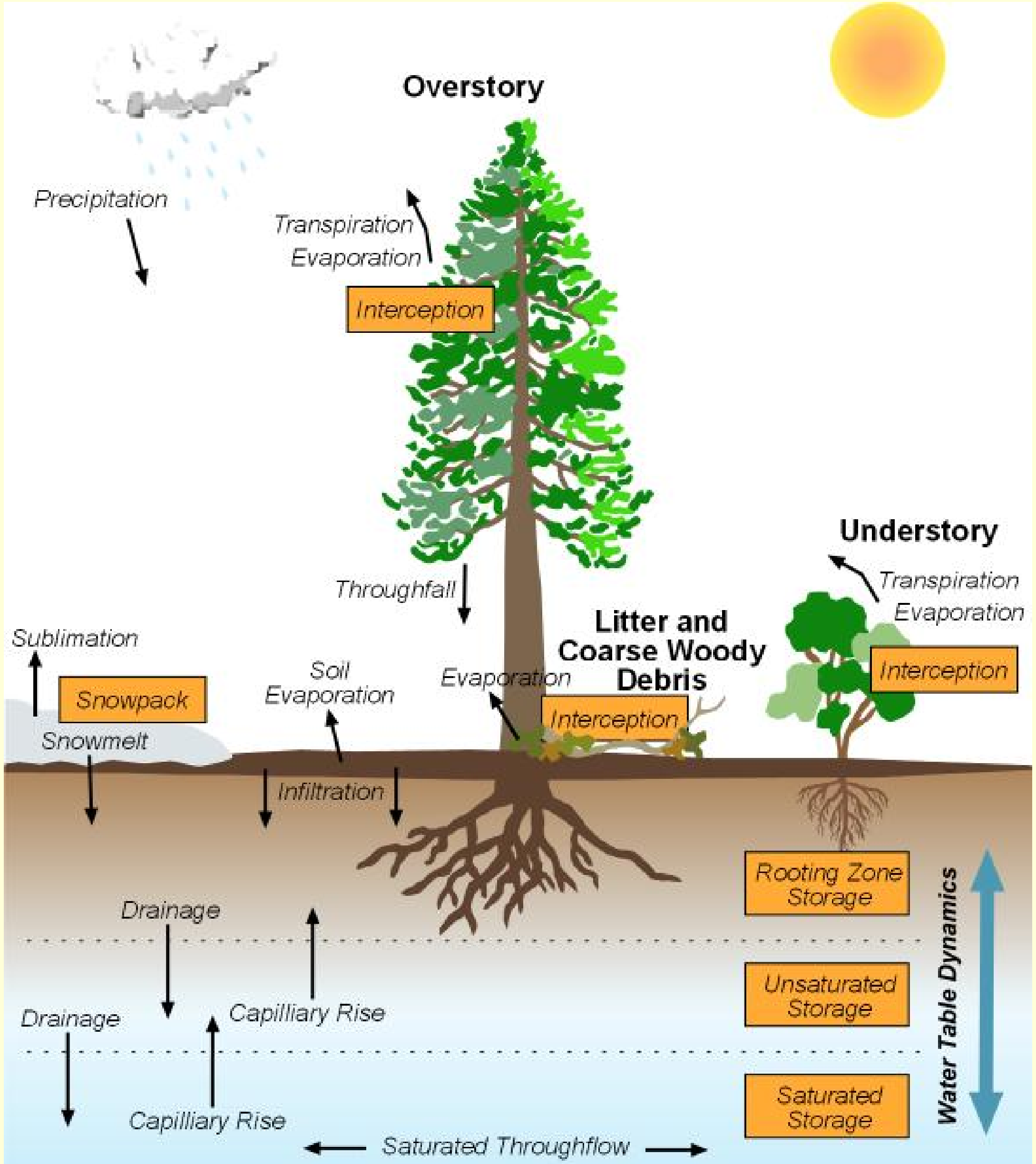


How will the interplay of snowpack dynamics and landscape drainage efficiency affect streamflow regimes under climate warming scenarios?

Using a hydrologic model (RHESSys) to explore streamflow response to climate warming

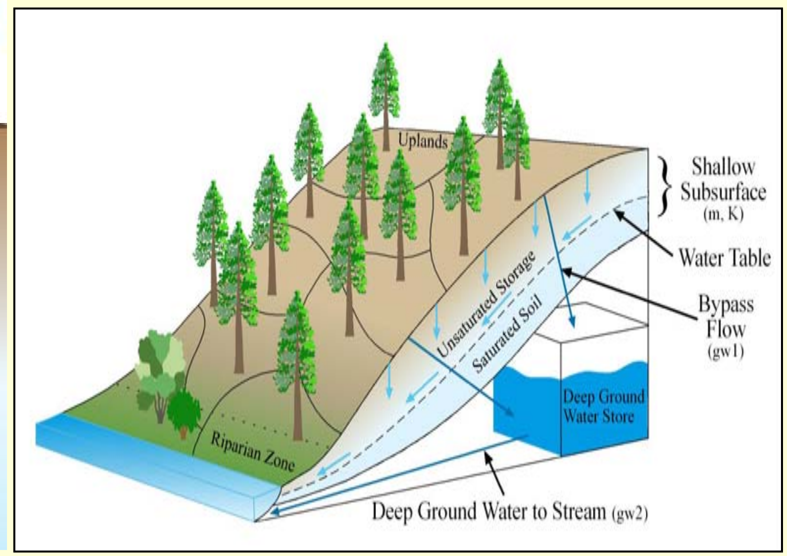


(Tague & Band, 2004)



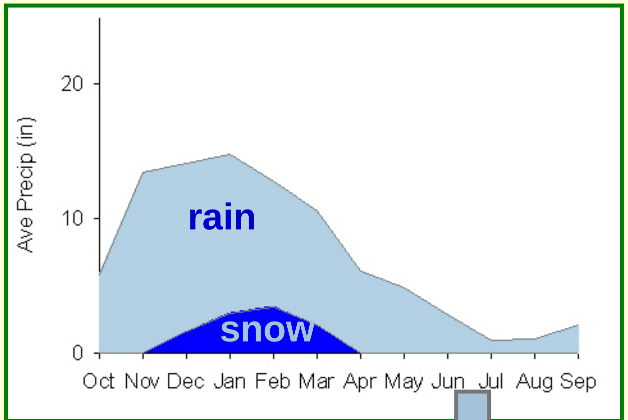
Original RHESSys framework

Additional deep groundwater component

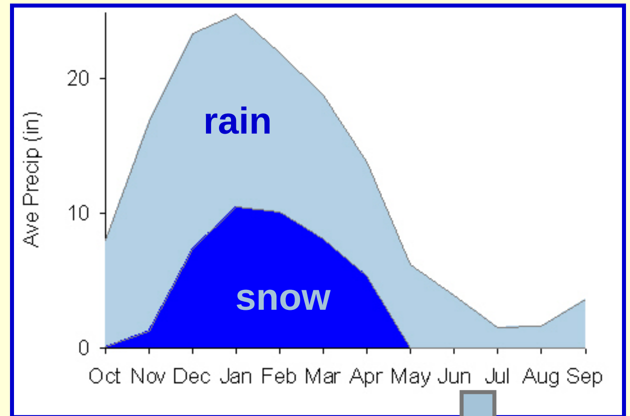


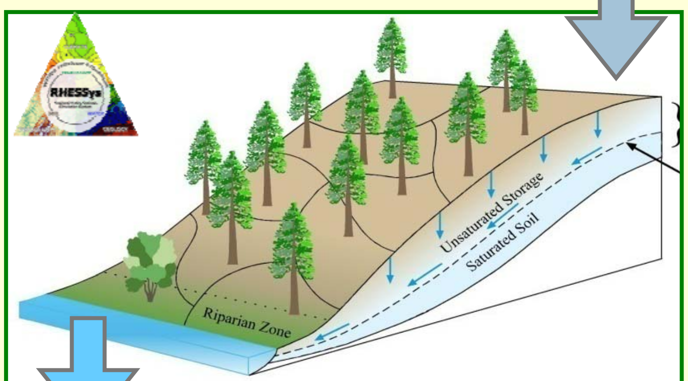
Western Cascades (surface-flow)

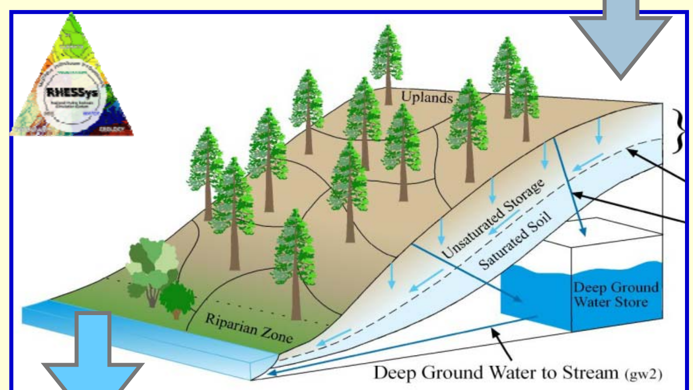
High Cascades (spring-fed)

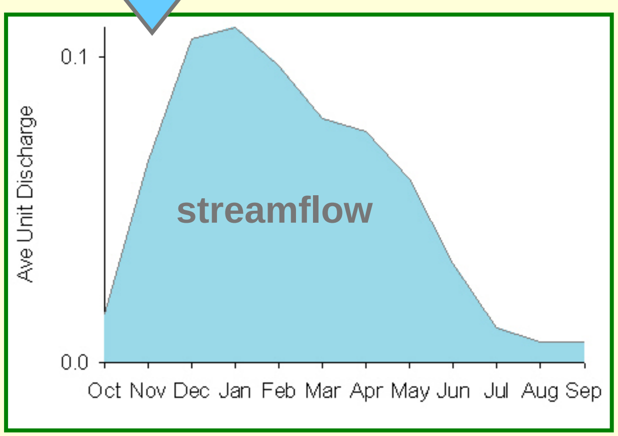


RECHARGE
Current climate

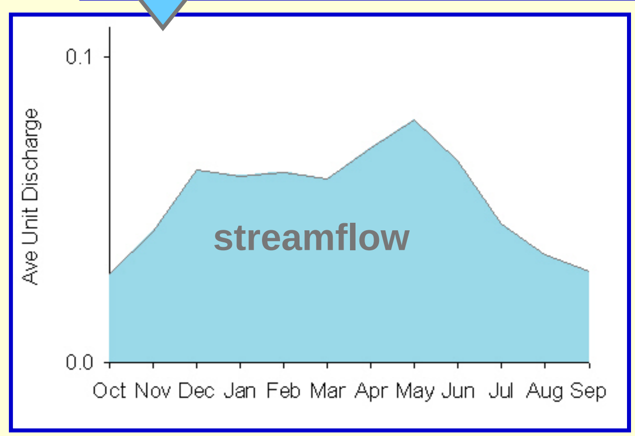


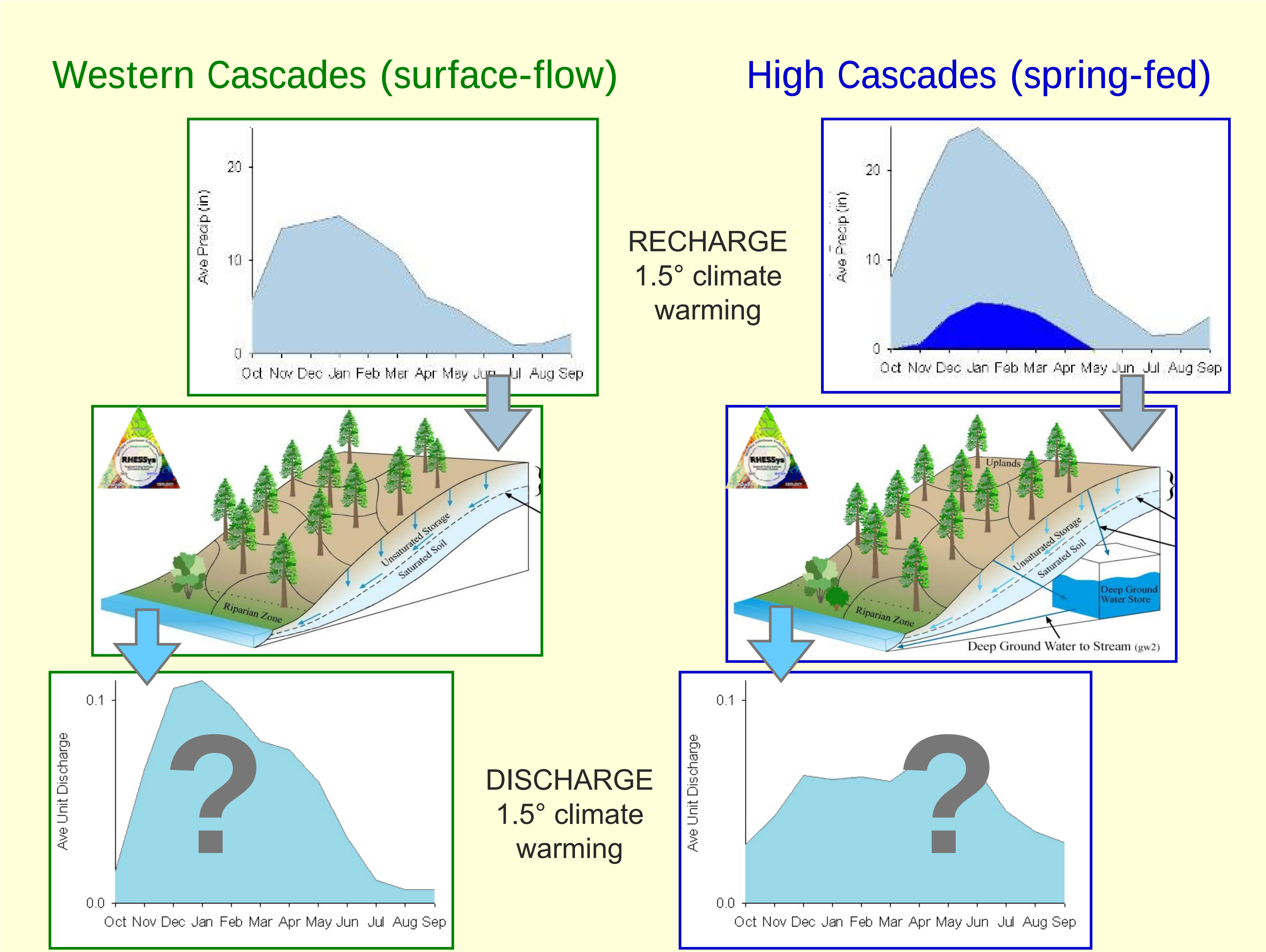




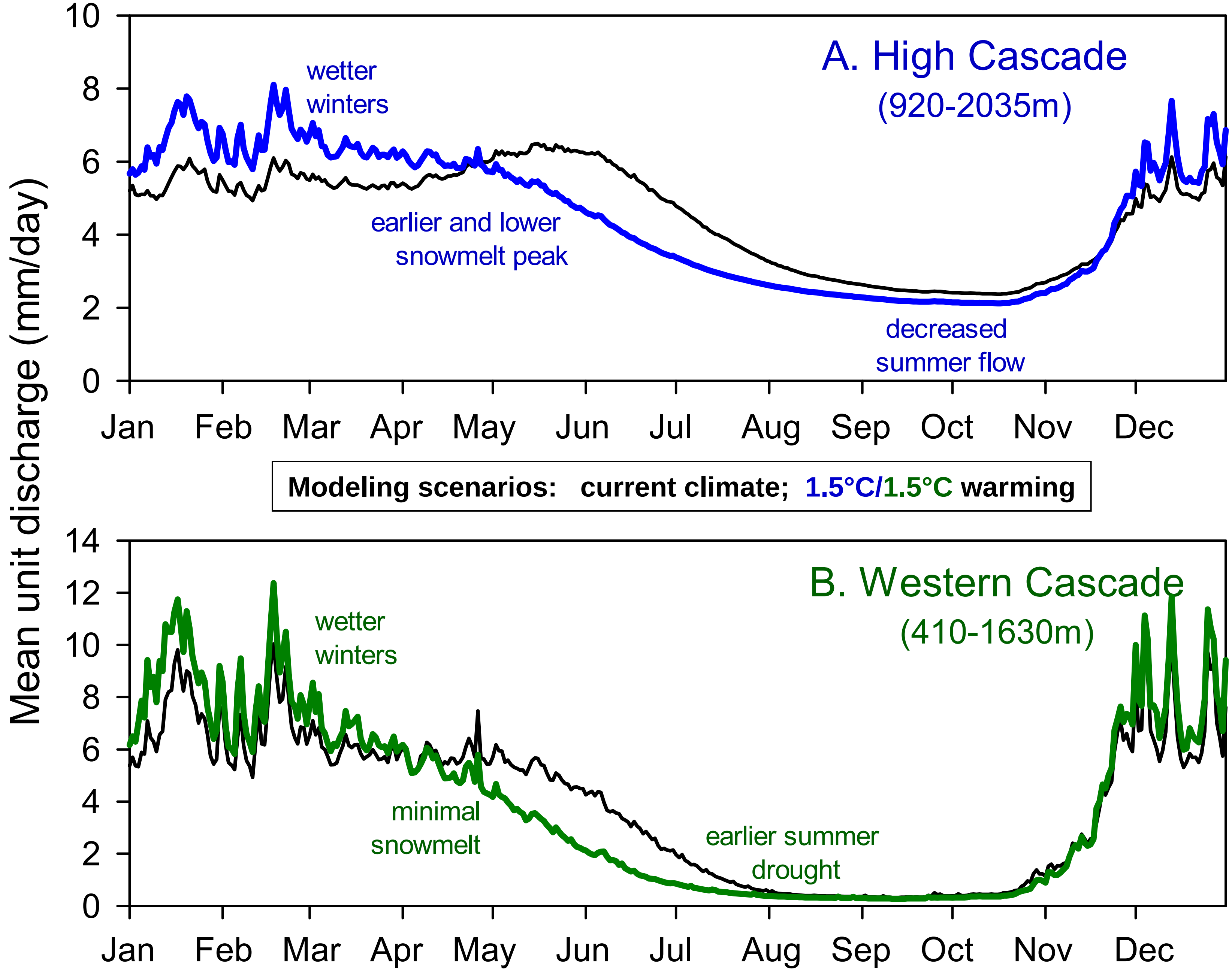


DISCHARGE
Current climate



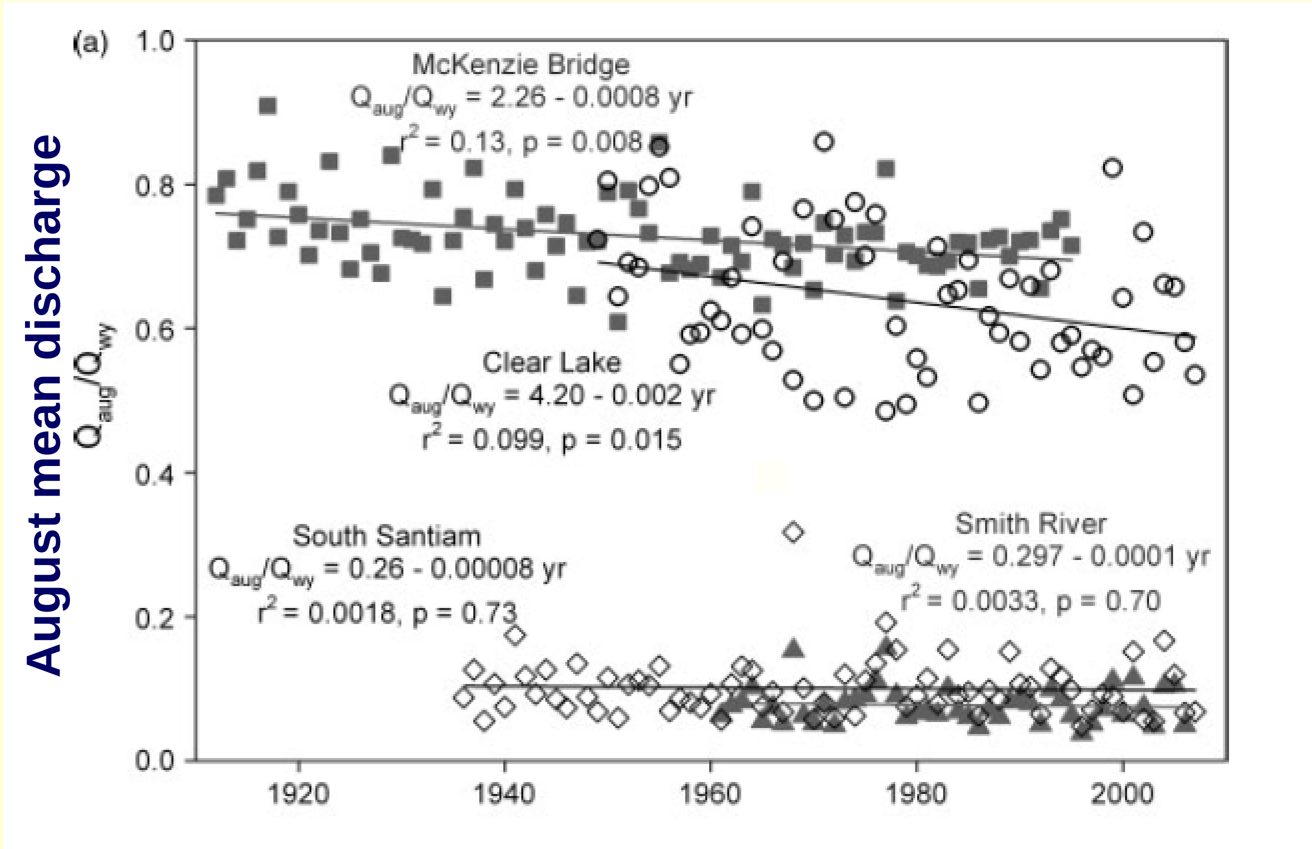


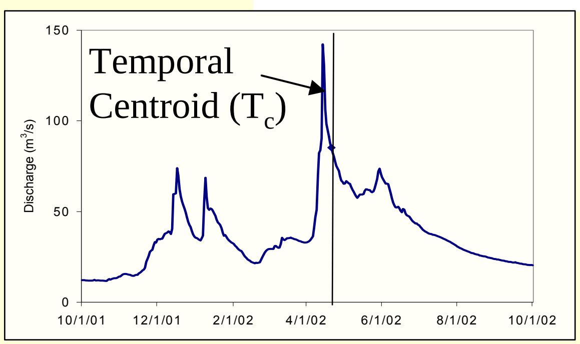
Western Cascades (surface-flow)
High Cascades (spring-fed)
Ave Precip (in)
20
10
0
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
RECHARGE
1.5° climate
warming
RHESSys
Uplands
Unsaturated Storage
Saturated Soil
Riparian Zone
Deep Ground Water Store
Deep Ground Water to Stream (gw2)
Ave Unit Discharge
0.1
0.0
?
DISCHARGE
1.5° climate
warming



Mean unit discharge (mm/day)
A. High Cascade
(920-2035m)
wetter
winters
earlier and lower
snowmelt peak
decreased
summer flow
10
8
6
4
2
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Modeling scenarios: current climate; 1.5°C/1.5°C warming
B. Western Cascade
(410-1630m)
wetter
winters
minimal
snowmelt
earlier summer
drought
14
12
10
8
6
4
2
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Historical Trends from Cascade Streams





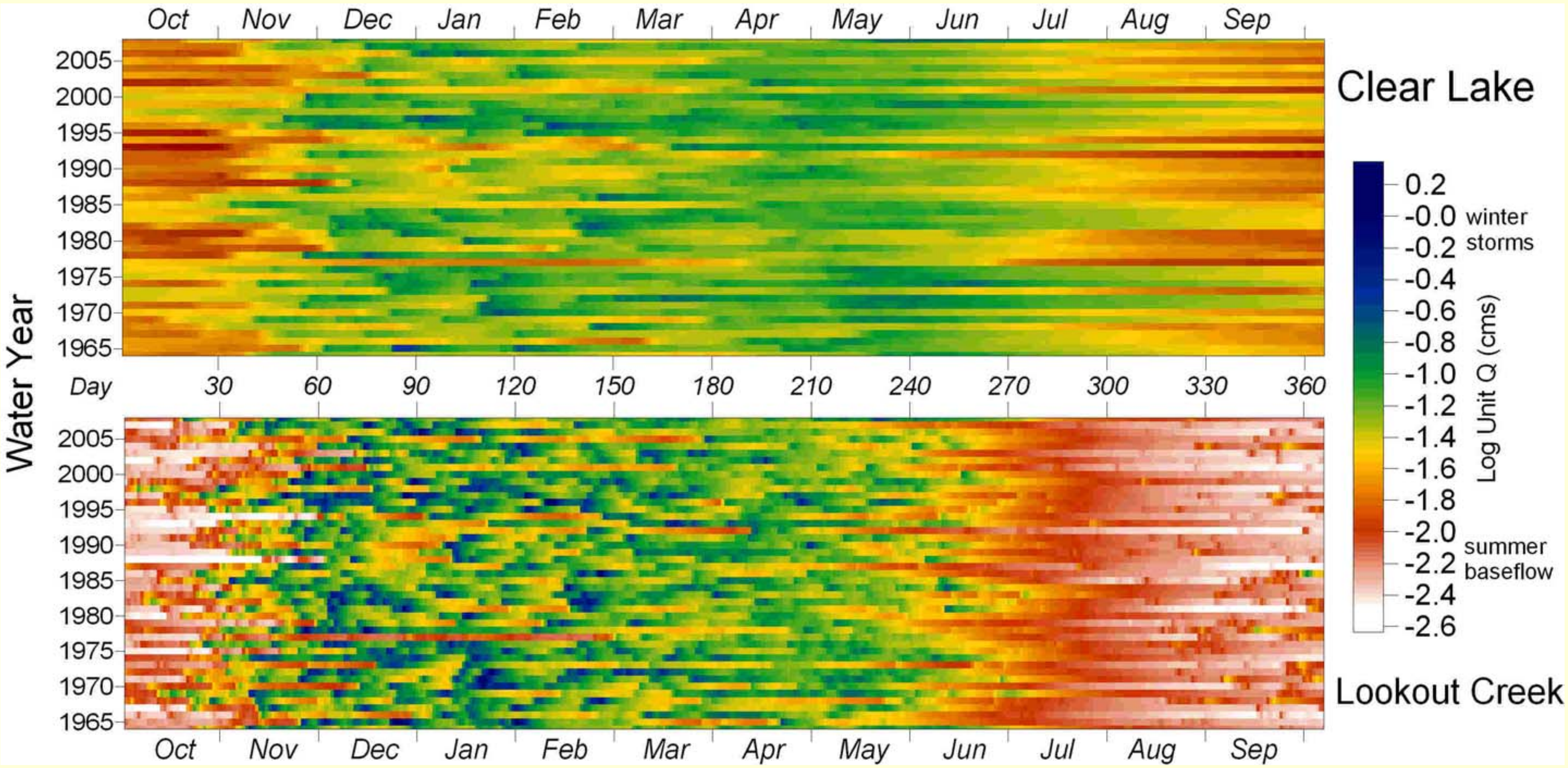
Between 1948 and 2006 for Clear Lake:

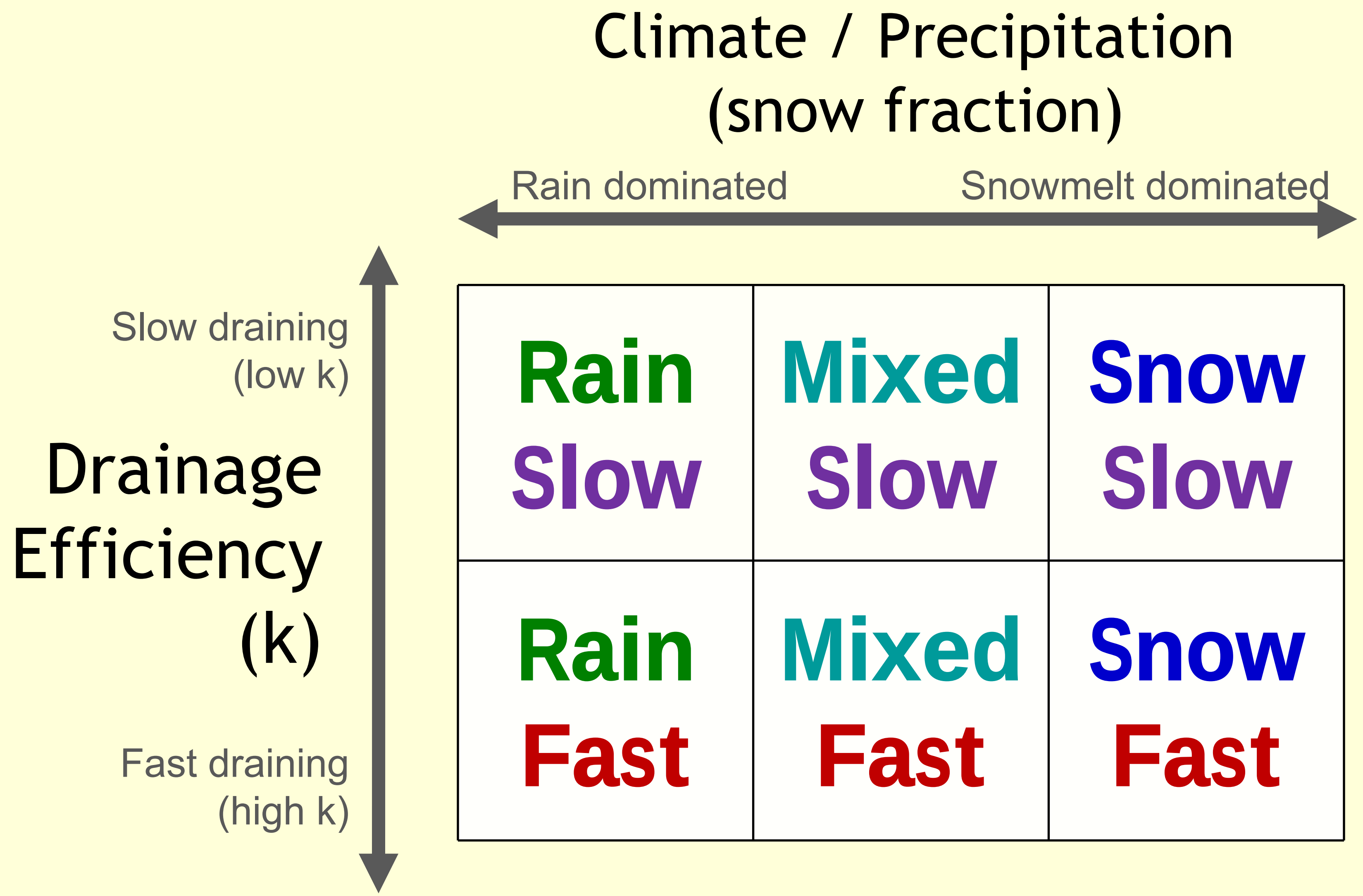
Temporal centroid - 14 days earlier

Autumn minimum discharge - 1.4 cms lower

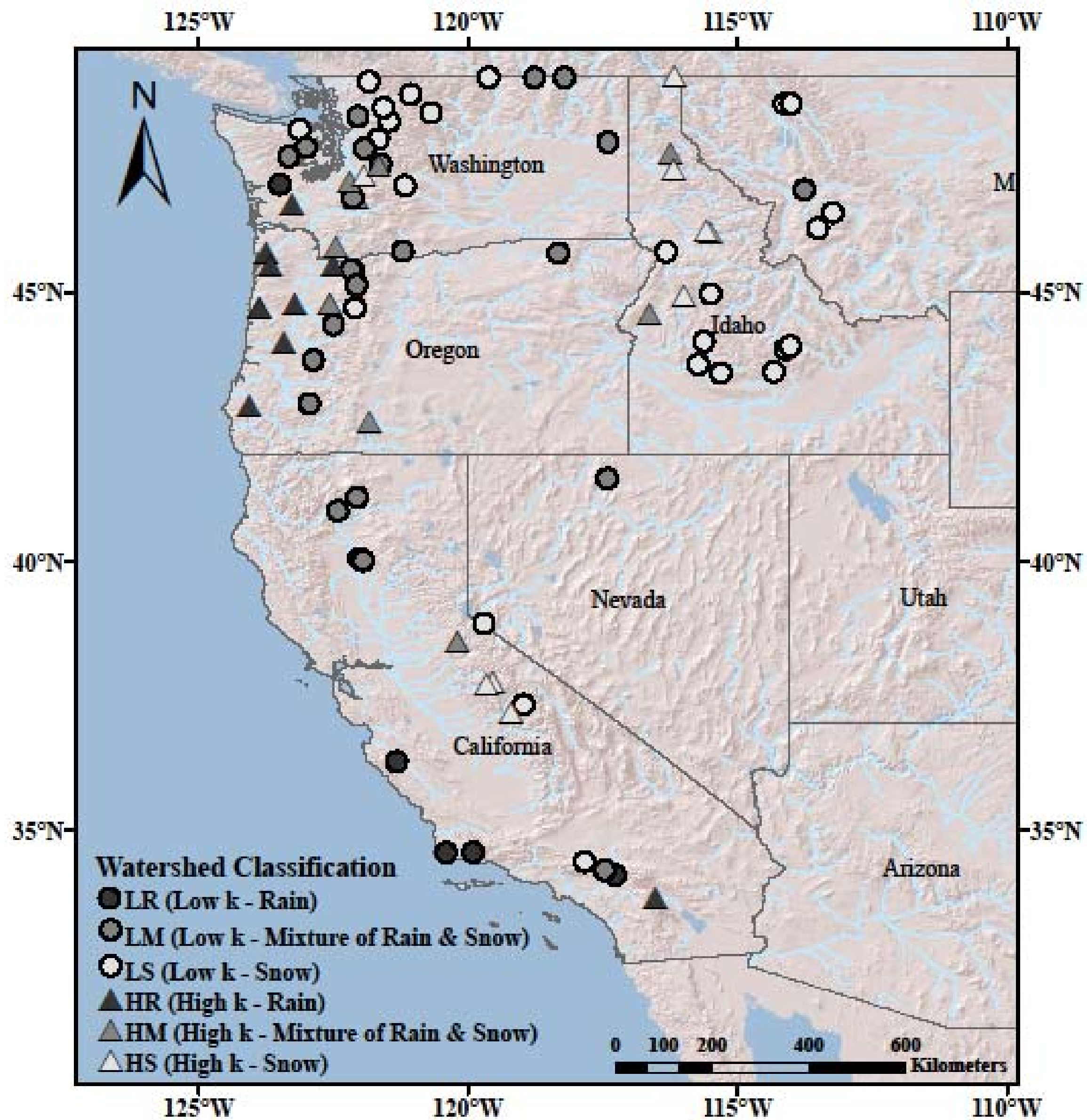
(Jefferson, 2006; Jefferson et al., 2008)

Daily discharge (log unit m^3/s) for 1964-2007



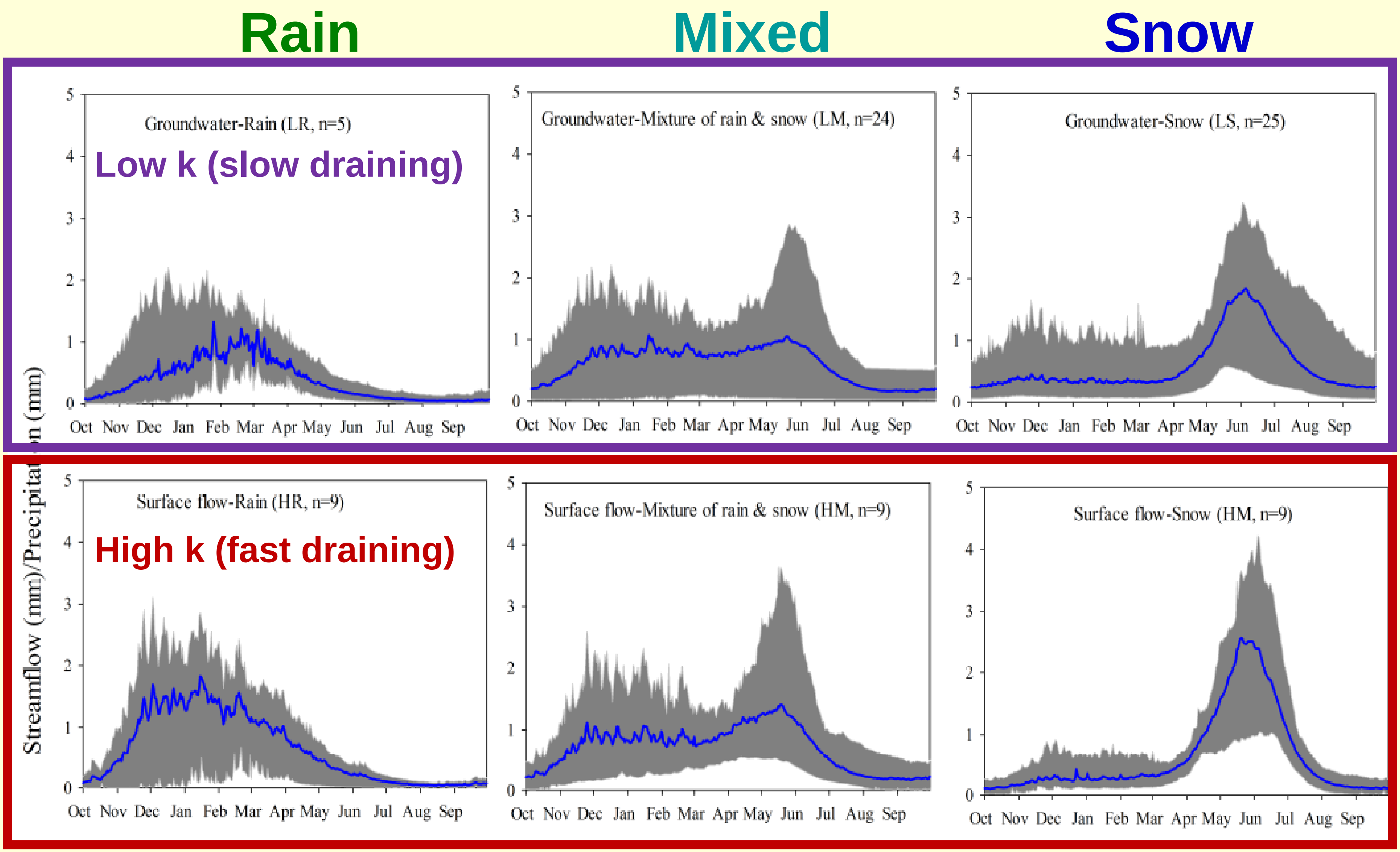

Climate / Precipitation
(snow fraction)
Rain dominated
Snowmelt dominated
Slow draining
(low k)
Drainage
Efficiency
(k)
Fast draining
(high k)
Rain Slow
Mixed Slow
Snow Slow
Rain Fast
Mixed Fast
Snow Fast

Classification of Study Basins



Source: Safeeq et al., in review

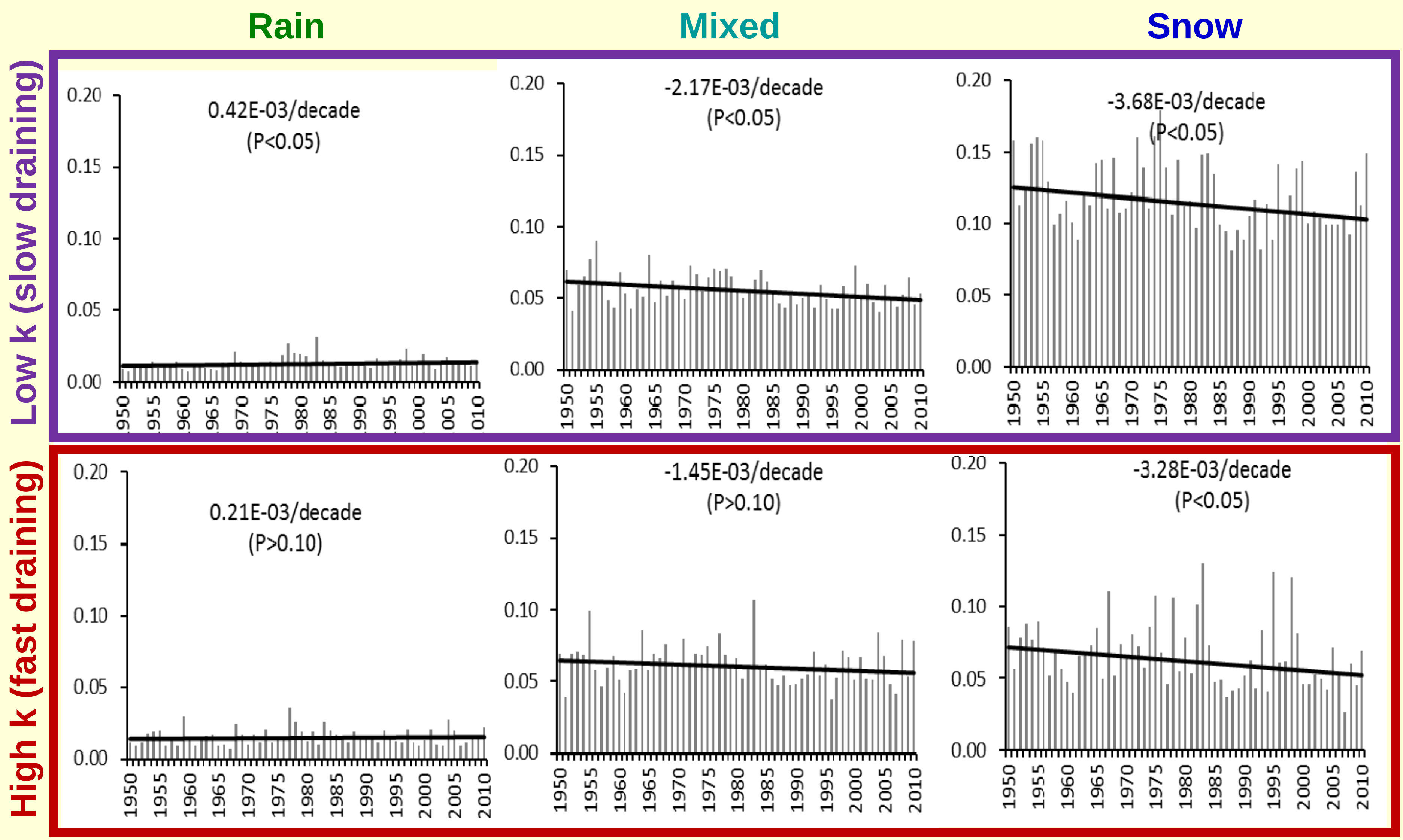
Ensemble Hydrographs



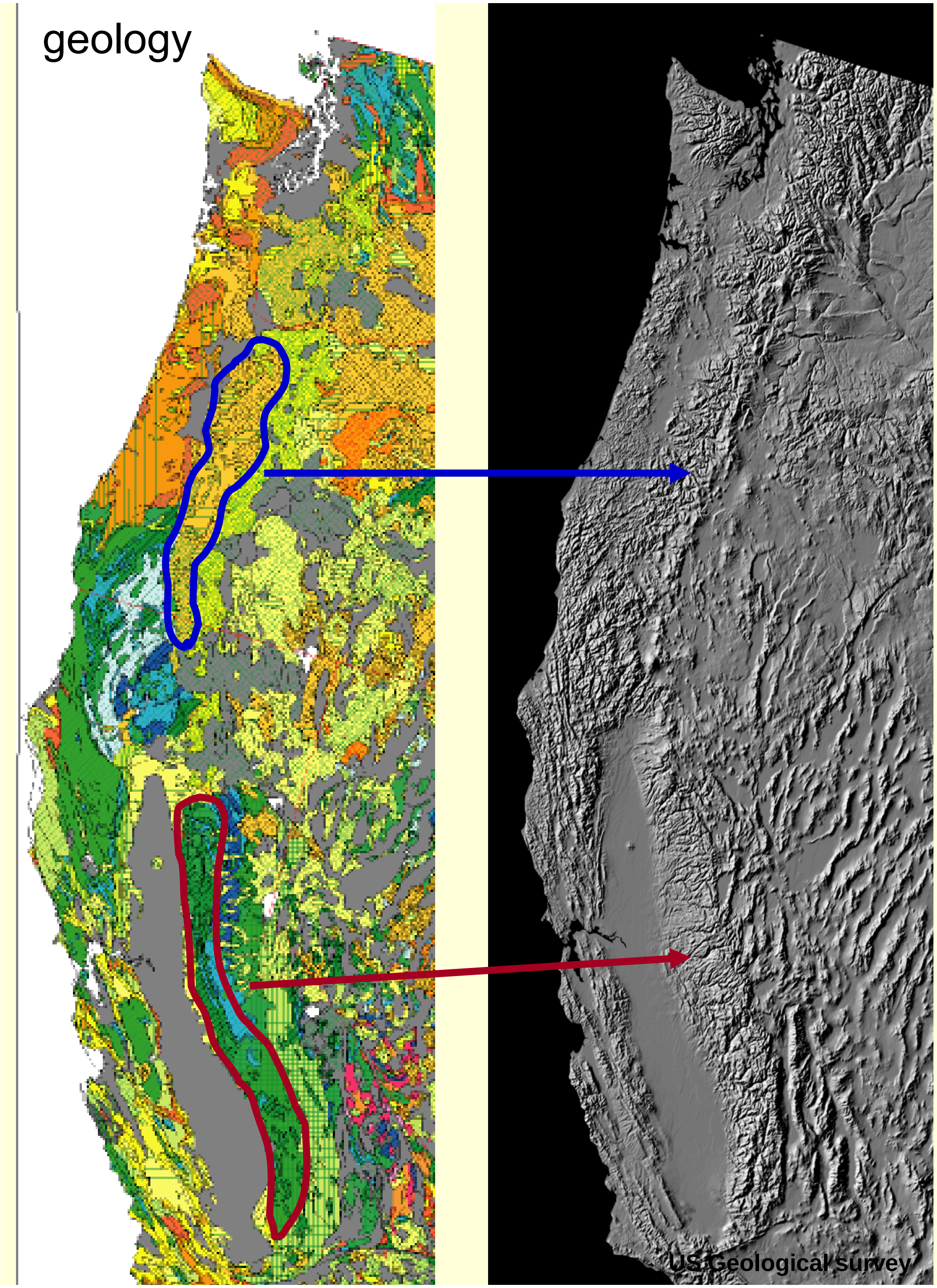
Source: Safeeq et al., in review

Historical Trends in Summer Runoff Ratio (1950–2010)

(Q_{summer} / Annual Precipitation)



Source: Safeeq et al., in review



Oregon Cascades

Young volcanic rocks =
Large groundwater system

Water stored in:

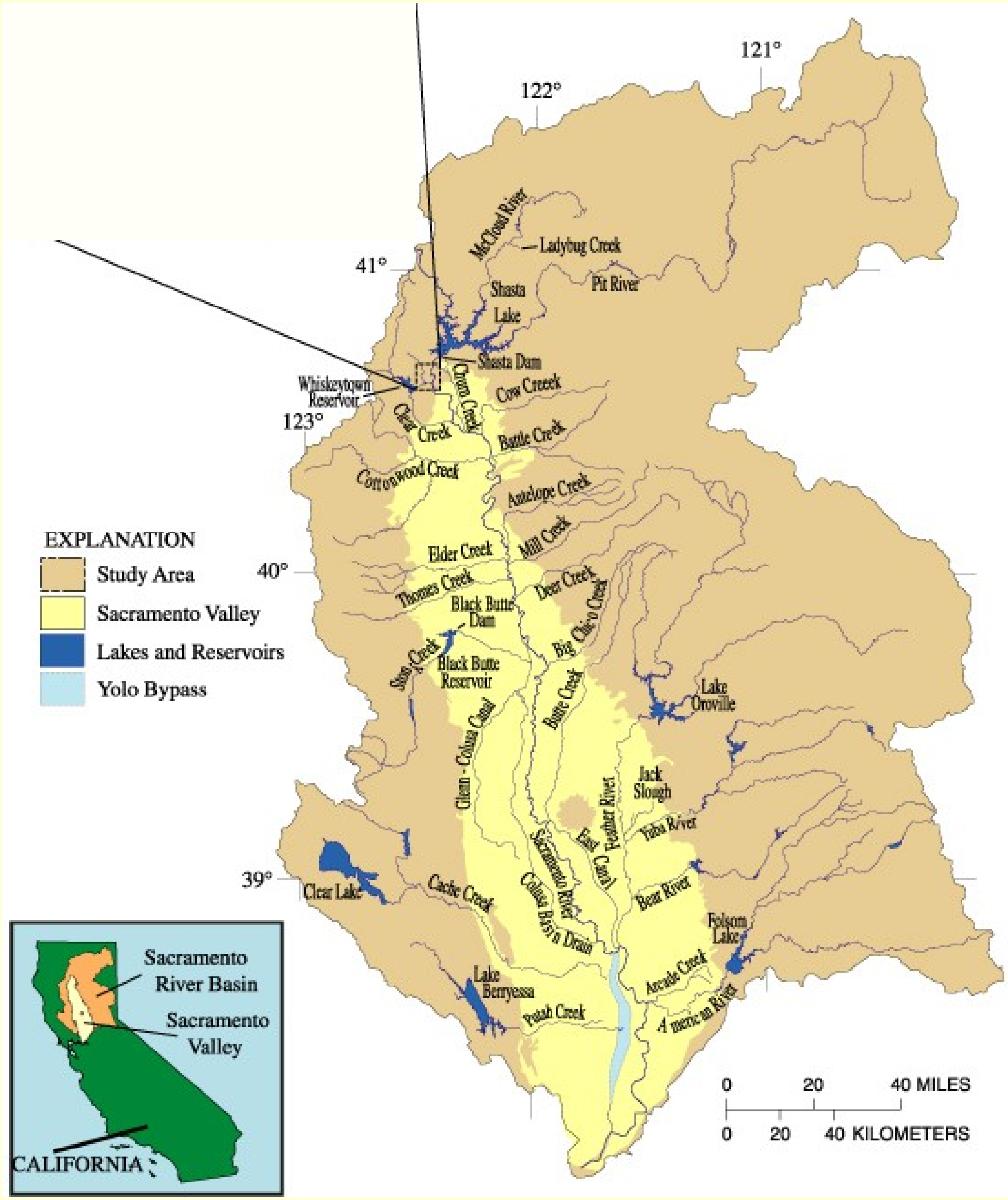
- groundwater
- snowpacks
- reservoirs

Sierra Nevada

Old granitic rocks =
Surface-flow dominated

Water stored in:

- snowpacks
- reservoirs



EXPLANATION
Study Area
Sacramento Valley
Lakes and Reservoirs
Yolo Bypass
121°
122°
41°
123°
40°
39°
McCloud River
Ladybug Creek
Pit River
Shasta Lake
Shasta Dam
Whiskeytown Reservoir
Churn Creek
Cow Creek
Clear Creek
Battle Creek
Cottonwood Creek
Antelope Creek
Elder Creek
Mill Creek
Thomes Creek
Deer Creek
Black Butte Dam
Big Chico Creek
Stony Creek
Black Butte Reservoir
Butte Creek
Lake Oroville
Glenn - Colusa Canal
Jack Slough
Feather River
Yuba River
East Canal
Sacramento River
Colusa Basin Drain
Clear Lake
Cache Creek
Bear River
Folsom Lake
Arcade Creek
Lake Berryessa
Putah Creek
American River
0 20 40 MILES
0 20 40 KILOMETERS
Sacramento River Basin
Sacramento Valley
CALIFORNIA

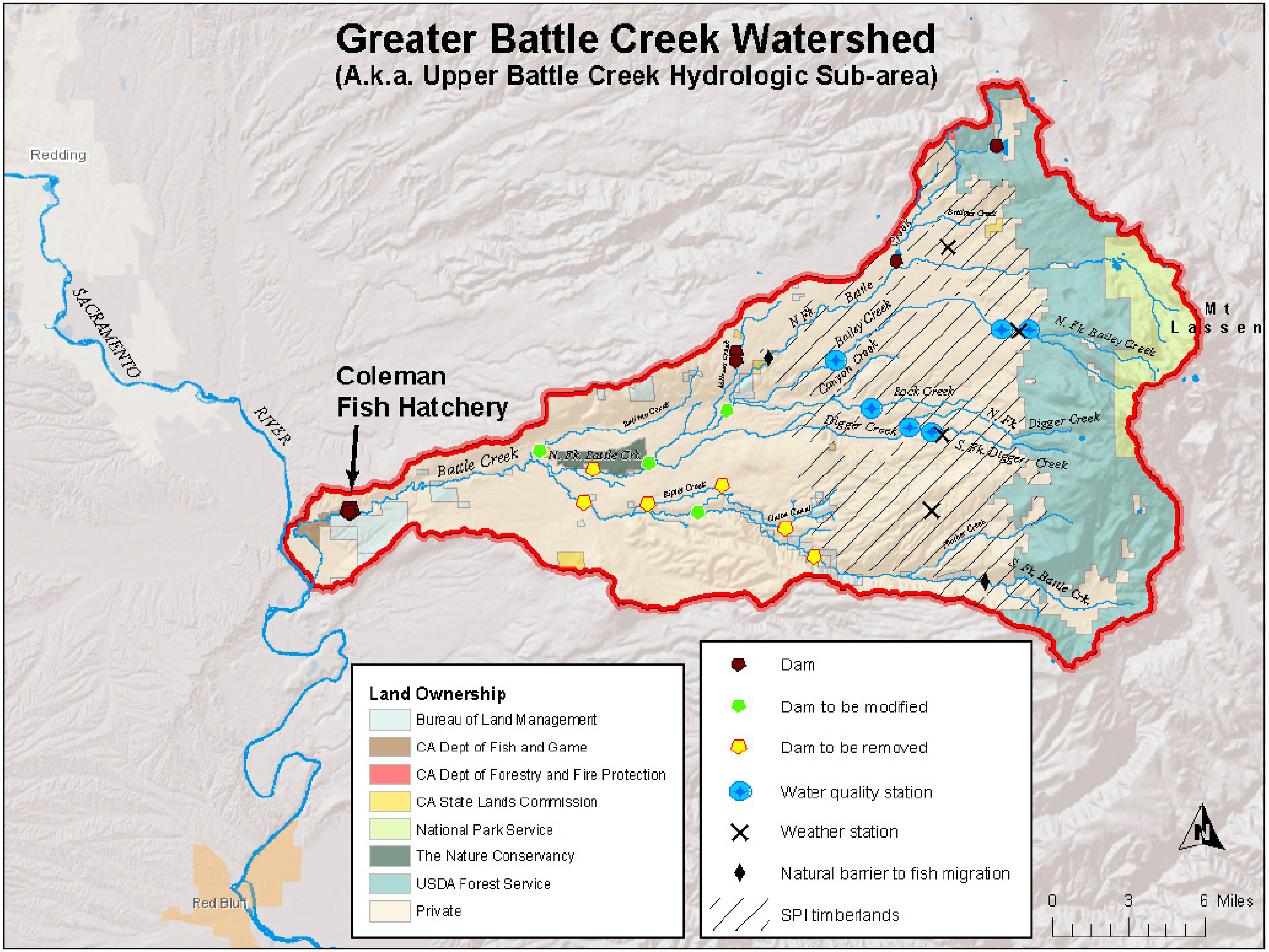
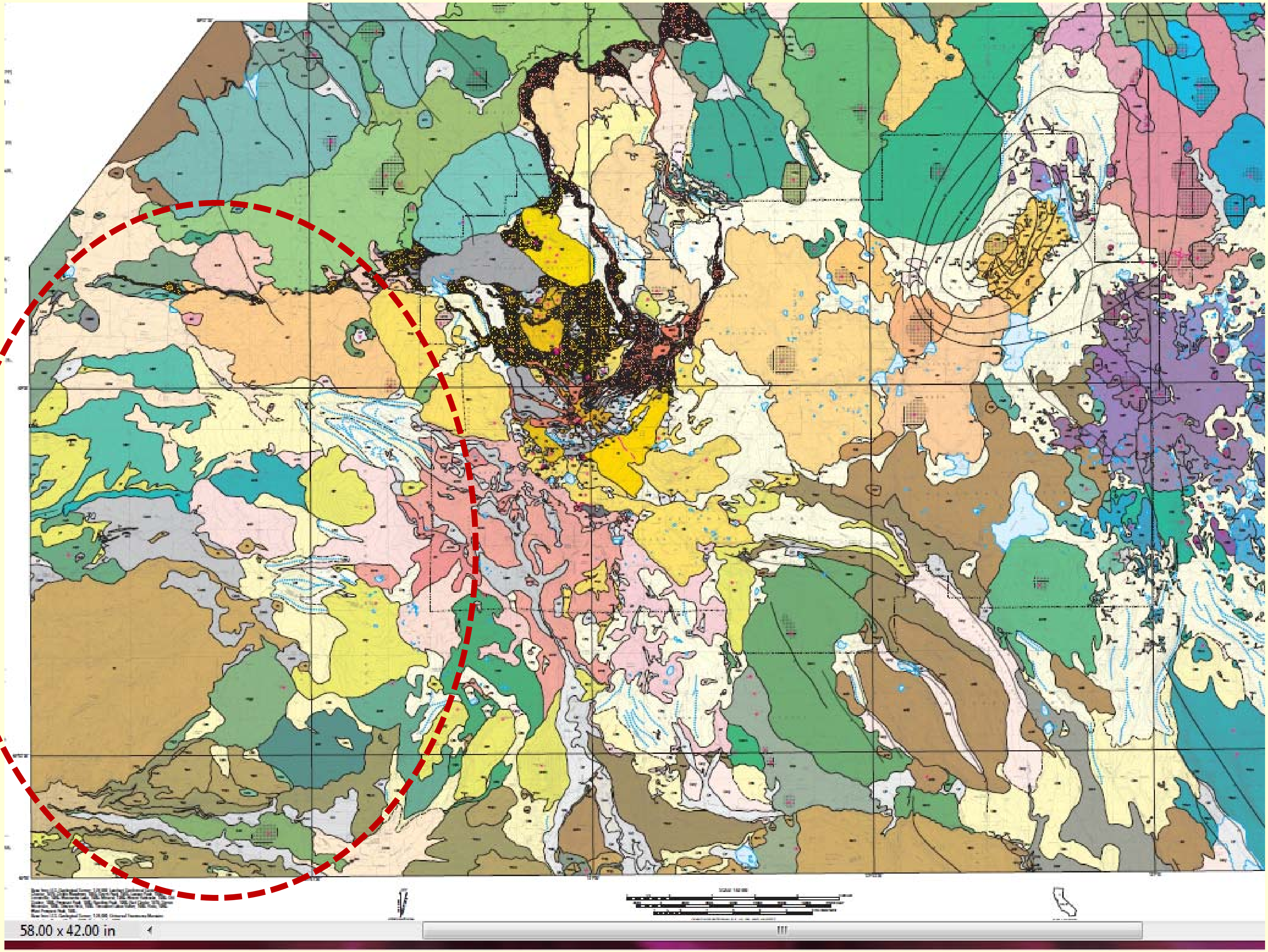


Figure 1 from James & MacDonald, 2012



From Clynne & Muffler, 2012: Geologic Map of Lassen Volcanic National Park and vicinity

Water Year 2009

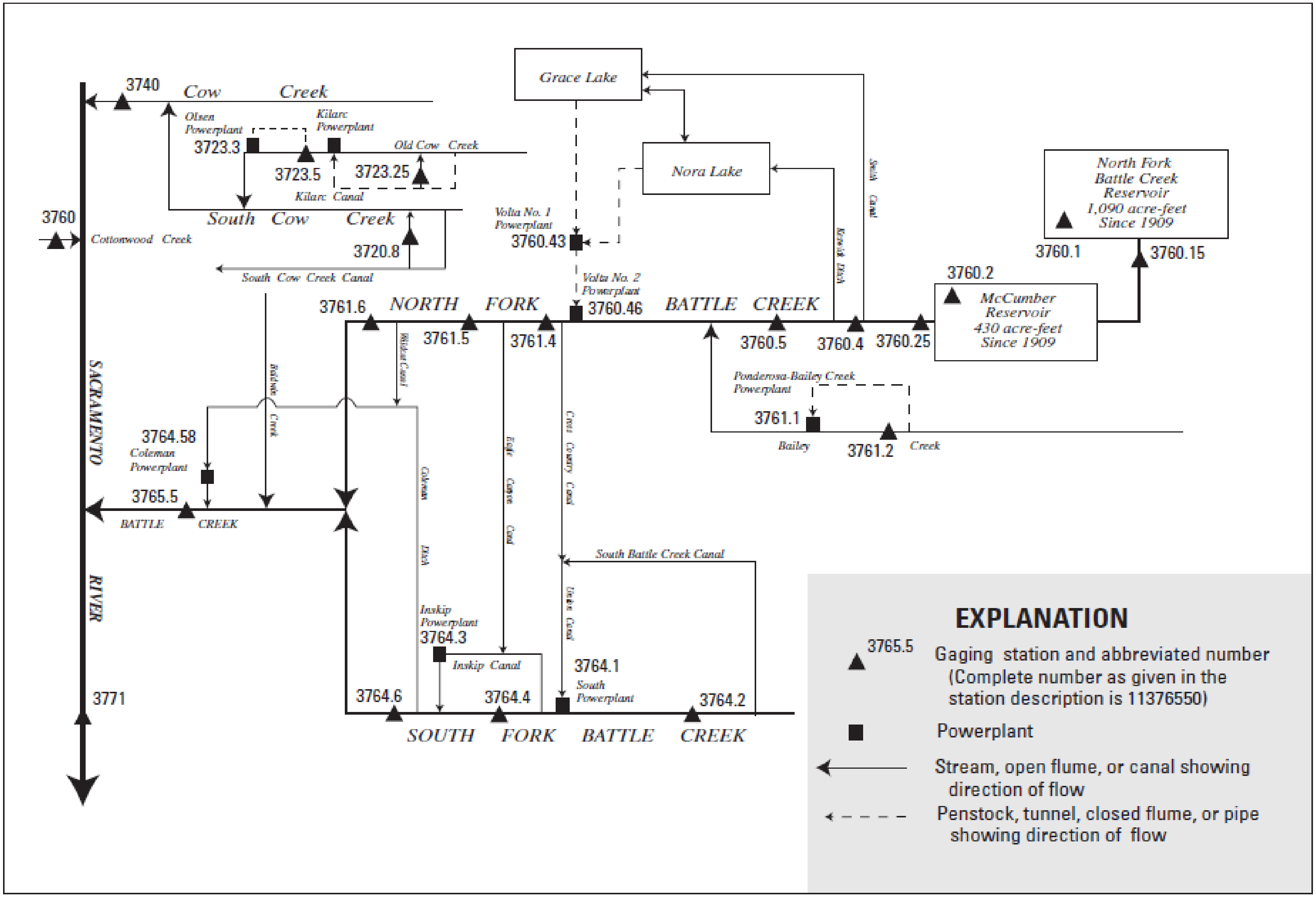
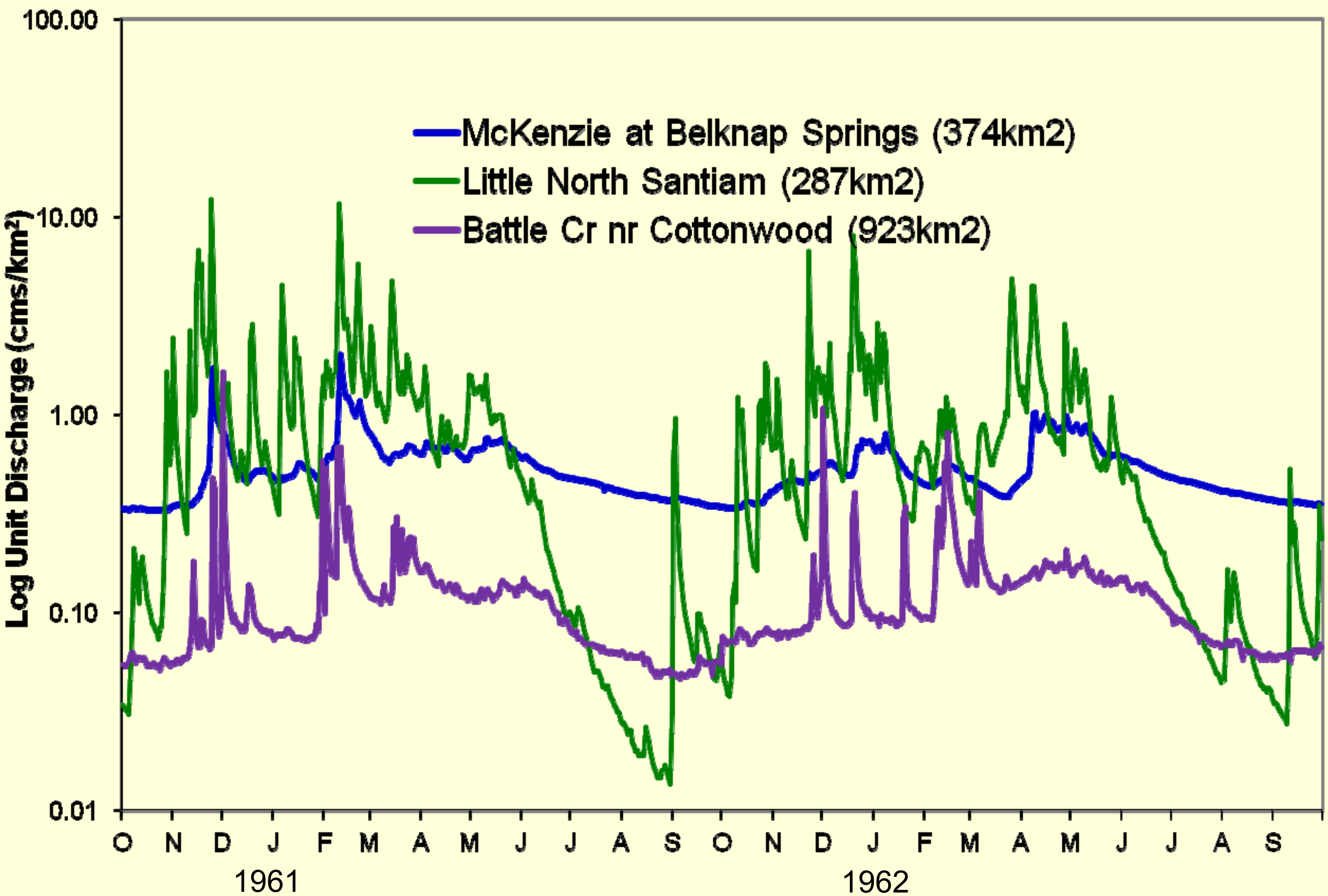
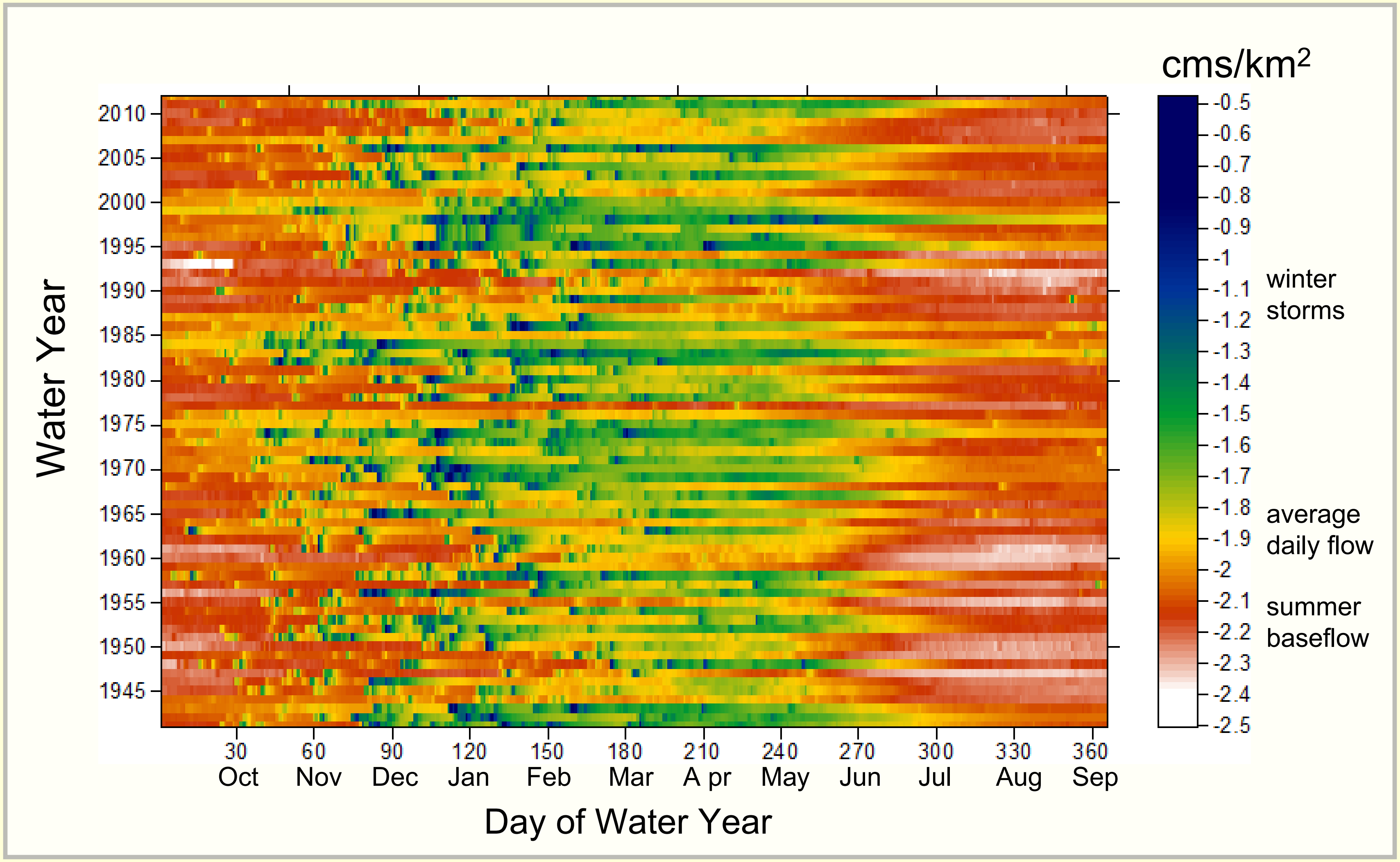


Figure showing diversions and storage in Battle Creek and Cow Creek Basins.


McKenzie at Belknap Springs (374km2)
Little North Santiam (287km2)
Battle Cr nr Cottonwood (923km2)
Log Unit Discharge (cms/km²)
100.00
10.00
1.00
0.10
0.01
O N D J F M A M J J A S O N D J F M A M J J A S
1961
1962

Daily discharge (log unit m^3/s) for Battle Creek

1942-1961 (#11376500) 1962-2011(#11376550)



Some thoughts on hydrologic response to vegetation manipulation (i.e., harvest) in young volcanic terranes with deep groundwater systems

Harvest effects on peak flows

- No paired watershed experiments to draw on
- From first principles, effect of harvest on peak flows should be LESS than in shallow subsurface flow systems
  - Lower drainage density
  - Longer response times
  - More bypass recharge

Grant et al, 2008; PNWGTR-760

Hydrologic effects of forest management activities in a young volcanic setting

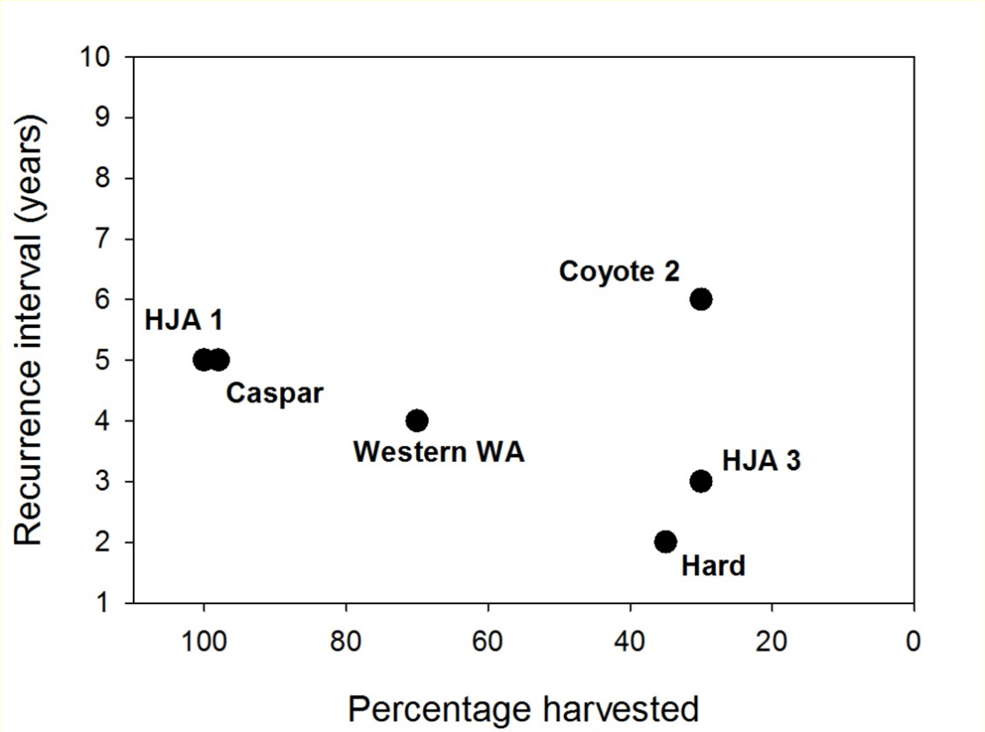
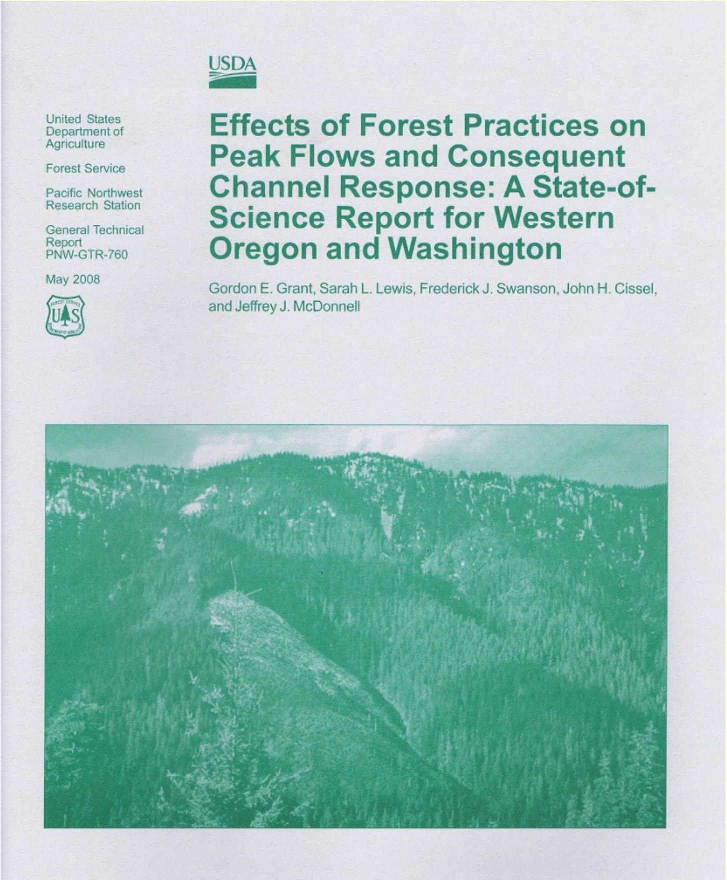


Figure 7 - Maximum recurrence interval at the detection limit as a function of the percent harvested.



Grant et al, 2008; PNWGTR-760

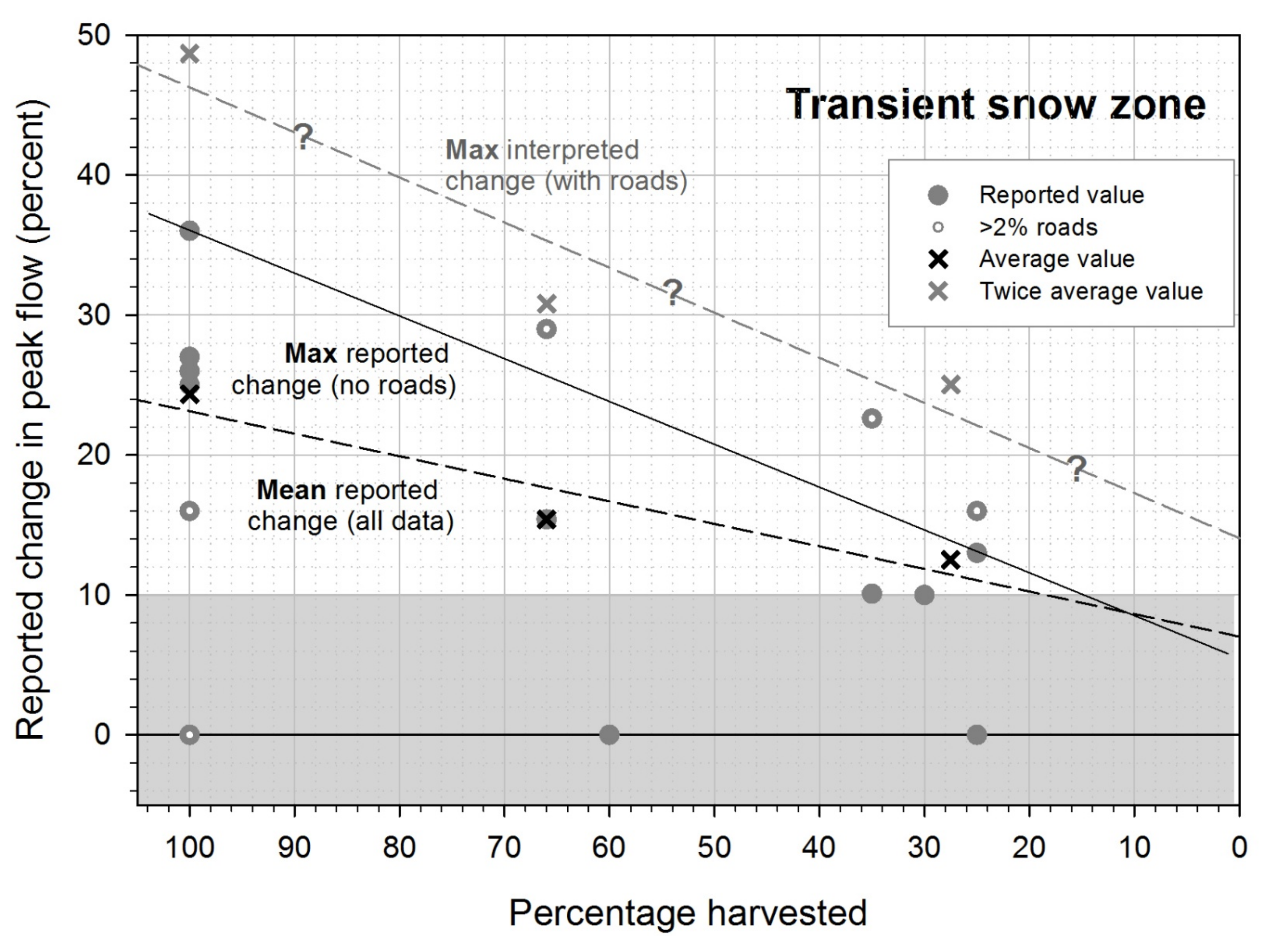


Figure 10 - Peak flow response to harvest in the transient snow hydrologic zone.
Solid line represents maximum values reported for basins without roads. Dashed line is a linear fit through the average values from figure 8d, and represents the mean reported change for all data. Dashed gray line represents interpreted change with roads, and is a linear fit through a doubling of the average values. Gray shading around zero indicates limit of detection (±10 percent).

Grant et al, 2008; PNWGTR-760

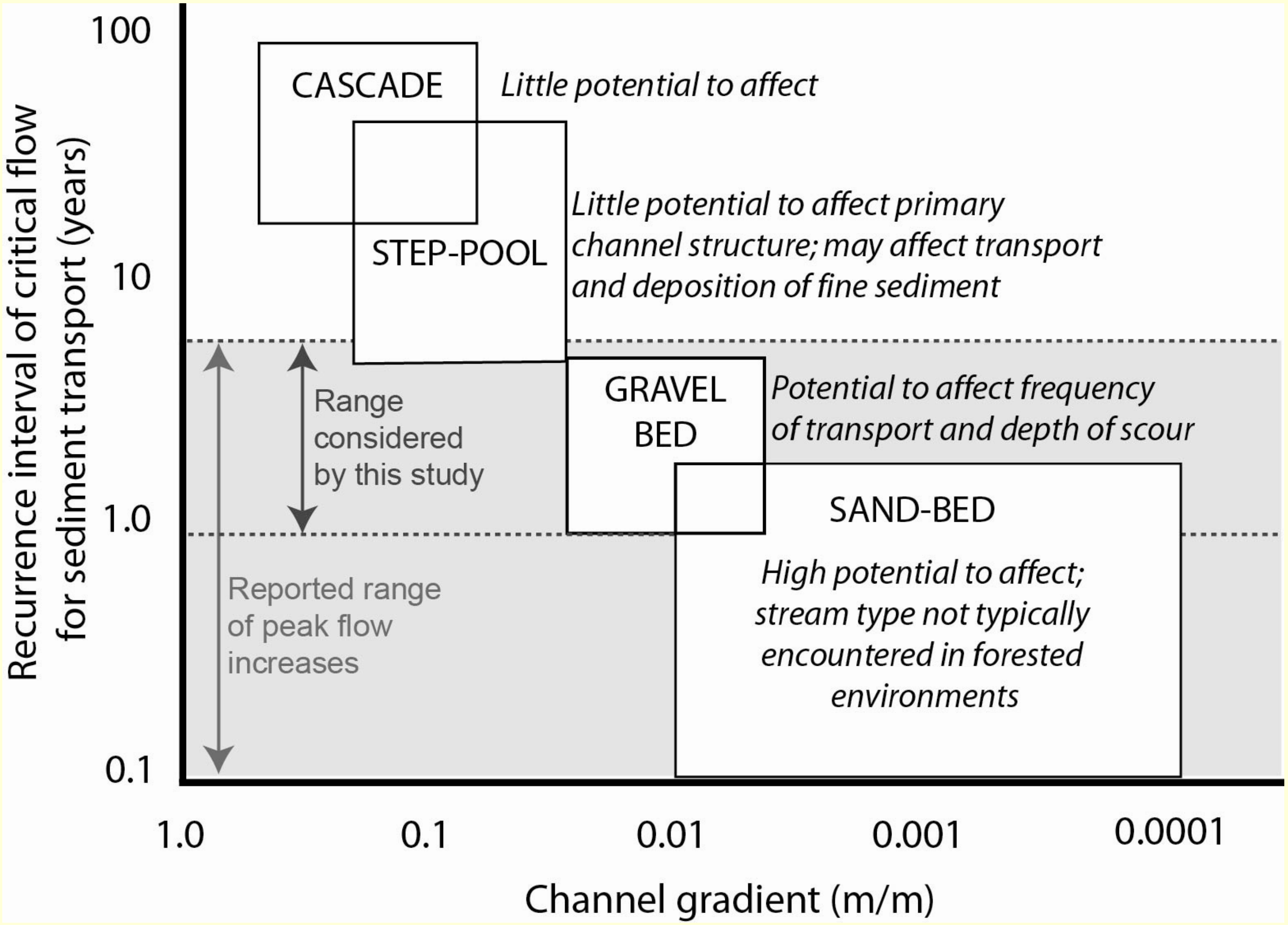


Figure 13 - Domains for initiation of bedload sediment transport as a function of channel type (Grant et al., 1990; Montgomery and Buffington, 1997) and recurrence interval (Pickup and Warner, 1976; Andrews, 1984; Grant et al., 1990; Wohl, 2000; Topping et al., 2000a,b).

Harvest effects on low flows

- No paired watershed studies
- On one hand, greater bypass recharge means less opportunity for vegetation effect
- On the other hand, system has longer “memory”, so may see effects of vegetation removal (increased low flows)
- Confounding effect of climate change?

Battle Creek turbidity

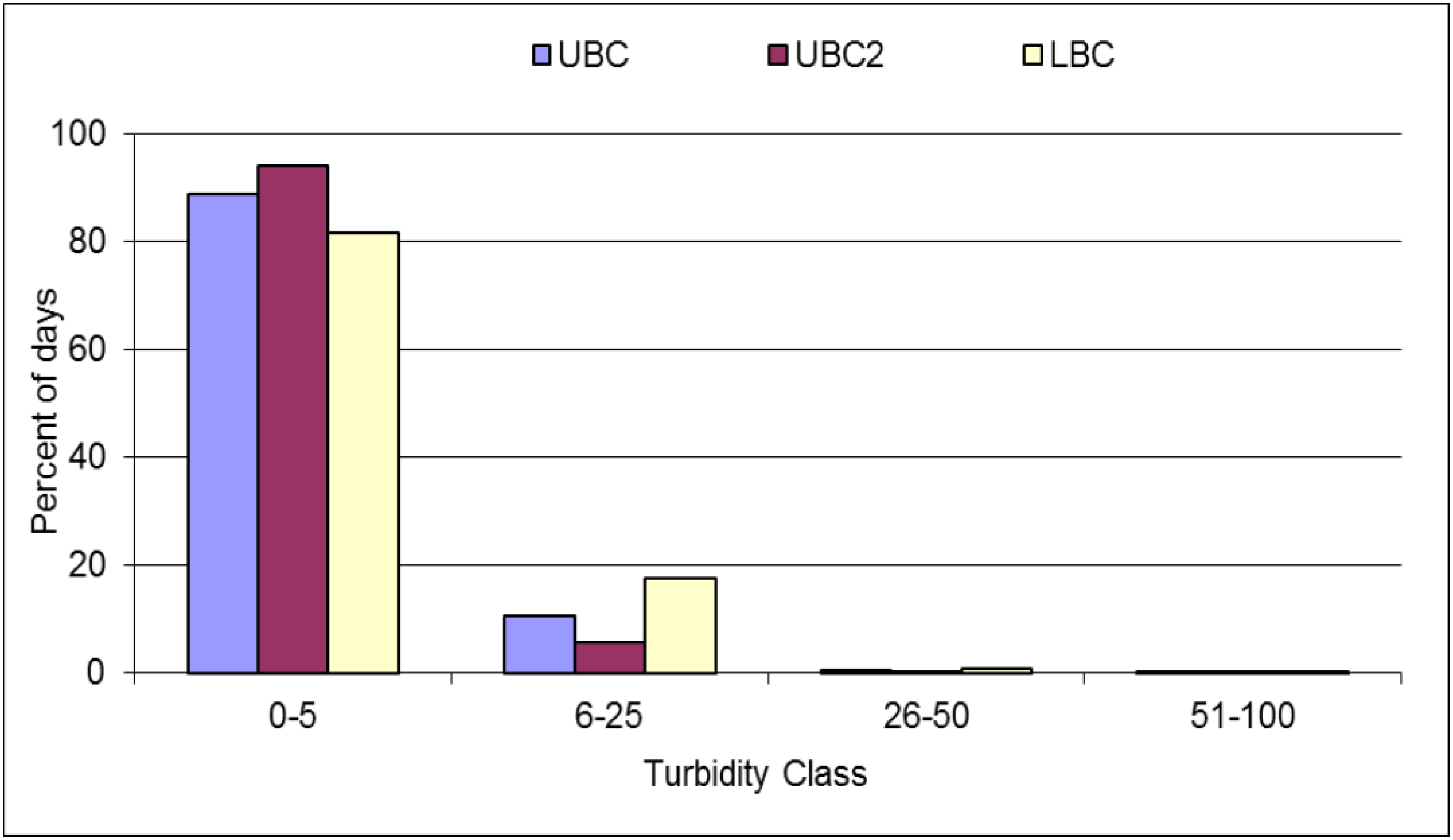
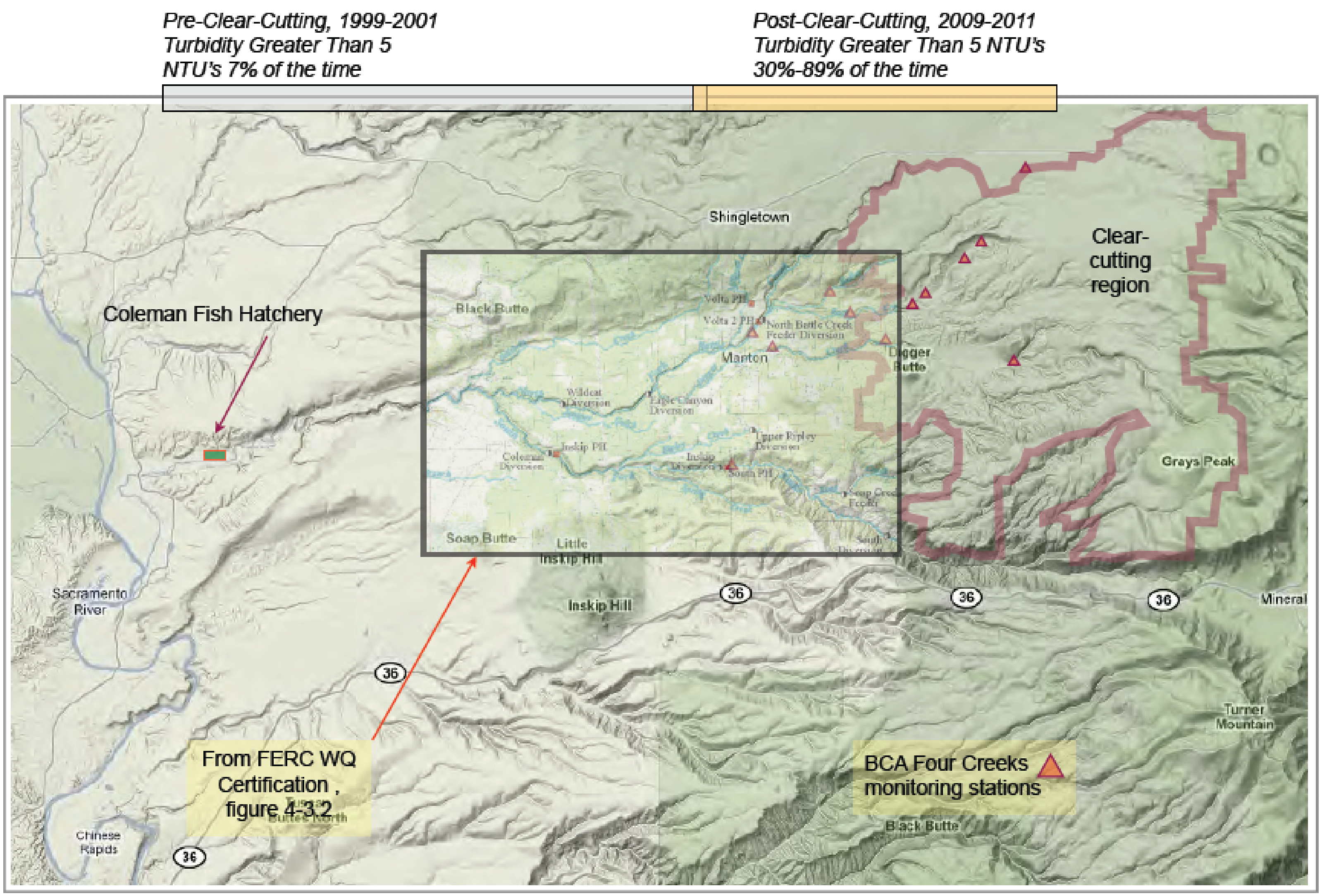


Figure 3. Frequency distribution of the mean daily turbidities by turbidity classes for the three long-term monitoring stations on Bailey Creek.

Battle Creek turbidity

Figure 2



Battle Creek turbidity

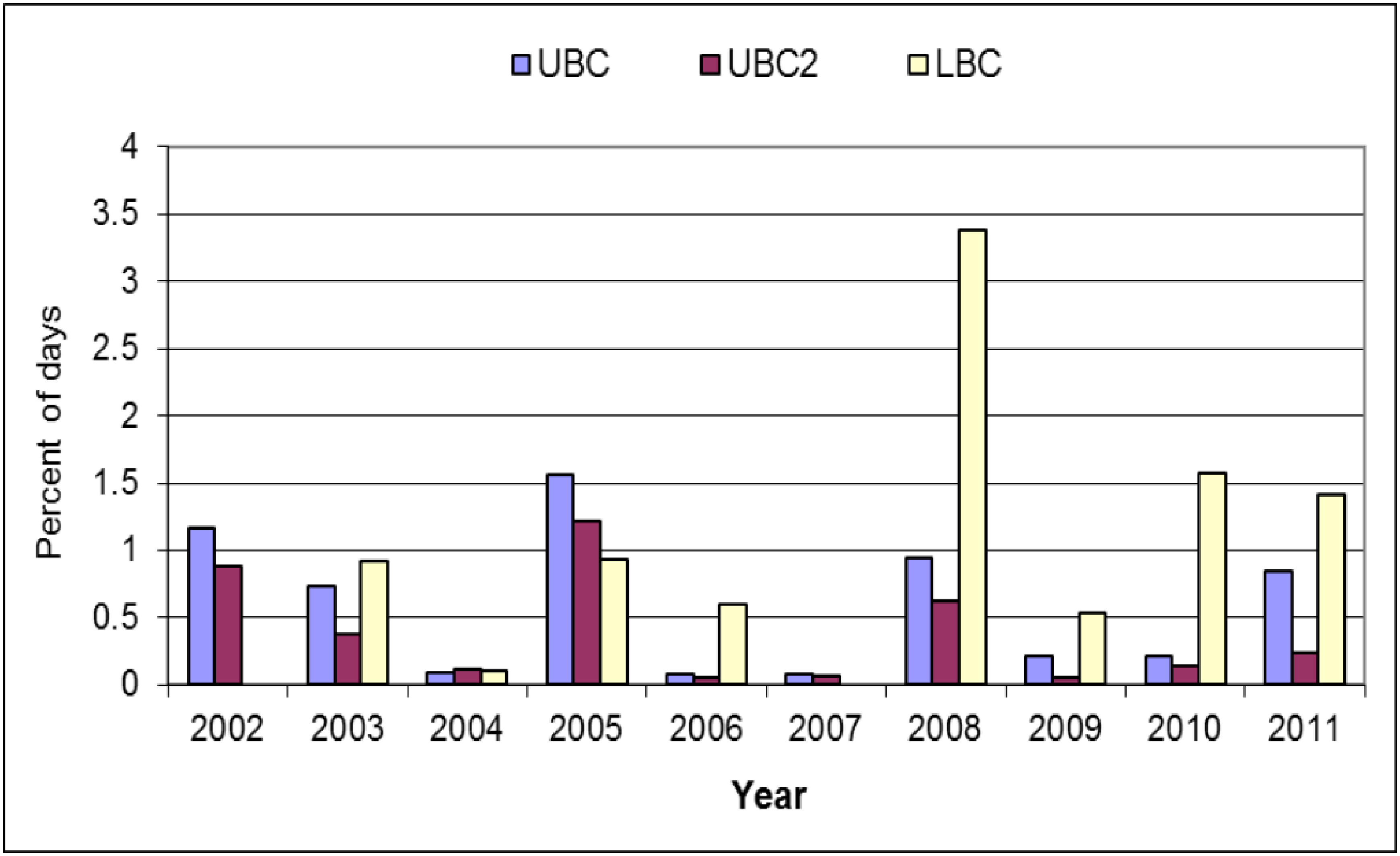


Figure 9. Percent of days with a mean turbidity ≥25 NTU by year for Upper Bailey Creek, Upper Bailey Creek 2, and Lower Bailey Creek.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