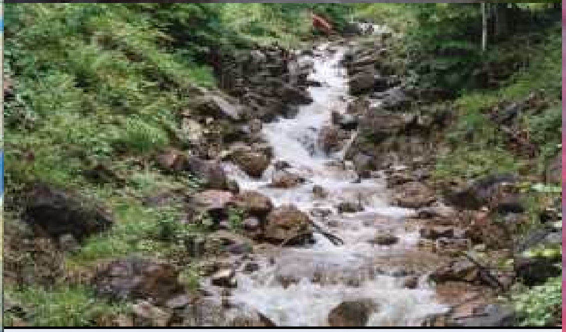
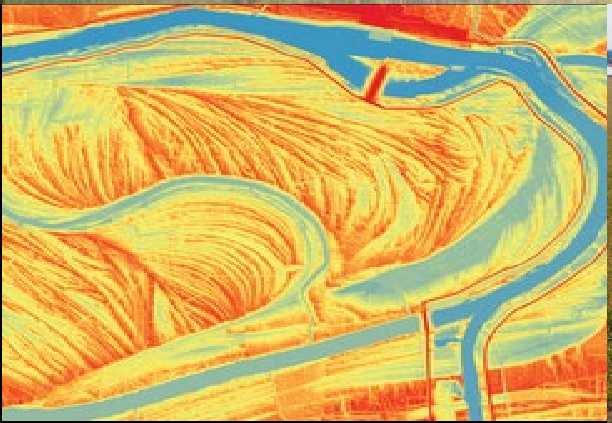
Watershed Hydrology & Sediment Dynamics

Sediment Transport in Stream Assessment and Design
Monday, July 29, 2024
Patrick Belmont

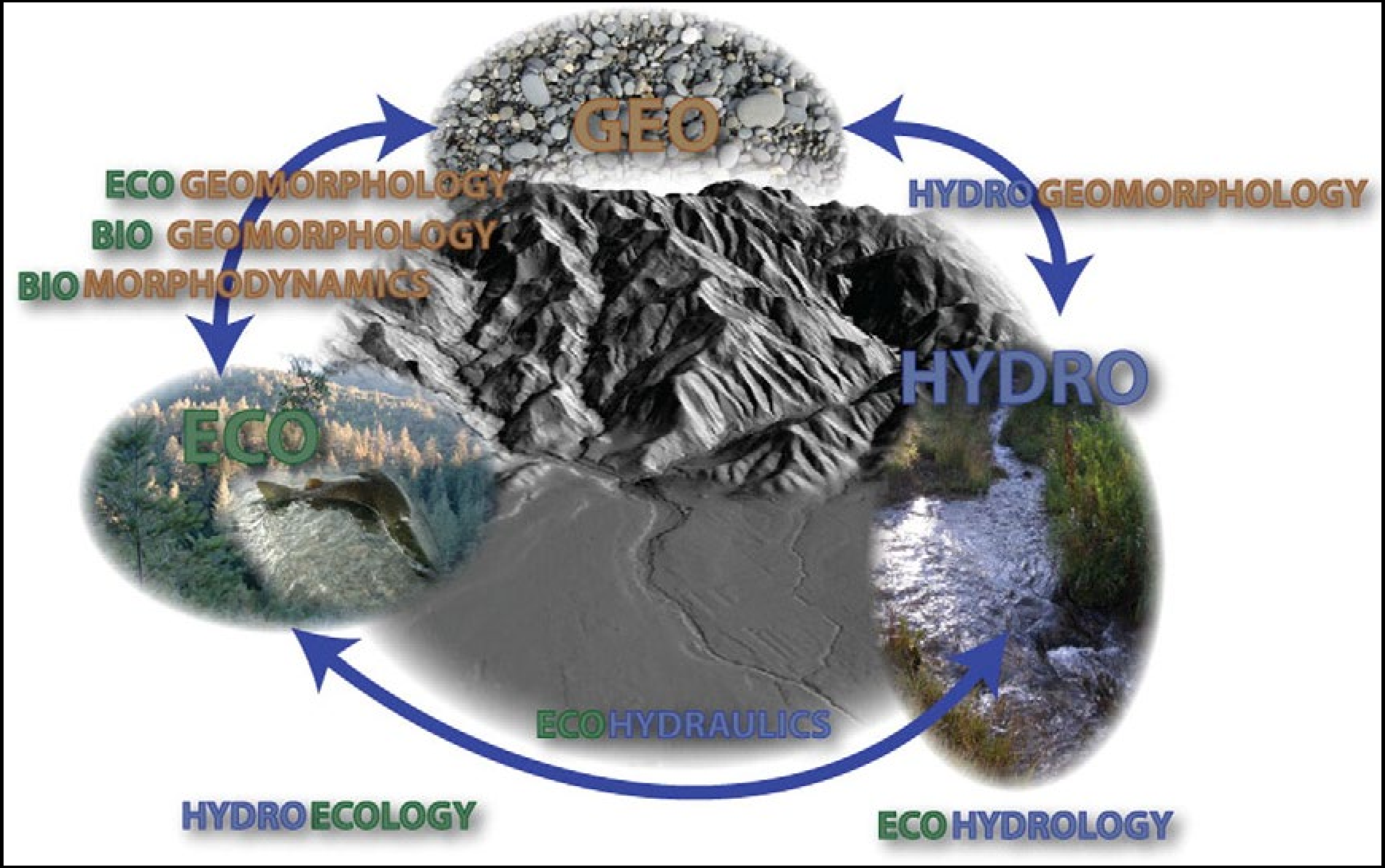
"It is hard to imagine that a transport estimate made in the absence of a sound understanding of watershed history and dynamics would be of much use at all."

Great diversity in channels and watersheds...





...emerging from complex interactions

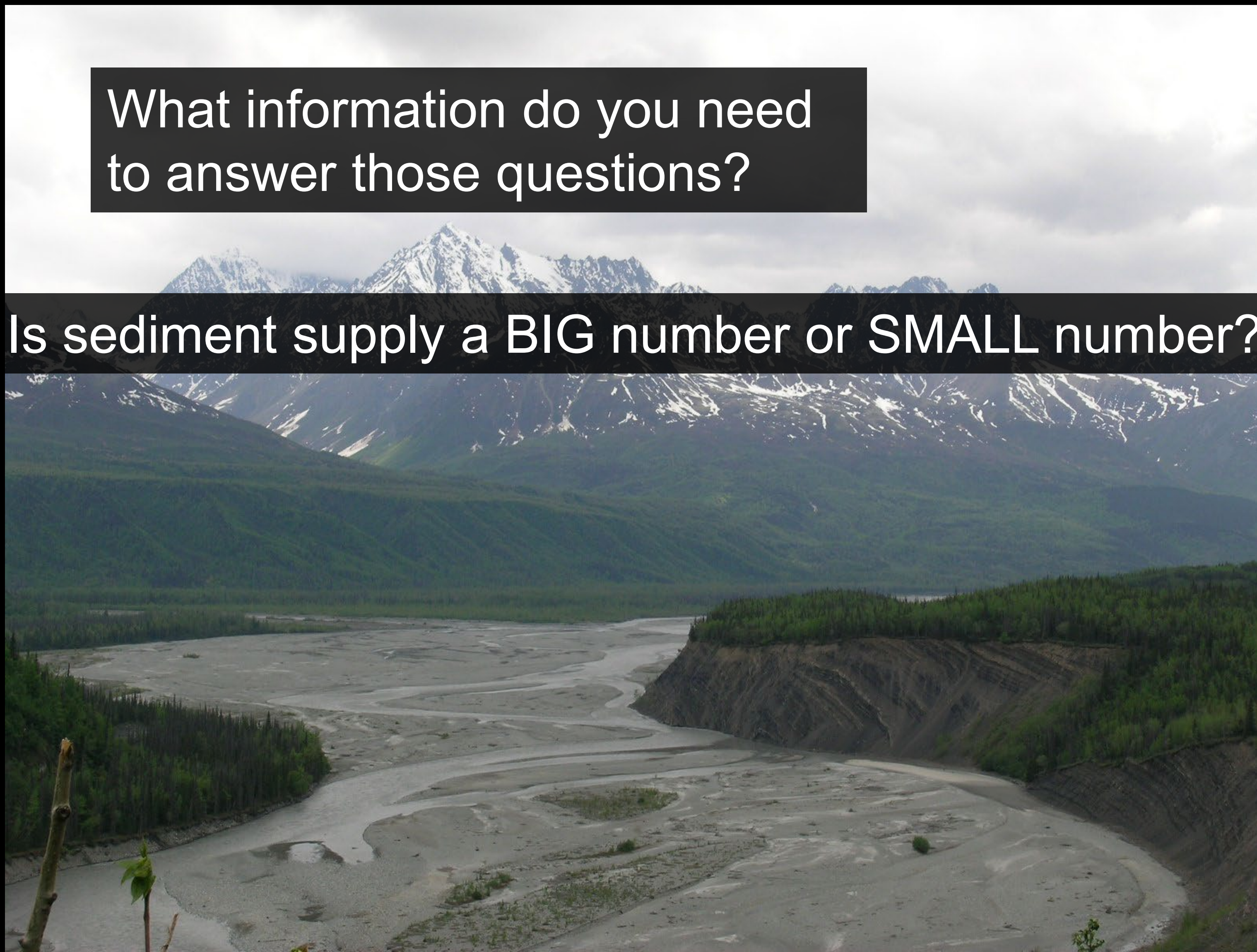


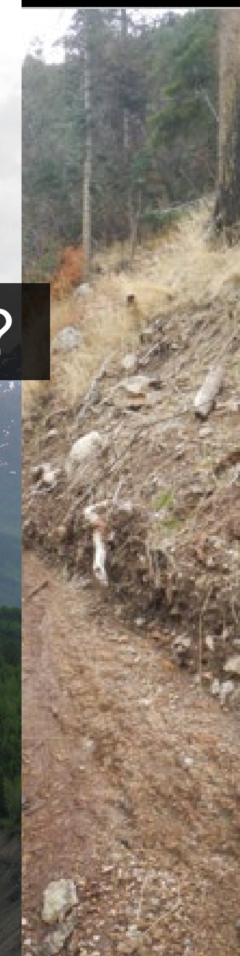
Wheaton et al., 2011

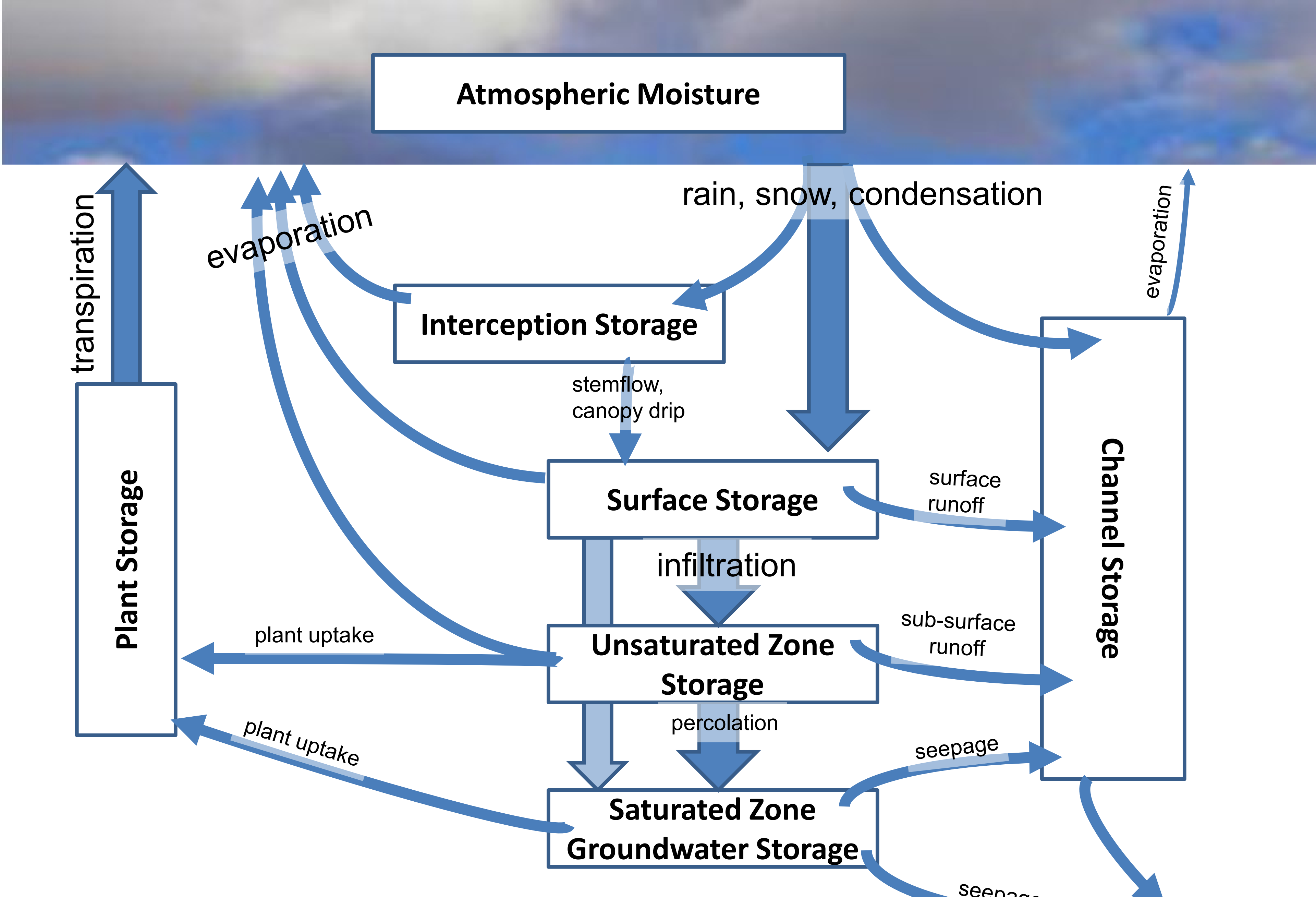
How *much* and what *type* of sediment is being delivered to this channel?

What information do you need to answer those questions?

Is sediment supply a BIG number or SMALL number?



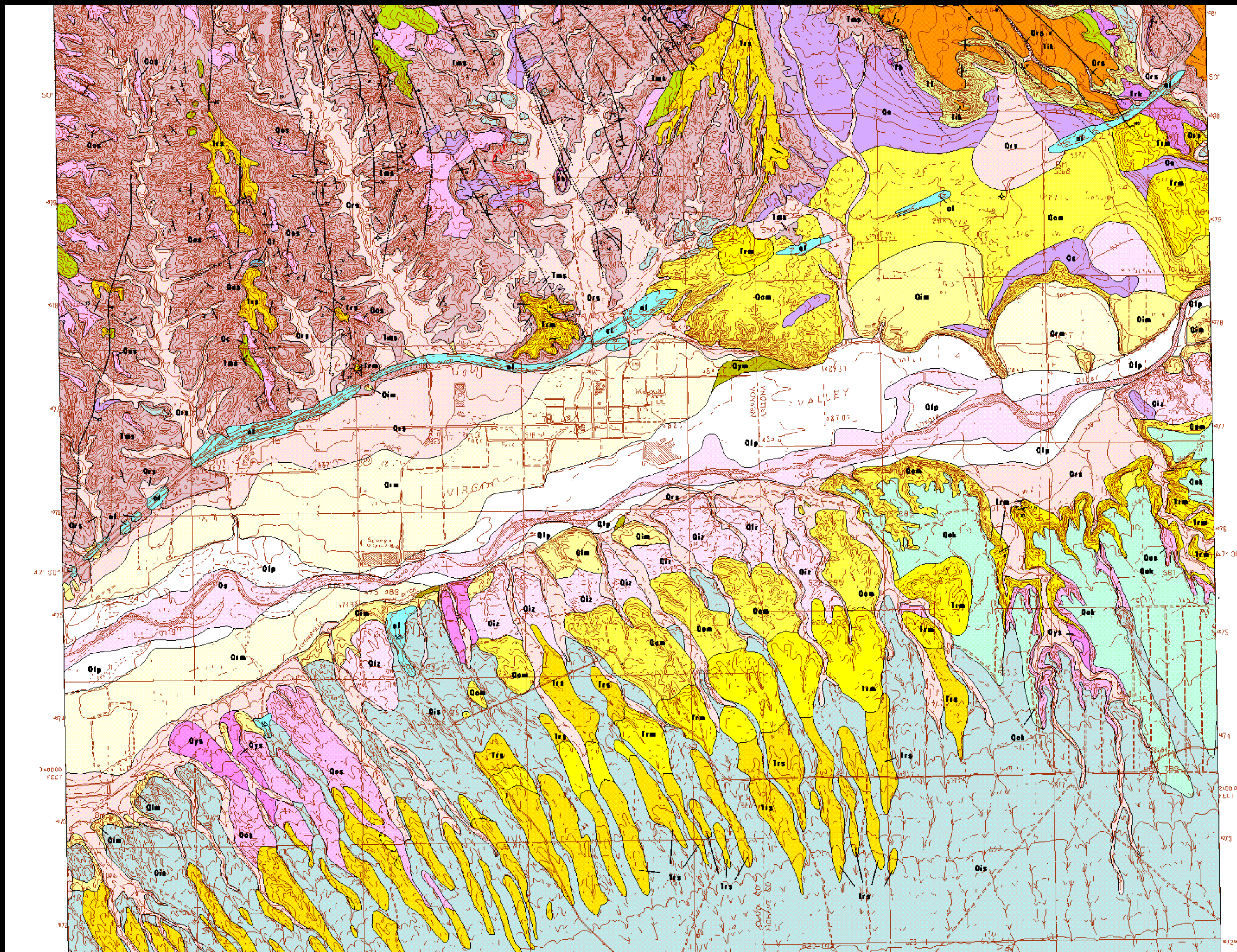




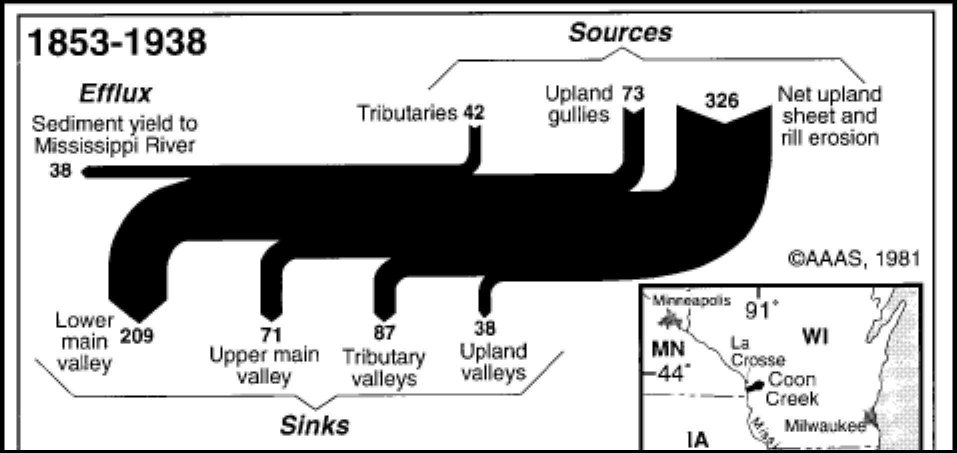
Hydrology matters...

Land use matters...

Soils, surficial and bedrock geology matter...



Storage matters...



Trimble, 1999

Natural and human-caused ‘legacy effects’

Sediment transport through watersheds is complicated

Grain size matters

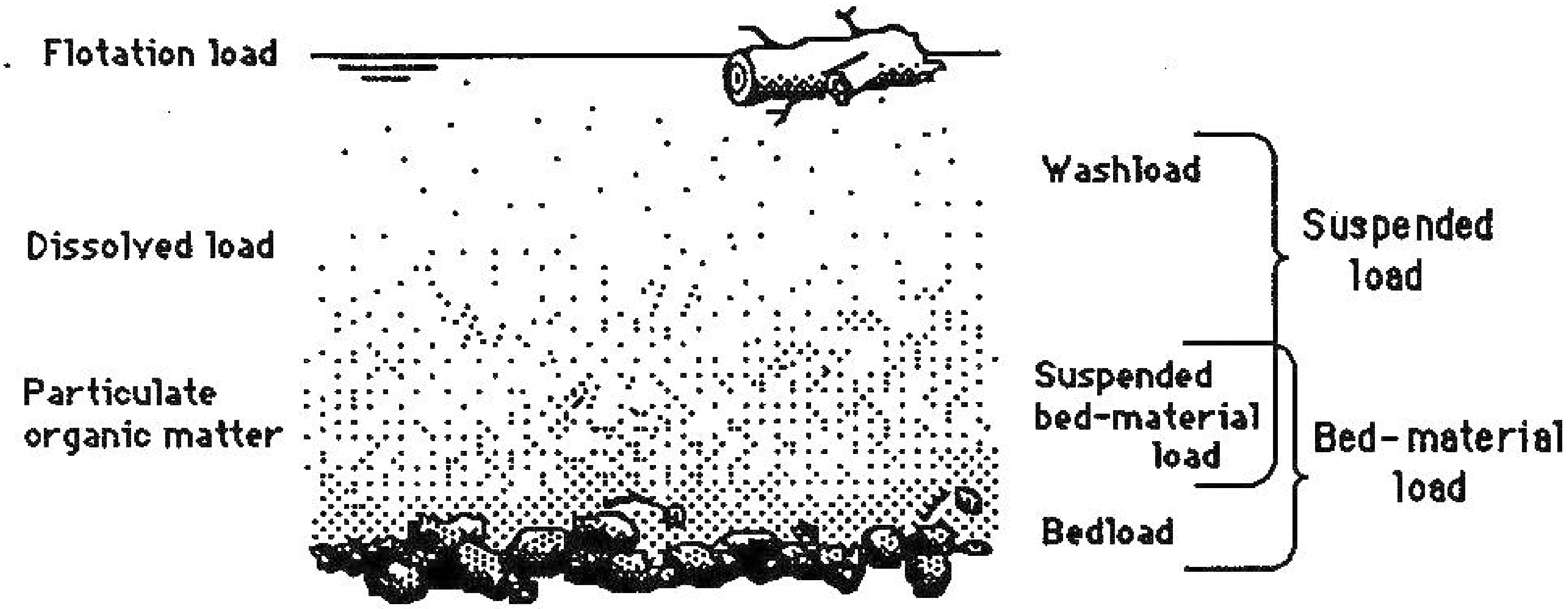
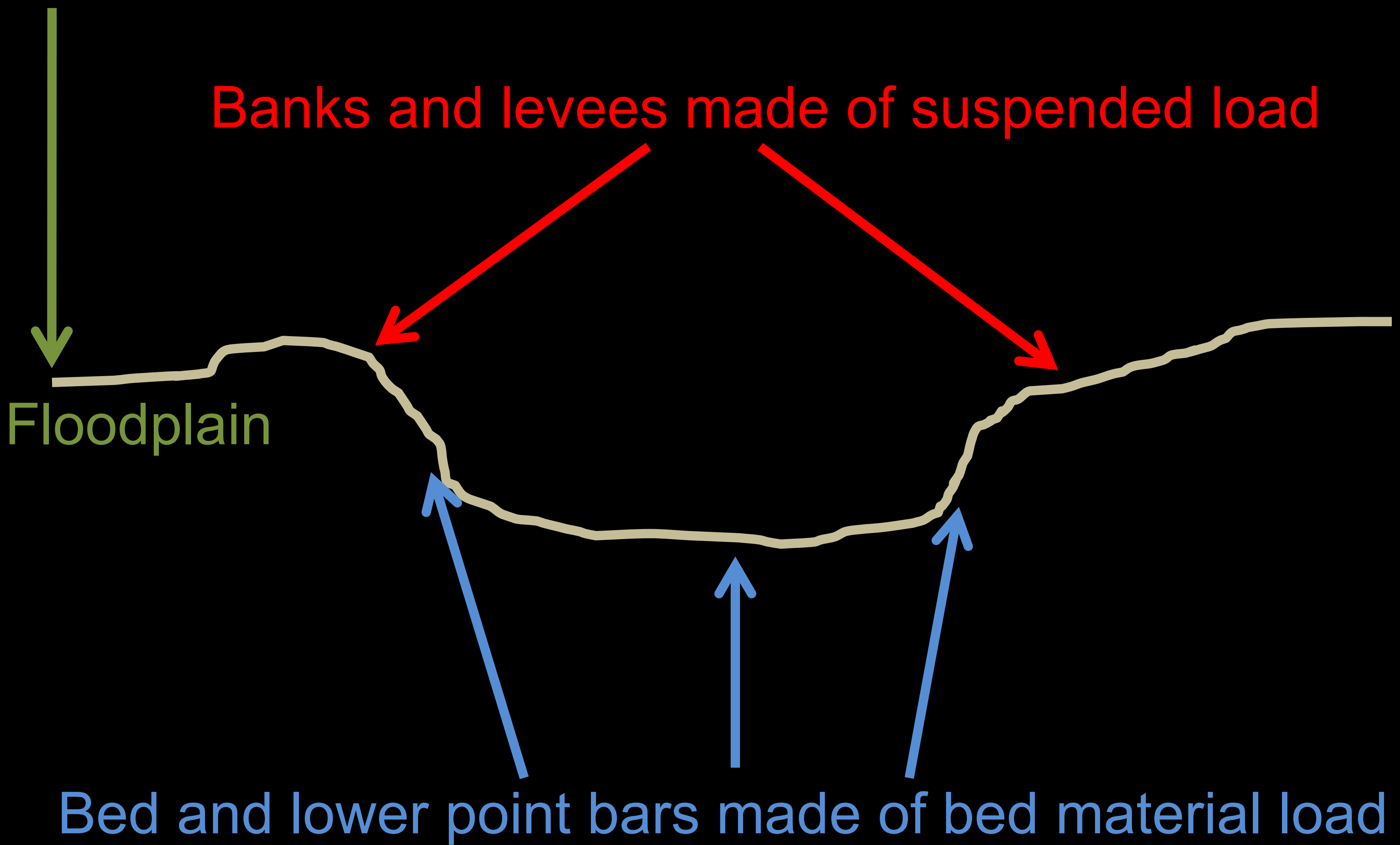


Figure 7.1. Categories of transported materials in a stream

Grain size matters...

Coarse and fine load often have different sources/transport paths

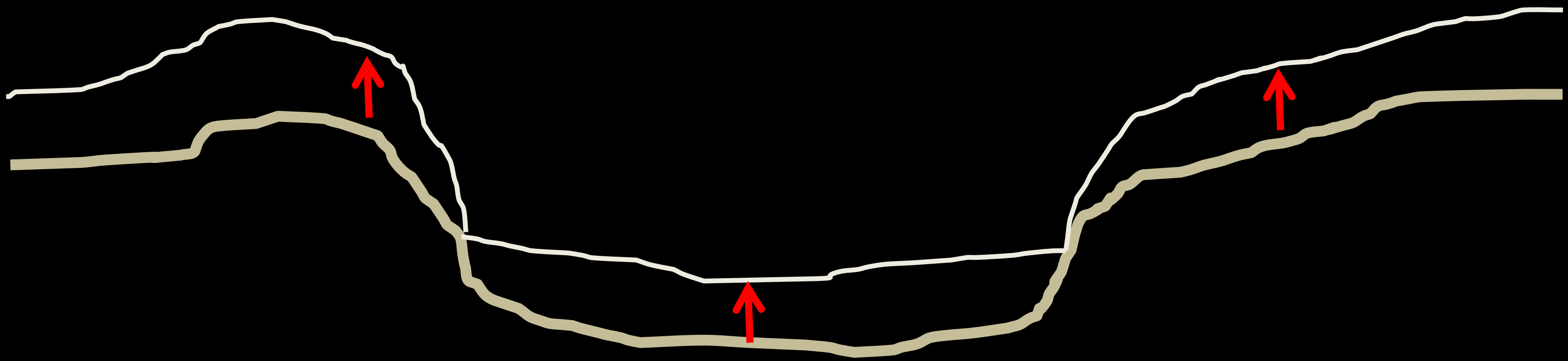
Floodplains preserve old channel deposits + overbank



Grain size matters...

Coarse and fine load often have different sources/transport paths

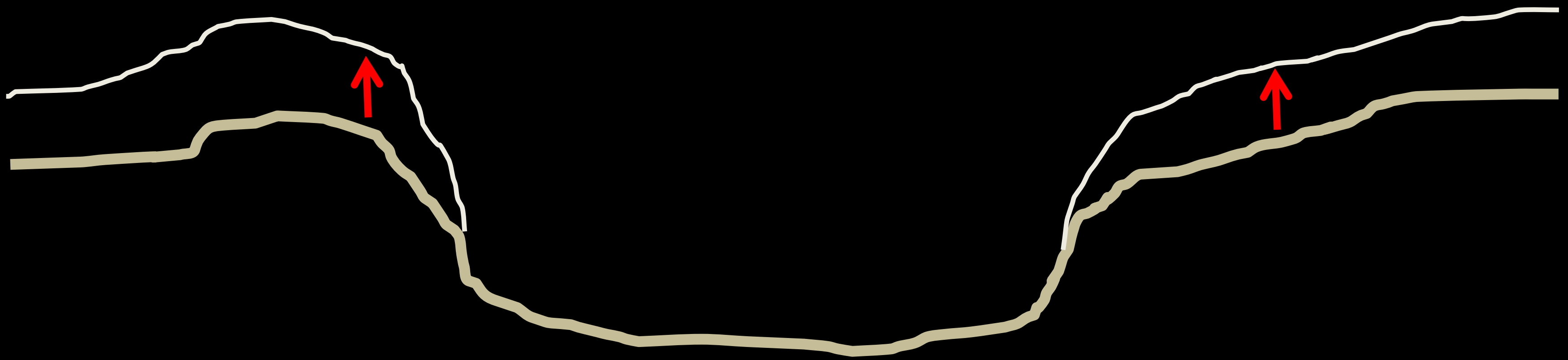
All else held constant,
aggradation on the bed causes…



Grain size matters...

Coarse and fine load often have different sources/transport paths

All else held constant,
aggradation on the floodplain…



So while the sources may be independent,
effects on channel morphology and hydraulics are linked

Big implications for habitat: Rachelly et al., 2020

How can we STOP erosion?

This is not always the right question to ask.

Bridge Creek, Oregon, Sarah Koenigsberg

The simple, key questions…

How much and what type of sediment is supplied?

How do flow and supply change over time and with distance downstream?

How many distinct ‘reaches’ are there along my stream?

In what ways might each reach adjust to changes in flow or sediment supply?

A few key messages up front…

In many cases, all that is needed/feasible is to know if supply is a big # or small #

Measuring channel behavior, morphology and bed characteristics will inform your understanding of supply and 'sensitivity'

Sometimes you need numbers, but good numbers don't come easy

- Spatial and temporal variability over wide range of scales, Interactions of many non-linear processes
- Develop conceptual model of reach types, sources, sinks, connectivity… …then measure/model key rates
- Multiple independent and semi-redundant estimates often needed

May need to know locations, mechanisms, and rates of erosion and deposition

- Size matters…boulders, cobbles, gravel, sand, mud play distinct roles
- Models can be useful and/or misleading
- Examine and consider implications of hydrologic non-stationarity
- Many new tools available, none are comprehensive or bullet-proof

Insightful books for watershed analysis and stream restoration

Kemper et al., 2023: channel change in

Roadmap

TODAY

Forget rates. What can we learn from basic form-process relationships?

Channel form/dynamics. (Dis)Continuity. Hydro-geomorphic Assessments.

Basic Reconnaissance

With a tight budget, what do you really need to know?

TOMMORROW

Case studies in sediment supply, transport, and morphodynamics

Hydrologic analysis and non-stationarity

Targeted modeling and metrics. Stationarity Assumption?

Push-button Geomorphology

The geek approach. What computer models can and can't tell you.

Basin-average erosion rates: The cosmo method

Millennial-scale landscape rates of erosion.

Reservoir and pond sedimentation rates

Time- and space-integrated measurements that may be useful.

Watershed Sediment Budget

Tools and techniques for robust constraints on sources and sinks.

How would you describe these channels?

Stages of a Watershed Assessment

Stage 1 Data Compilation (description and mapping)

- Evaluate watershed context
- Determine landscape units
- Assess river character

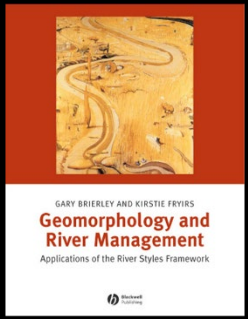
Stage 2 Data Analysis

- Define and interpret River Styles
- Explain contemporary character/behavior
- Assess river history

Stage 3 Predict future river structure

Stage 4 Prioritize watershed management issues

Stage 5 Identify target conditions for river



River Styles Hierarchy

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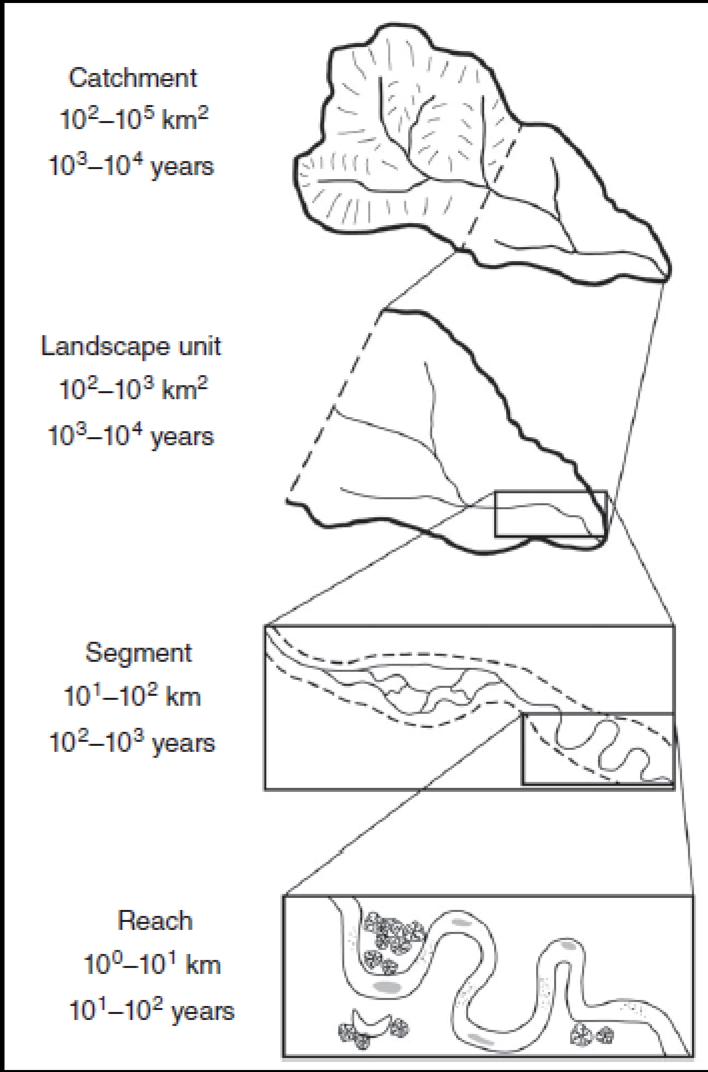
Microhabitat	Individual elements (e.g., logs, rocks, gravel patches) within a stream.

Many other classification schemes out there

TABLE 1 | Temporal Change Is Investigated at Different Spatial Scales

Spatial Scale	Characteristics
Catchment	Land cover/land use (LCLU)
	Land topography
Landscape unit	LCLU and sediment production
	Land topography and sediment production
	Rainfall and groundwater
Segment	Valley setting
	Channel gradient
	River flows and levels
	Sediment delivery
	Riparian corridor and wood production
Reach	Channel planform, migration, and features
	Channel geometry
	Sediment transport
	Riparian vegetation, aquatic vegetation, wood

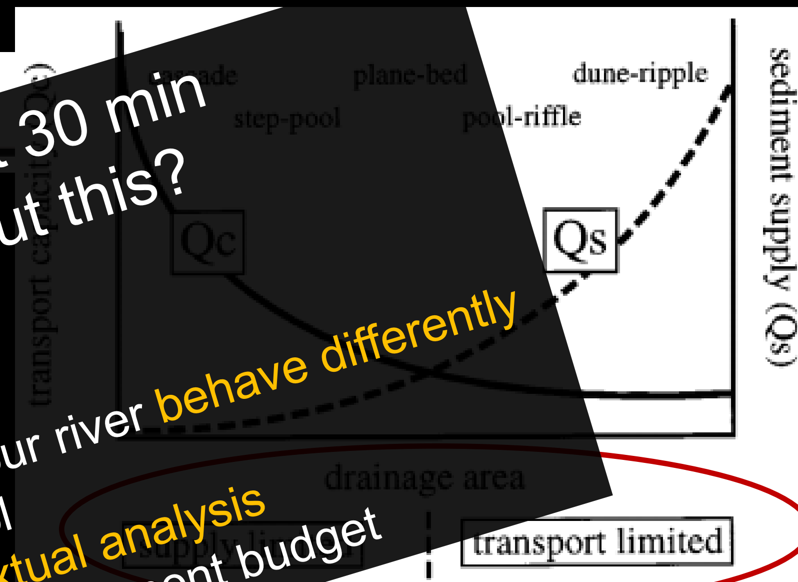
Grabowski et al. 2014



Many other classification schemes out there

Channel-reach morphology in mountain drainage basins

Montgomery and Buffington, 1997



Why are we going to spend the next 30 min
+ most of the afternoon talking about this?

This is the first step in:
- Understanding why **different parts** of your river **behave differently**
- Designing a **rapid assessment** protocol
- Determining what to pursue for **contextual analysis**
- Deciding **what/where to measure** for a sediment budget

TABLE 1. DIAGNOSTIC FEATURES OF EACH CHANNEL TYPE

	Dune ripple	Pool riffle	Plane bed	Step pool	Cascade	Bedrock	Colluvial
Typical bed material	Sand	Gr	Gravel, cobble	Cobble-boulder	Boulder	Rock	Variable
Bedform pattern	Multilayered	Lateral oscillatory	Featureless	Vertically oscillatory	Random	Irregular	Variable
Dominant roughness elements	Sinuosity, bedforms (dunes, ripples, bars), grains, banks	Bedforms (bars, pools), grains, sinuosity, banks	Grains, banks	Bedforms (steps, pools), grains, banks	Grains, banks	Boundaries (bed and banks)	Grains
Dominant sediment sources	Fluvial, bank failure	Fluvial, bank failure	Fluvial, bank failure, debris flows	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Hillslope, debris flows
Sediment storage elements	Overbank, bedforms	Overbank, bedforms	Overbank	Bedforms	Lee and stoss sides of flow obstructions	Pockets	Bed
Typical confinement	Unconfined	Unconfined	Variable	Confined	Confined	Confined	Confined
Typical pool spacing (channel widths)	5 to 7	5 to 7	None	1 to 4	<1	Variable	Unknown

Rapid Assessment vs Contextual Analysis

Rapid Assessments:

- Aim to be repeatable, quantitative, and representative
- Limited ability to discern cause of problems in complex systems
- Often require frequent sampling, large number of sites

Contextual Analysis:

- Aim to attain comprehensive, holistic understanding of the system
- Often difficult to quantify components
- Can guide assessments, monitoring, measurements for sed budget

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CAN RAPID ASSESSMENT PROTOCOLS BE USED TO JUDGE SEDIMENT IMPAIRMENT IN GRAVEL-BED STREAMS? A COMMENTARY[1]

Thomas E. Lisle, John M. Buffington, Peter R. Wilcock, and Kristin Bunte[2]

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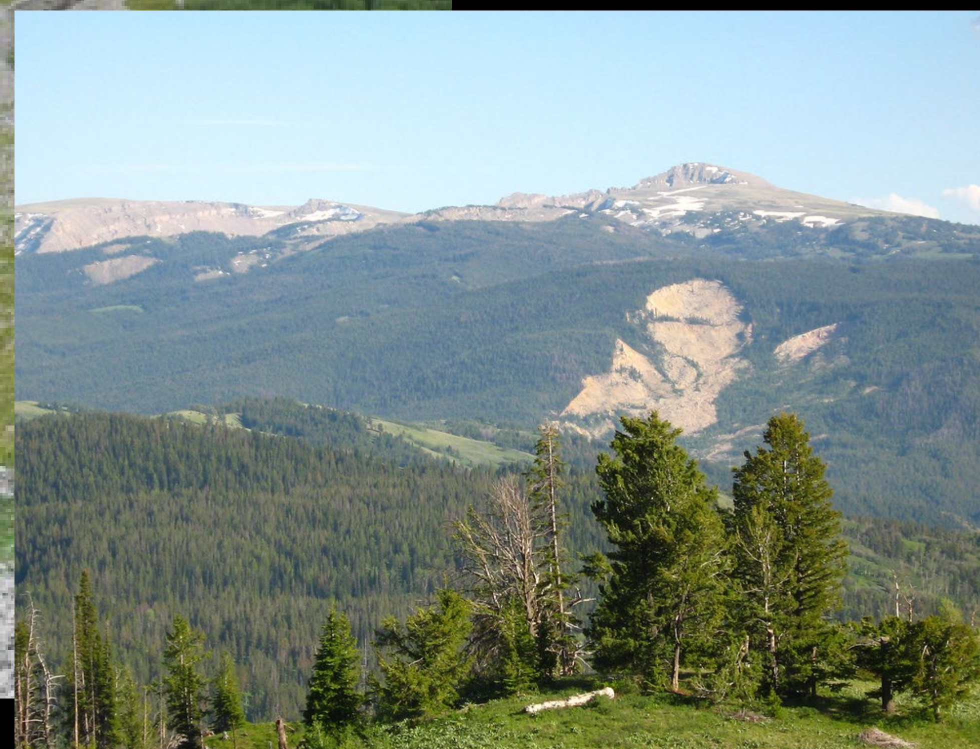
What are the different parts of the watershed?

Which detachment, transport, deposition processes are occurring where?

Quiescent

Rills and gullies

Debris flows



Landslides

How well connected is the system?

Where are complete or partial barriers?
How has/might connectivity change?

see Fryirs et al., 2007

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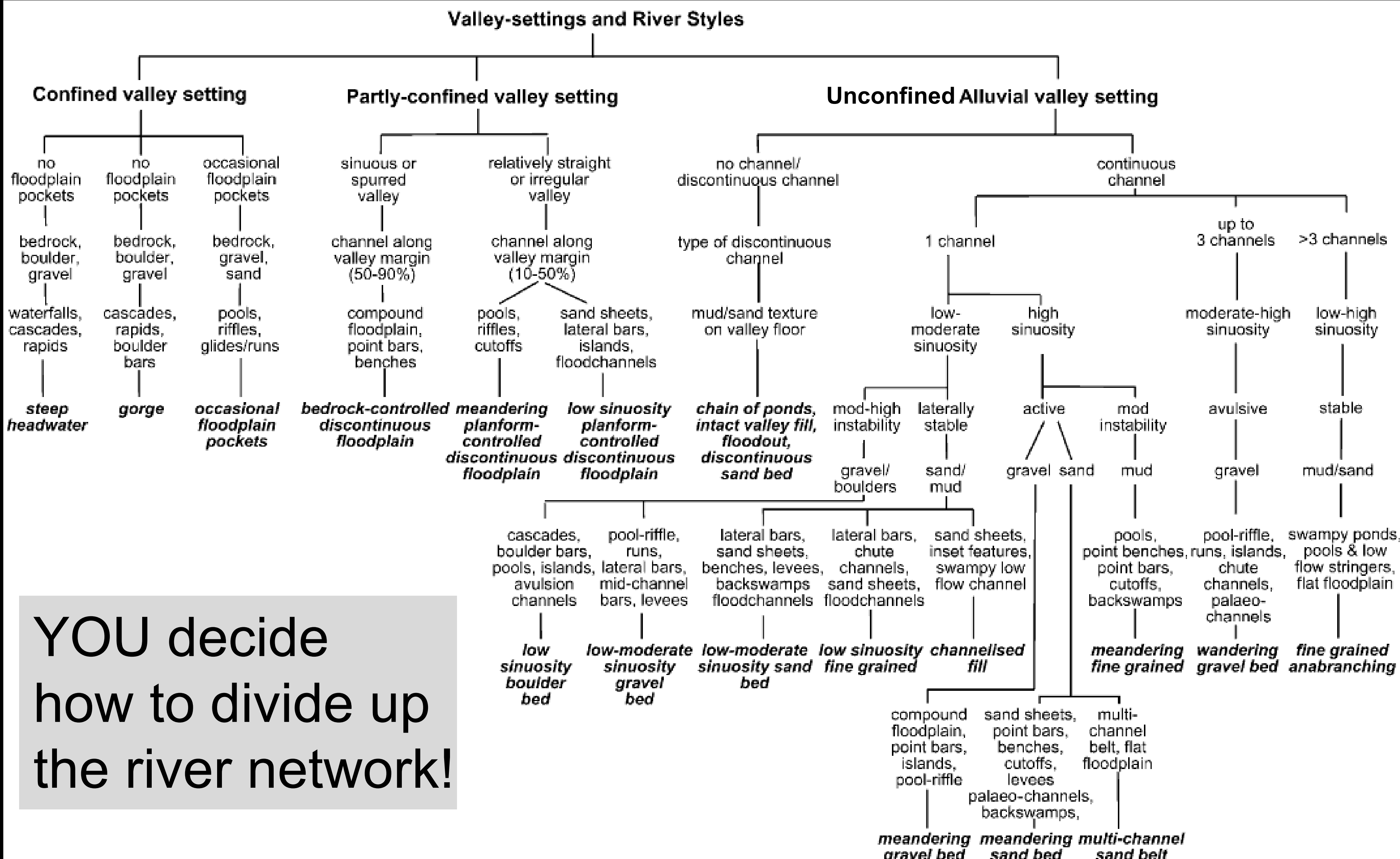
What are the different parts of the river network?

River Styles™ tree developed for NSW, Australia



YOU decide how to divide up the river network!

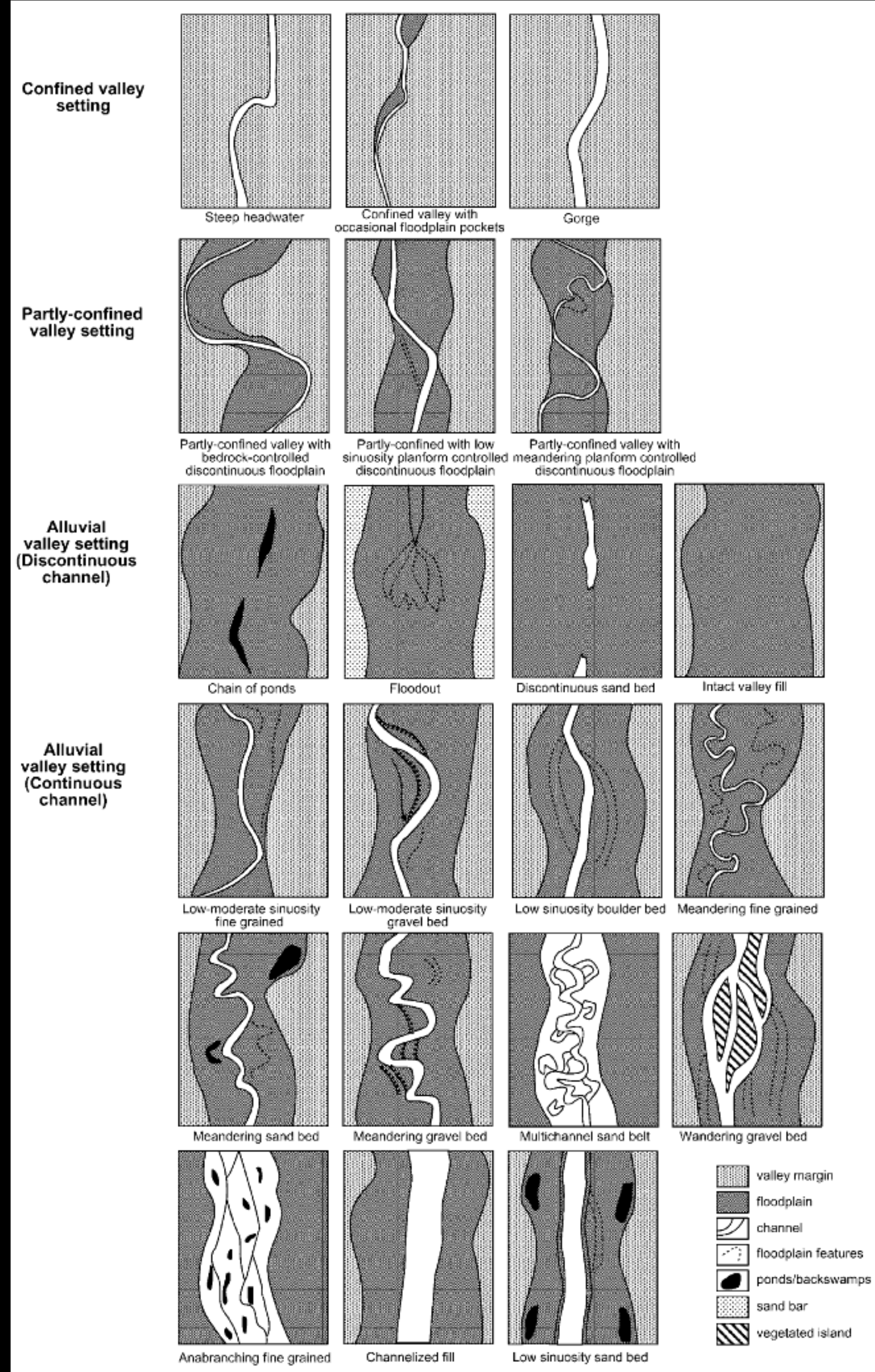
Brierley et al., 2002

Visual representation of NSW River Styles

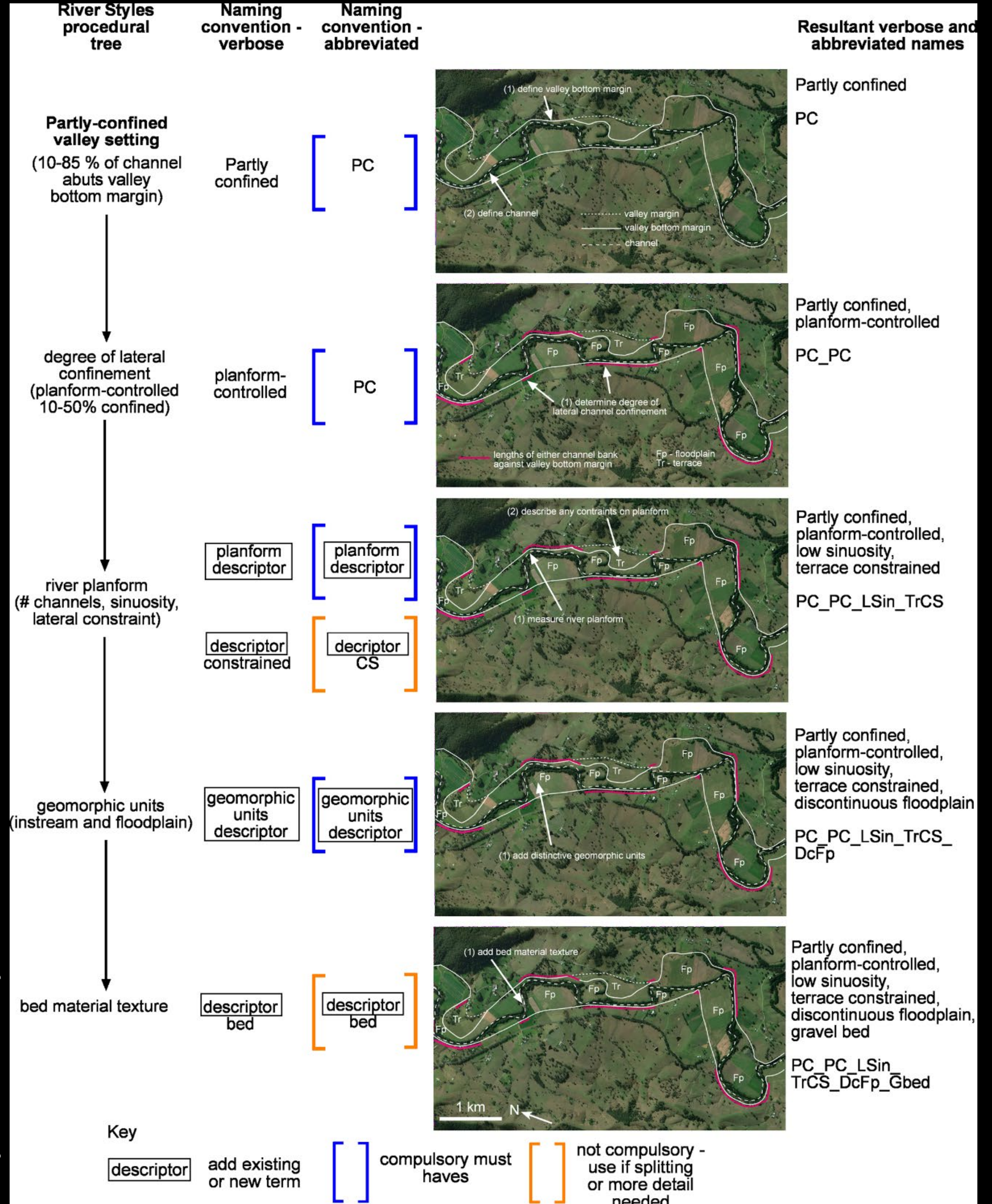
Which river styles are you working on?

These are each different
'process domains'

Different ecological functions
hydro-geomorphic processes
sensitivities to change
potential for recovery



What’s in a name?



Fryirs and Brierley, 2018

A common taxonomy for describing rivers

TYPES OF MARGIN CONTROL OR CONSTRAINTS		**PLANFORM TYPES**	
Bedrock	Br	Headwater	Hw
Terrace	Tr	Gorge	Gge
Fan	Fn	Canyon	Cyn
Dune	Dn	Braided	Braid
TYPES OF ANTHROPOGENIC MARGIN		Meandering	Meand
Stopbank	SBk	Wandering	Wan
Constructed levee	CoLv	Low sinuosity	LSin
Embankment	EBk	Anastomosing	Anast
Bank revetment	BkRe	Anabranching	Anbr
Railroad	RaRd	Chain of ponds	CoP
Road	Rd	Valley fill	VFi
Pipe	Pip	Swamp	Swp
Concrete	Crt	Floodout	Fout
Earth	Ea	Canal	Cnl
INSTREAM GEOMORPHIC UNITS			
Sculpted, erosional geomorphic units		**Mid-channel geomorphic units**	
Bedrock step (waterfall)	BrSt	Alluvial riffle	ARi
Step-pool	SPo	Alluvial pool	APo
Cascade	Cc	Longitudinal bar (medial bar)	LoBa
Rapid	Rp	Transverse bar (linguoid bar)	TBa
Run (glide, plane-bed)	Ru	Diagonal bar (diamond bar)	DBa
Forced riffle	FoRi	Expansion bar	EBa
Forced pool	FoPo	Island	Isl
Plunge pool	PPo	Boulder mound	BMd
Pot hole	PHo	Bedrock core bar	BrCBa
Bank-attached geomorphic units		Sand sheet	SSh
Lateral bar (alternate or side bar)	LaBa	Gravel sheet	GSh
Scroll bar	ScBa	Forced mid-channel bar (pendant bar, wake bar, lee bar)	FMcBa
Point bar	PtBa	Compound mid-channel bar	CMcBa
Tributary confluence bar (channel junction bar, eddy bar)	TCBa	Alluvial riffle	ARi
Ridge	Ri	Alluvial pool	APo
Chute channel	CCh	Longitudinal bar (medial bar)	LoBa
Ramp (chute channel fill)	Rp	**Fine-grained sculpted geomorphic units**	
Bench	Be	Sculpted lateral bar	SLaBa
Point bench	PtBe	Sculpted longitudinal bar	SLoBa
Ledge	Le	Sculpted point bar	SPtBa
Point ledge	PtLe	Sculpted run	SRu
Boulder berm	BBrm	Sculpted pool	SPo
Concave bank bench	CCBe		
Compound bank-attached bar	CBABa		
Forced bank-attached bar	FBABa		
FLOODPLAIN GEOMORPHIC UNITS			
Occasional floodplain	OccFp	Palaeochannel (prior channel, abandoned, ancestral channel)	FpPc
Discontinuous floodplain	DcFp	Ridge	FpRi
Floodplain (alluvial flat)	Fp	Swale	FpSw
Levee	Lv	Valley fill (swamp, swampy meadow)	Vfi
Crevasse splay	CSp	Meander cutoff (neck cutoff, billabong)	FpMCu
Floodchannel (back channel)	FCh	Ox bow	FpOx
Flood runner	FRu	Chute cut-off	FpChCu
Backswamp (distal floodplain, floodplain wetland, floodplain lake)	BSw	Floodplain channel anabranch (secondary or flood channel)	FpCab
Floodplain sand sheet	FpSs		
BED MATERIAL TEXTURE			
Bedrock	Br	Gravel	G
Boulder	B	Sand	S
Cobble	C	Fine grained	F

https://doi.org/10.1371/journal.pone.0201909.t001

Fryirs and Brierley, 2018

Begin to classify channel network with these primary gradients…

Valley confinement

River longitudinal profile

Flow accumulation

Valley confinement

Confined

>90% interacting with confining margins

Partly Confined

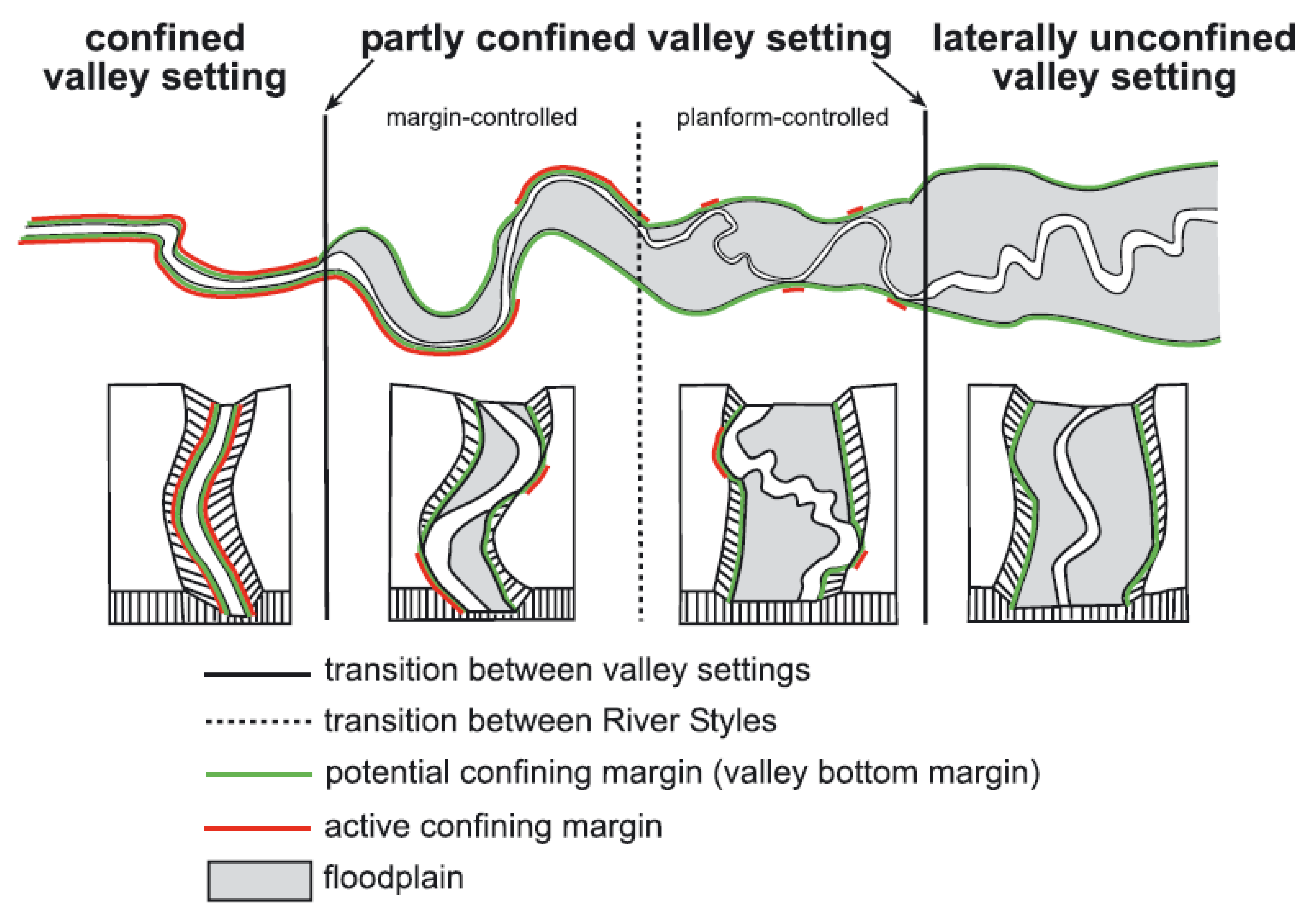
90-50%: margin controlled

10-40%: planform controlled

Unconfined

<10% interacting with cm

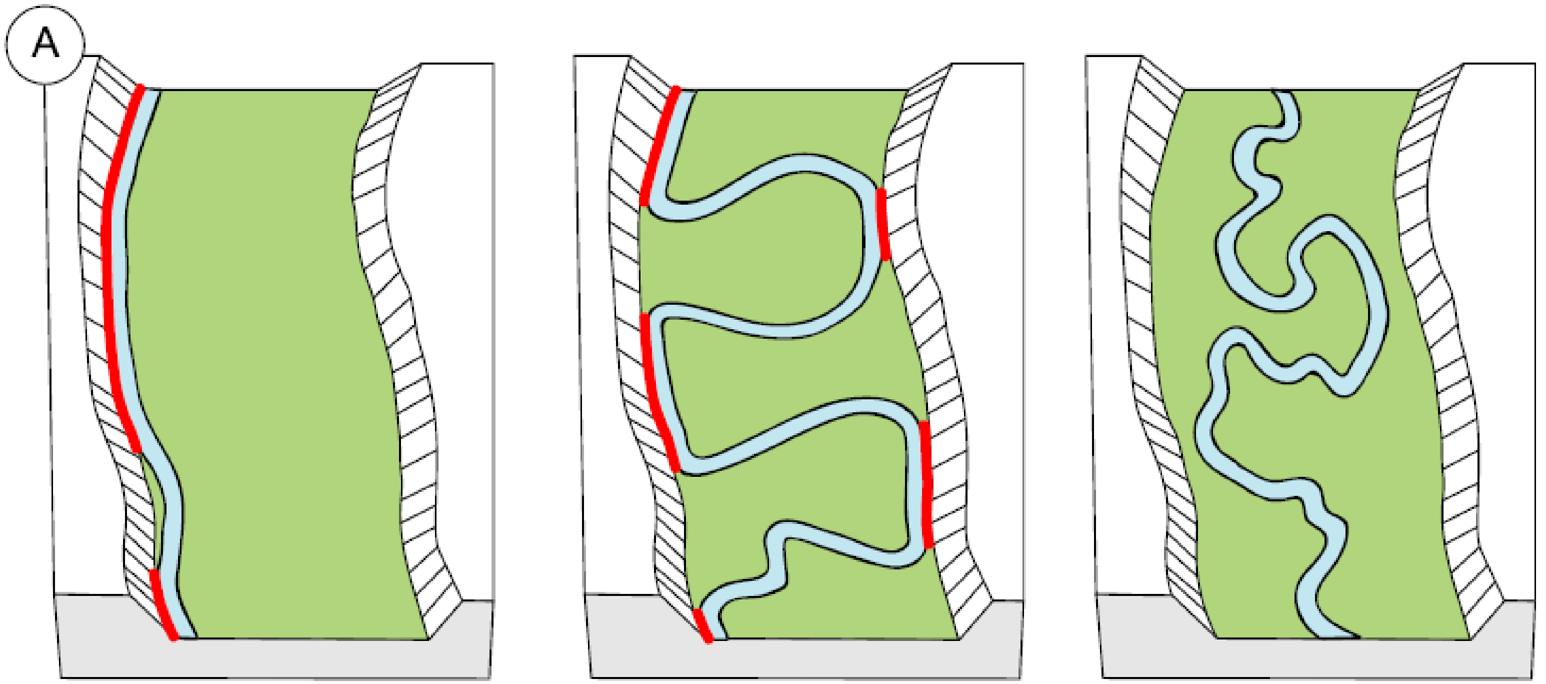
Confinement tells you more than any other metric about channel constraints and adjustment capacity



O'Brien et al., 2019

Confinement tells you more than any other metric about channel constraints and adjustment capacity

All have the same channel/valley ratio!



1 Valley and channel measures

valley bottom width: 400 m
valley length: 1000 m
channel width: 40 m
channel length: 1000 m
channel contact: 900 m

Confinement metrics

confinement: 0.90
channel width:valley bottom width: 0.10

2 Valley and channel measures

valley bottom width: 400 m
valley length: 1000 m
channel width: 40 m
channel length: 2200 m
channel contact: 850 m

Confinement metrics

confinement: 0.41
channel width:valley bottom width: 0.10

3 Valley and channel measures

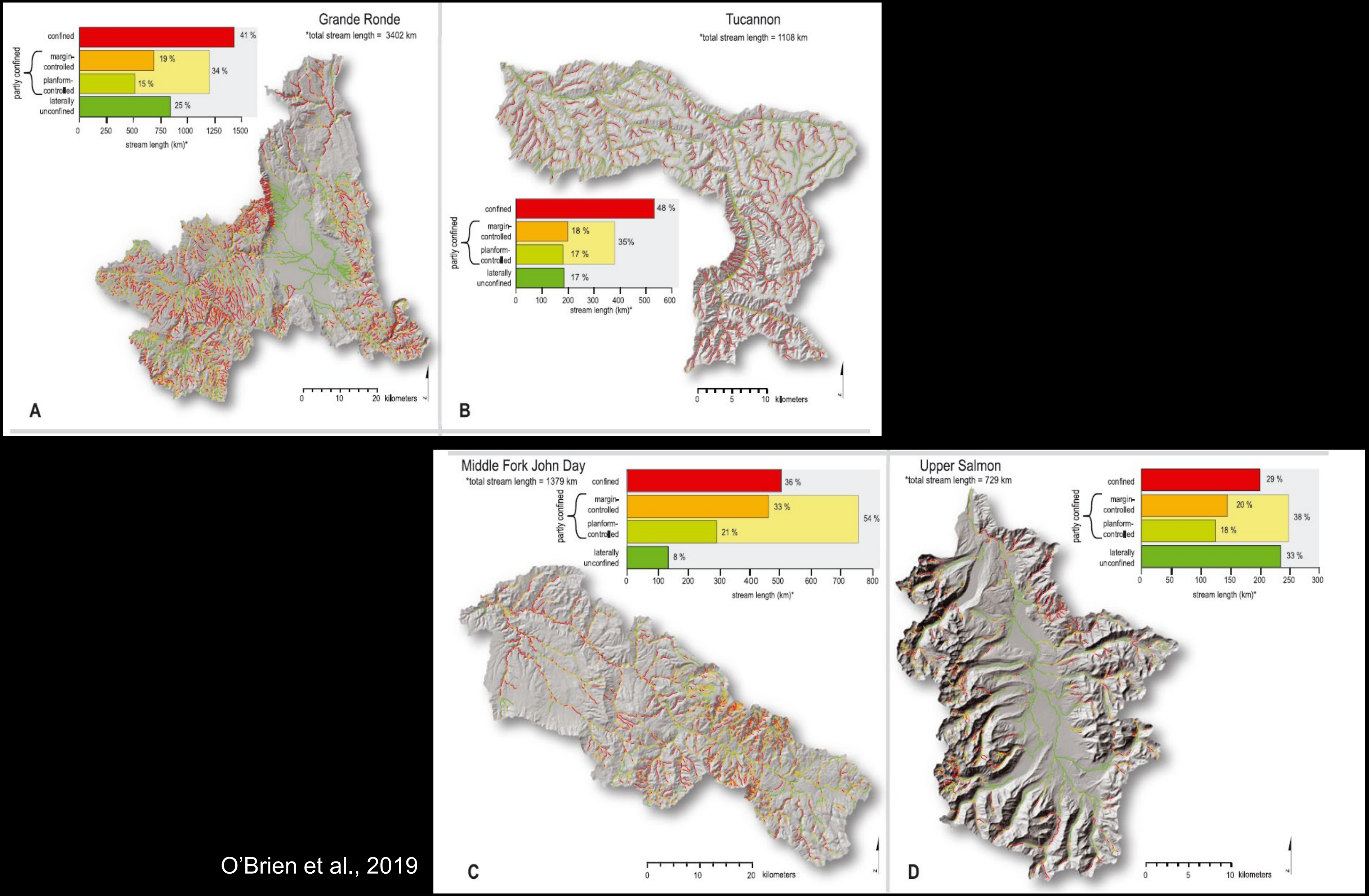
valley bottom width: 400 m
valley length: 1000 m
channel width: 40 m
channel length: 1800 m
channel contact: 0

Confinement metrics

confinement: 0
channel width:valley bottom width: 0.10

O'Brien et al., 2019

Confinement tells you more than any other metric about channel constraints and adjustment capacity



O'Brien et al., 2019

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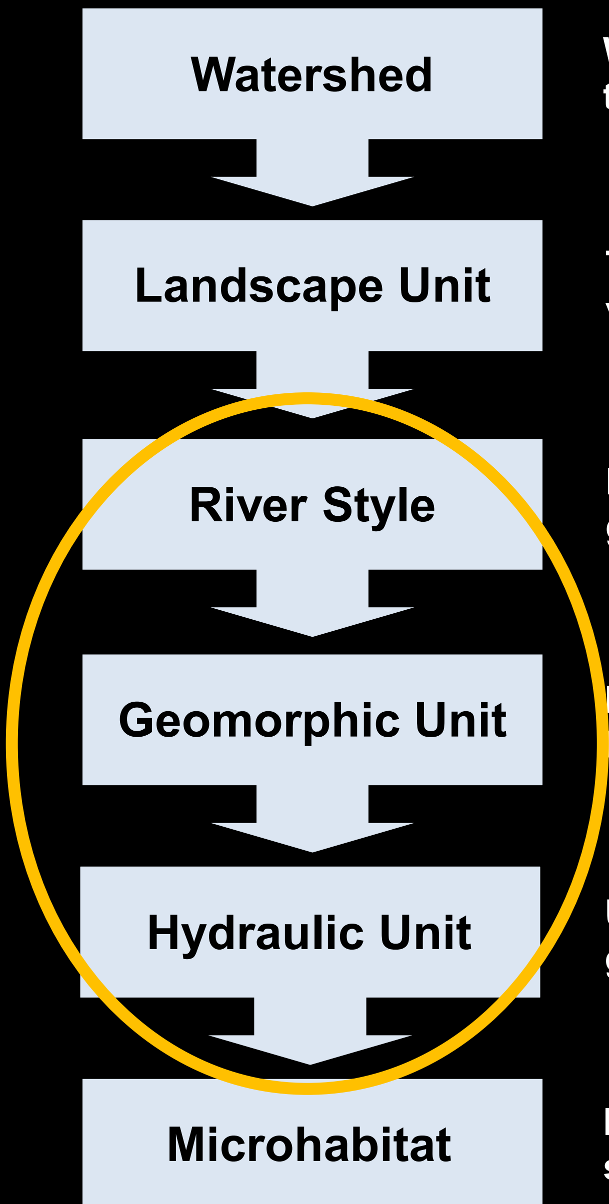

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Uniform patches of flow and substrate material within a geomorphic unit.

Individual elements (e.g., logs, rocks, gravel patches) within a stream.

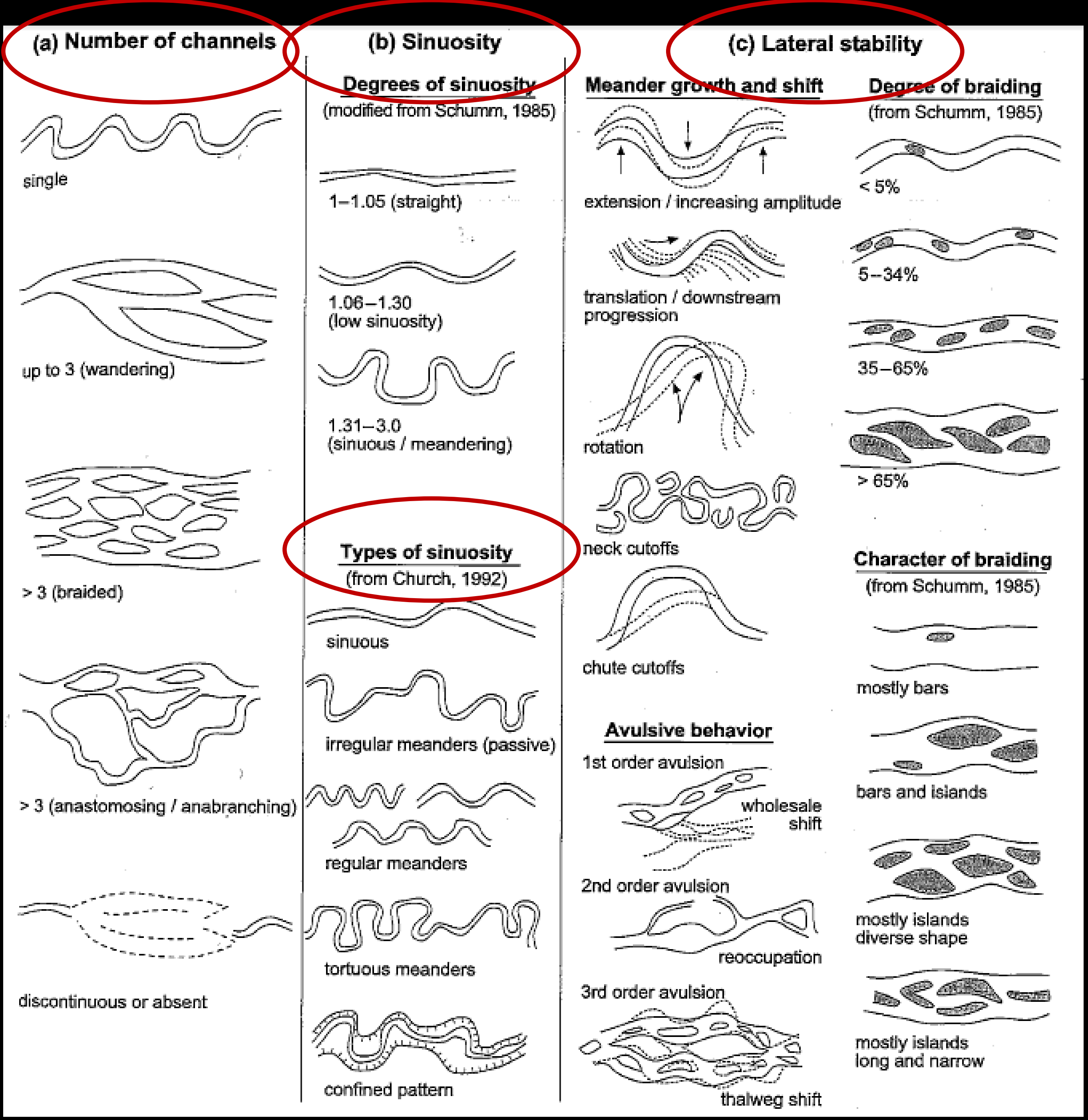
Second tier characteristics for classification
Indicators of channel behavior

Assemblage of geomorphic units that make up a reach

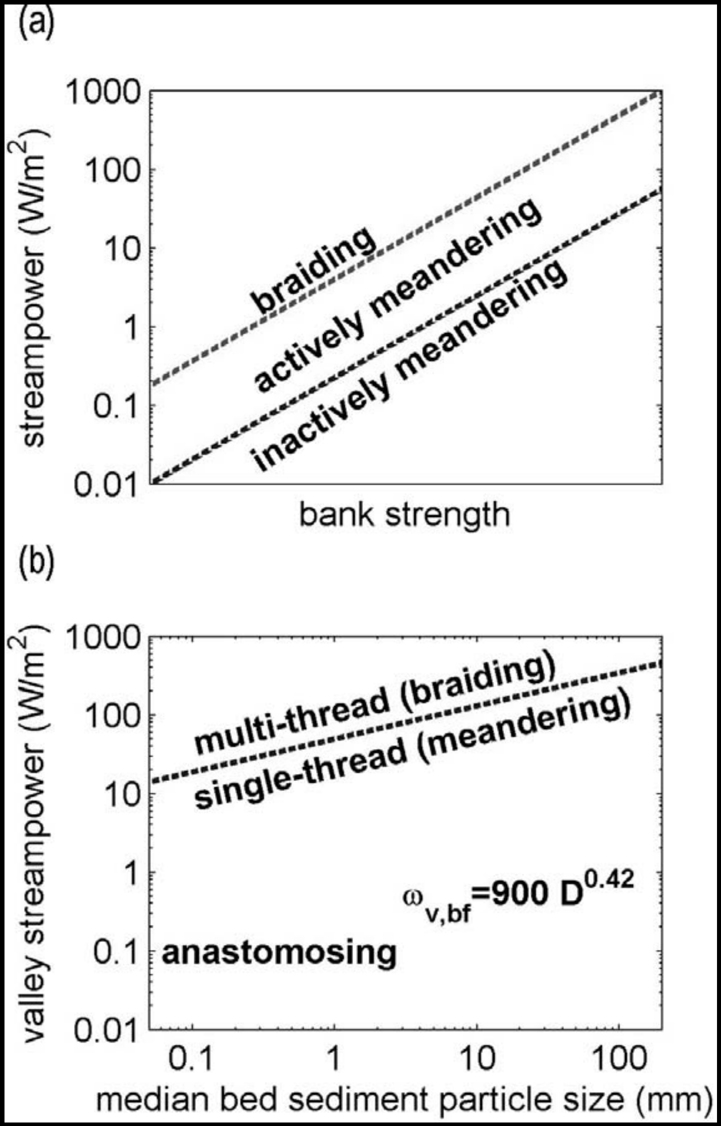
Channel planform

Bed material texture

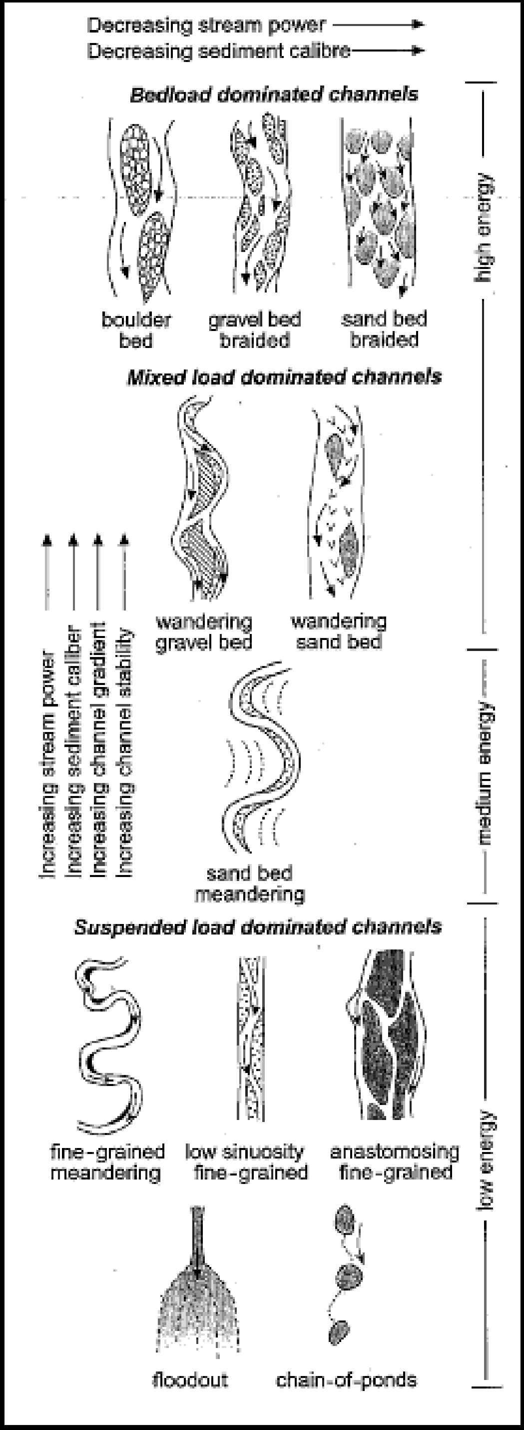
Metrics of channel planform



Interpretations from channel planform



Kleinhans, 2010



Modes of adjustment vary considerably for different river types

Table 32.1 Reach-scale channel type and degrees of freedom for morphologic change. (+ = likely; p = possible; – = unlikely)[a]

Channel type	Channel change			
	Grain size	Width & depth	Bedforms	Stream gradient (sinuosity/elevation)[b]
Colluvial	p	p	–	–/p[c]
Bedrock	–	–	–	–/–
Cascade	p	–	–	–/–
Step-pool	p	–/p[d]	p	-- /p
Plane-bed	+	p/+	–	–/p
Braided	+	+	+	+/+
Pool-riffle	+	+	+	+/+
Dune-ripple	p	+	+	+/+

confined

unconfined

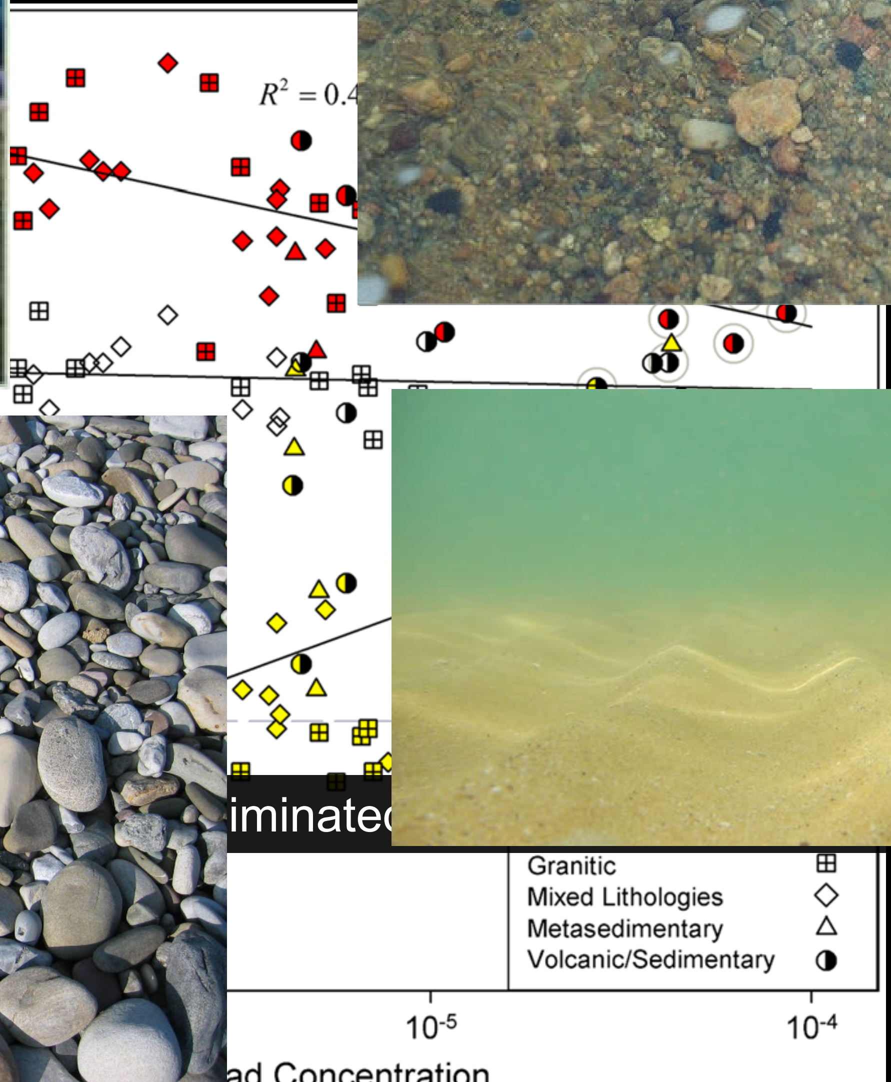
[a] Modified from Montgomery and Buffington (1997). Response potential for each channel type is discussed elsewhere (Montgomery and Buffington, 1997; 1998; Buffington *et al.*, 2003).

[b] Changes in stream gradient may occur via altered sinuosity or incision/aggradation that alter the absolute elevation change across a reach. Slashes in the table distinguish these two responses.

[c] Fluvial incision/deposition is possible, depending on the degree of colluvial fill.

[d] Changes in channel depth can occur via pool fill/scour.

gravel bed rivers
nsport ra
changes



iminated

Mueller and Piti

Tools for geomorphic assessments

https://riverscapes.net

TABLE 1 Some of the available automated and semi-automated tools for the geomorphic analysis of rivers

Tool	Website or download page	Key related paper/s
Confinement and valley setting		
Valley-bottom extraction tool (V-BET)	http://rcat.riverscapes.xyz/Documentation/Version_1.0/VBET.html	Gilbert, Macfarlane, and Wheaton (2016)
Valley bottom confinement tool (VBCT)	http://confinement.riverscapes.xyz	Fryirs et al. (2016) O'Brien et al. (2019)
Fluvial corridor toolkit (FCT)	https://github.com/EVS-GIS/Fluvial-Corridor-Toolbox-ArcGIS	Roux, Alber, Bertrand, Vaudor, and Piégay (2015)
TerEx toolbox (terrace and floodplain mapping)	https://qcnr.usu.edu/labs/belmont_lab/resources	Clubb et al. (2017) Stout and Belmont (2014)
River planform		
Fluvial corridor toolkit (FCT)	https://github.com/EVS-GIS/Fluvial-Corridor-Toolbox-ArcGIS	Roux et al. (2015)
Geomorphic network and analysis toolkit (GNAT) Beaver restoration assessment tool (BRAT)	http://gnat.riverscapes.xyz/ http://brat.riverscapes.xyz/	Macfarlane, Gilbert, et al. (2017); Macfarlane, Wheaton, et al. (2017)
Geomorphic units		
Geomorphic unit tool (GUT)	http://gut.riverscapes.xyz/	Bangen, Wheaton, Bouwes, Bouwes, and Jordan (2014) Wheaton et al. (2015)
Geomorphic unit survey (GUS)	https://reformrivers.eu/geomorphic-units-survey-and-classification-system-gus	Belletti et al. (2017)
Support vector machine classifier (SVMc)	Remote sensing software for example, eCognition http://www.ecognition.com/, ORFEO https://www.orfeo-toolbox.org/	Belletti et al. (2017) Demarchi, Bizzi, and Piégay (2016, 2017)
Hydrodynamic modeling	Variety of software are available for example, SRH-2D https://www.usbr.gov/tsc/techreferences/computer%20software/models/srh2d/index.html	Wyrick and Pasternack (2016) Wyrick, Senter, and Pasternack (2014)
Bed material texture		
Digital grain size project (DGSP)	https://dbuscombe-usgs.github.io/DGS_Project/	Buscombe (2013)
BASEGRAIN	https://basement.ethz.ch/download/tools/basegrain.html	Detert and Weitbrecht (2013)
Digital Gravelometer	http://www.sedimetrics.com/	Graham, Rice, and Reid (2005)
Topographic analysis tools (TAT), including ToPCAT	http://tat.riverscapes.xyz/	Brasington, Vericat, and Rychkov (2012)
River behavior		
Morphological change—Geomorphic change detection (GCD)	http://gcd.riverscapes.xyz/	Wheaton, Brasington, Darby, and Sear (2010); Wheaton et al. (2013)

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Tools for geomorphic assessments

TABLE 1 (Continued)

Tool	Website or download page	Key related paper/s
Channel migration toolbox	https://fortress.wa.gov/ecy/publications/SummaryPages/1406032.html	Legg, Heimburg, Collins, and Olson (2014)
Planform statistics	https://repository.nced.umn.edu/browser.php?current=author&author=37&dataset_id=15	–
Measures of channel width and centreline (RivWidth, ChanGeom, RivMap, PyRIS)	RivWidth: http://uncglobalhydrology.org/rivwidth/ ChanGeom: https://www.burchfisher.com/data.html RivMap: http://live.ece.utexas.edu/research/rivamap/ https://www.mathworks.com/matlabcentral/fileexchange/58264-rivmap-river-morphodynamics-from-analysis-of-planforms PyRIS: https://github.com/fmonegaglia/pyris	Pavelsky and Smith (2008) Fisher, Bookhagen, and Amos (2013) Isikdogan, Bovik, and Passalacqua (2017) Schwenk, Khandelwal, Fratkin, Kumar, and Foufoula-Georgiou (2017) Monegaglia, Zolezzi, Güneralp, Henshaw, and Tubino (2018)
SCREAM	–	Rowland et al. (2016)
Google earth engine	https://earthengine.google.com/	Gorelick et al. (2017)
Downstream patterns of rivers and controls		
Longitudinal profile—ArcMap stacked profile tool	http://www.arcgis.com/index.html	–
Network Profiler Tool	https://riverscapes.github.io/NetworkProfiler/	–
Geospatial modeling environment	http://www.spatialecology.com/gme/	Beyer (2012)
Catchment area—ArcMap flow accumulation tool	http://www.arcgis.com/index.html	–
Gross stream power	http://brat.riverscapes.xyz/	Macfarlane, Gilbert, et al. (2017); Macfarlane, Wheaton, et al. (2017)

Note: This is not intended to be an exhaustive list of all available tools, rather a guide to direct the reader to the tools identified in Figures 2b and 3, and mentioned in the text. All websites were accessed June 17, 2019.

Fryirs, et al., 2019

Roadmap

TODAY

Forget rates. What can we learn from basic form-process relationships?

Channel form/dynamics. (Dis)Continuity. Hydro-geomorphic Assessments.

Basic Reconnaissance

With a tight budget, what do you really need to know?

TOMMORROW

Case studies in sediment supply, transport, and morphodynamics

Hydrologic analysis and non-stationarity

Targeted modeling and metrics. Stationarity Assumption?

Push-button Geomorphology

The geek approach. What computer models can and can't tell you.

Basin-average erosion rates: The cosmo method

Millennial-scale landscape rates of erosion.

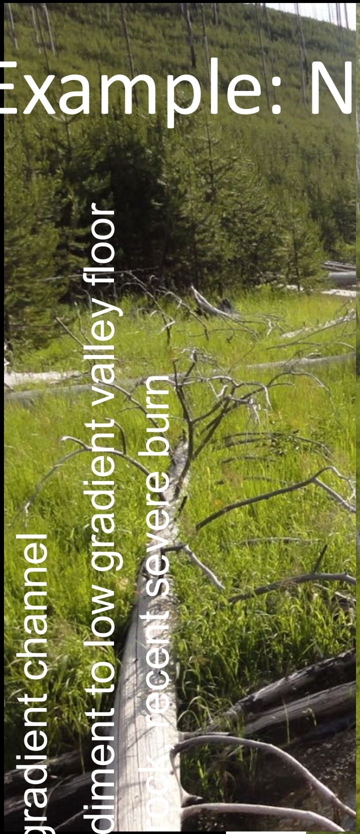
Reservoir and pond sedimentation rates

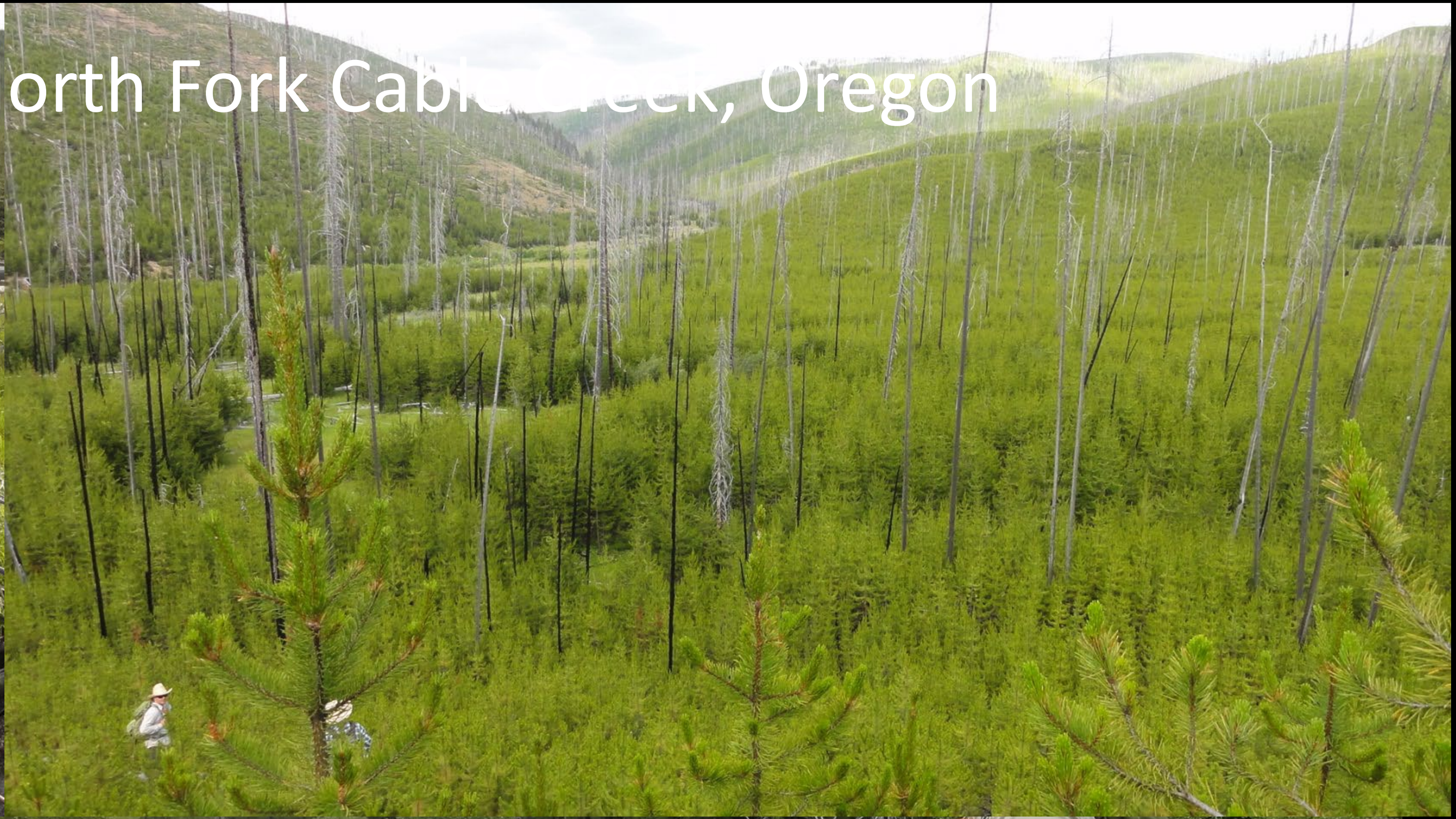
Time- and space-integrated measurements that may be useful.

Watershed Sediment Budget

Tools and techniques for robust constraints on sources and sinks.

Example: North Fork Cable Creek, Oregon





Reach 1

Laterally unconfined, low gradient channel

Steep hillslopes deliver sediment to low gradient valley floor

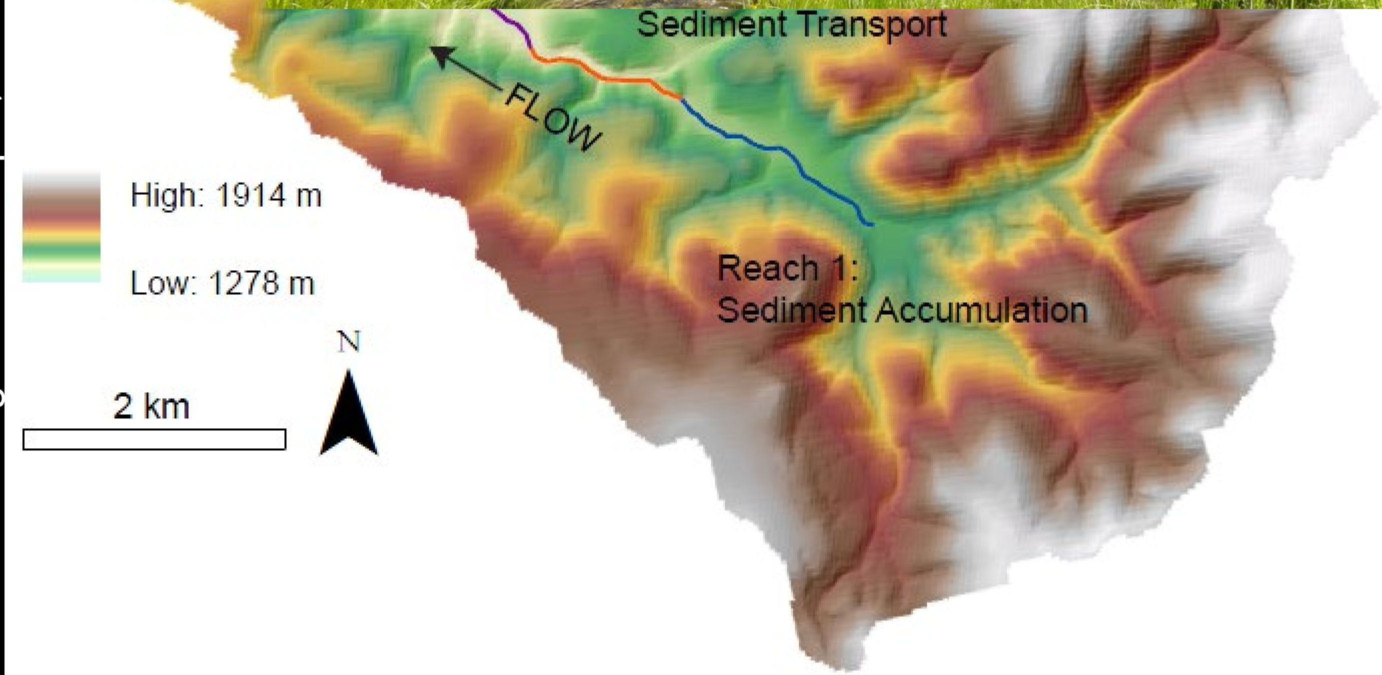
Weak tuff and rhyolite bedrock, recent severe burn

Reach 2

Partly confined, planform controlled with strong veg influence

Channel incised into a narrow, high-gradient valley

Channel gradient steeper, bed material coarser, less heterogeneity



Reach 3

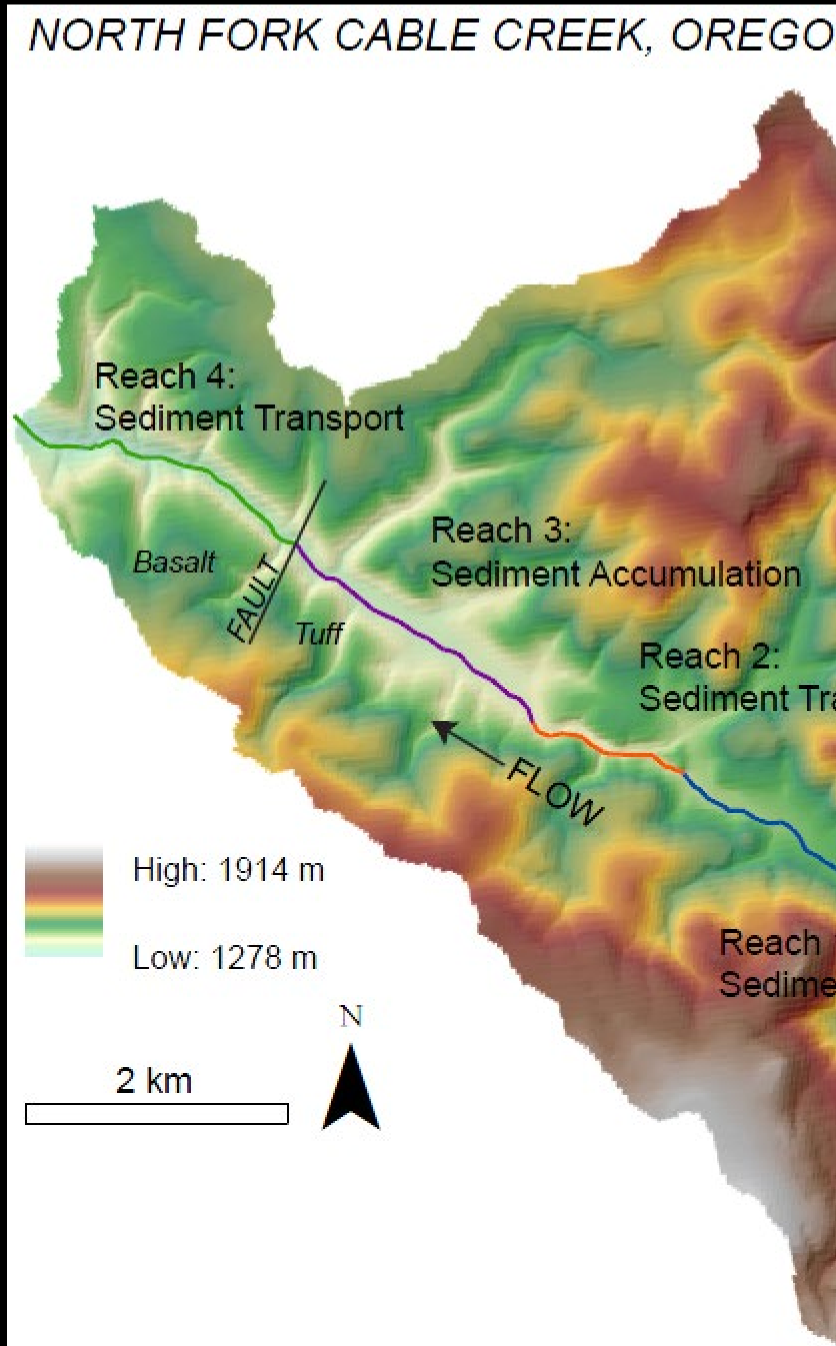
Laterally unconfined, occasional confining terraces
Valley widens, well developed (and connected) floodplain
Much gravel deposition and heterogeneity in bedforms

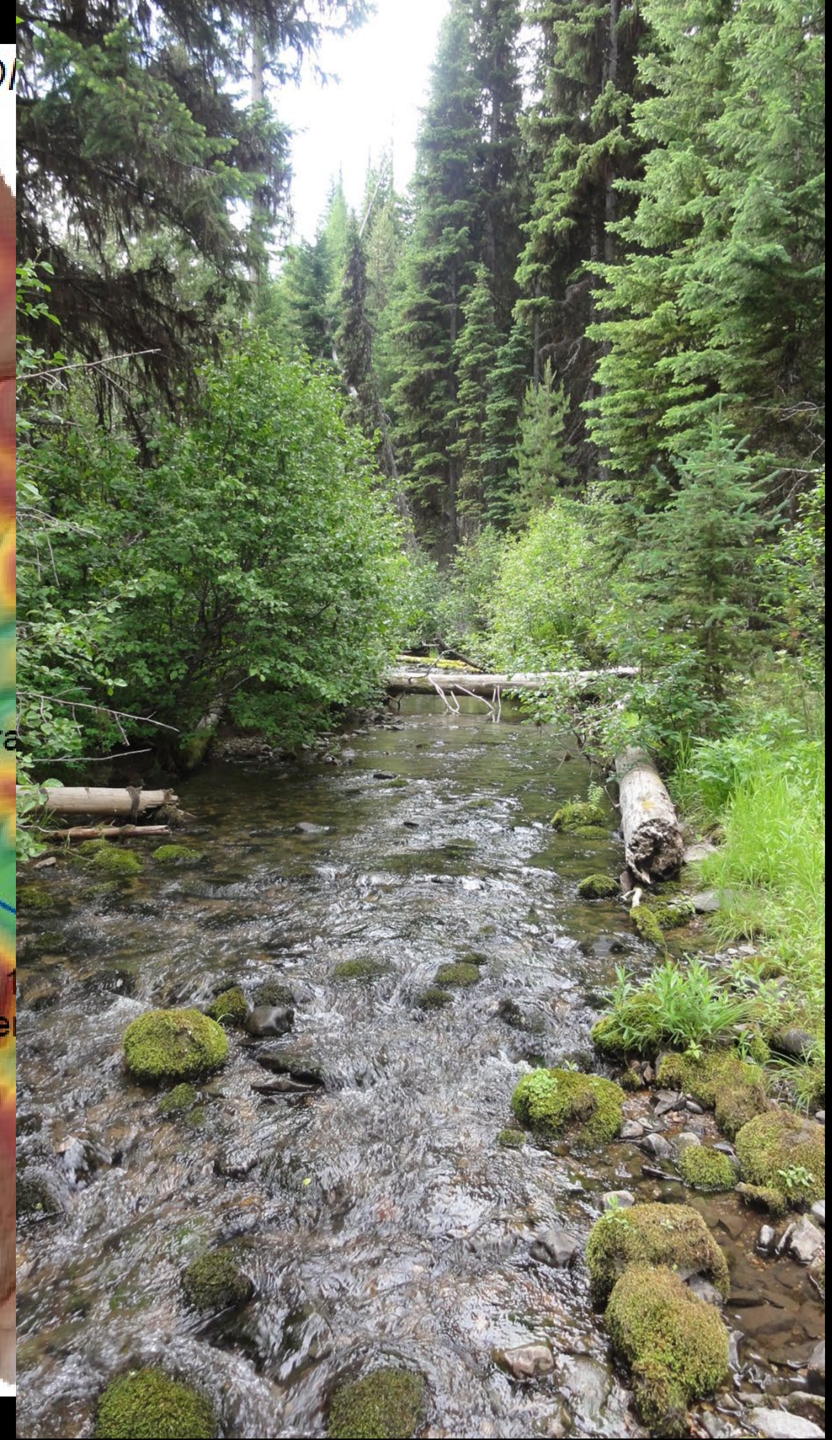
Reach 4

Partly confined, margin controlled

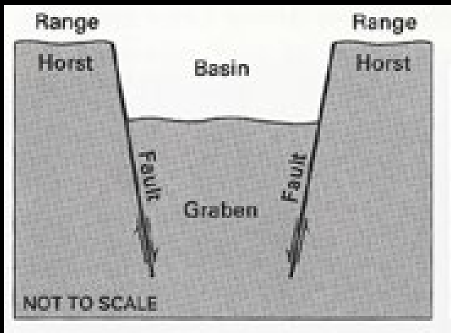
Channel crosses fault and enters onto hard Columbia River Basalt

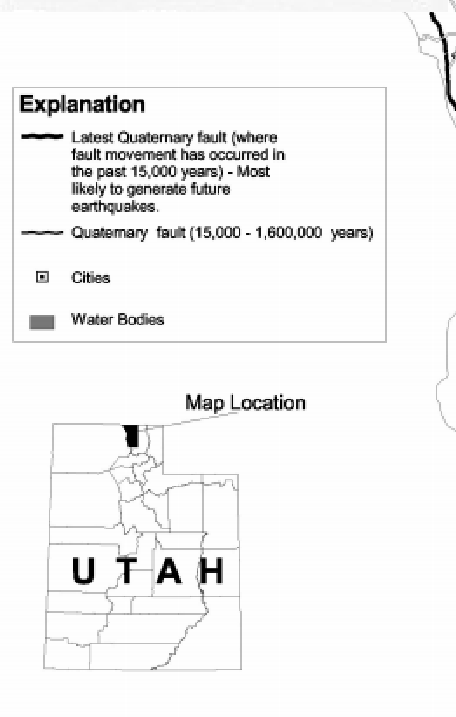
Step-pool to pool-riffle morphology

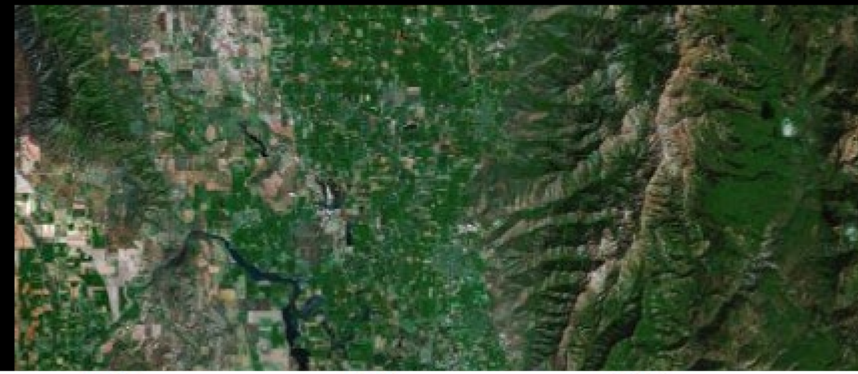


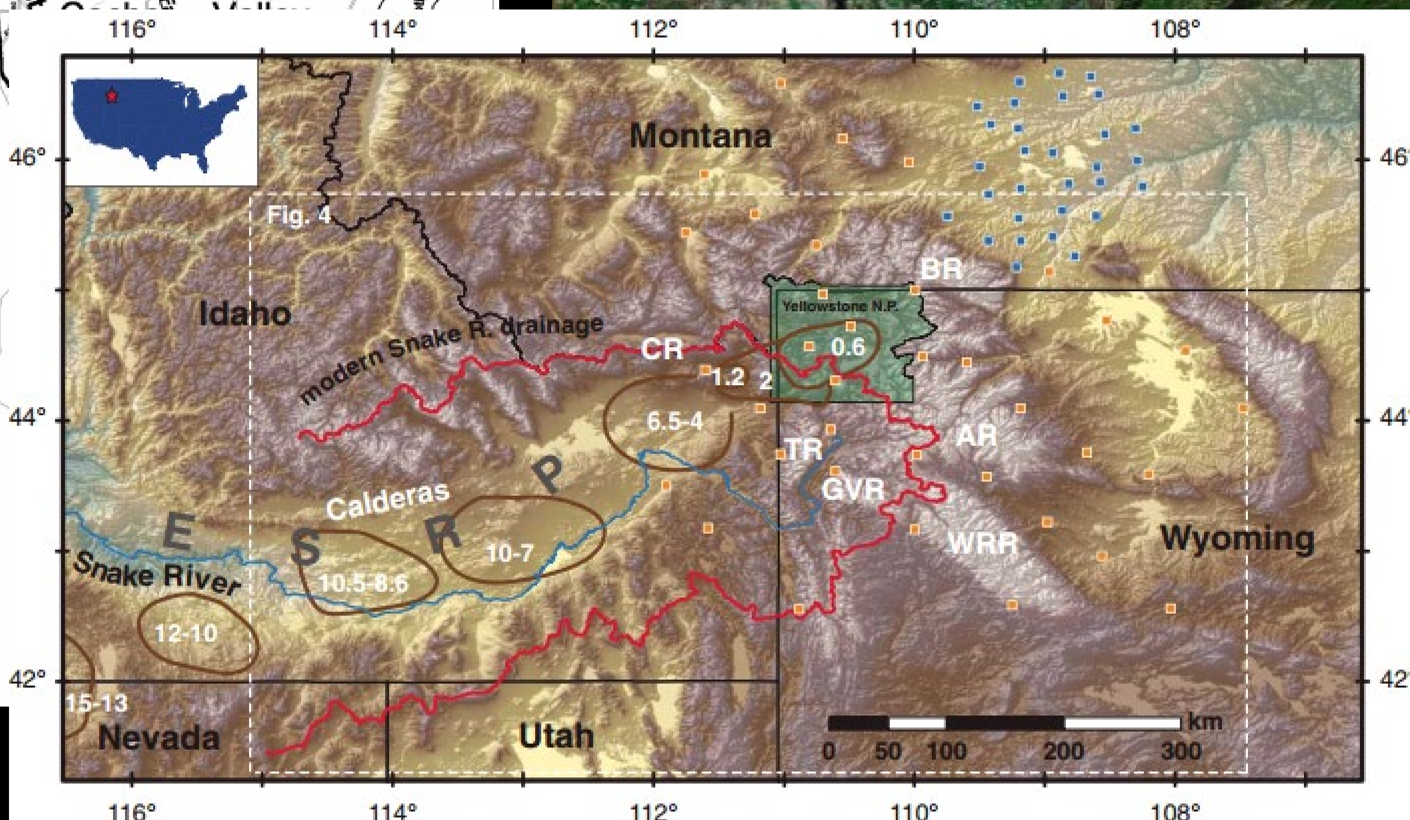


Some history on the landscape we'll be examining this afternoon

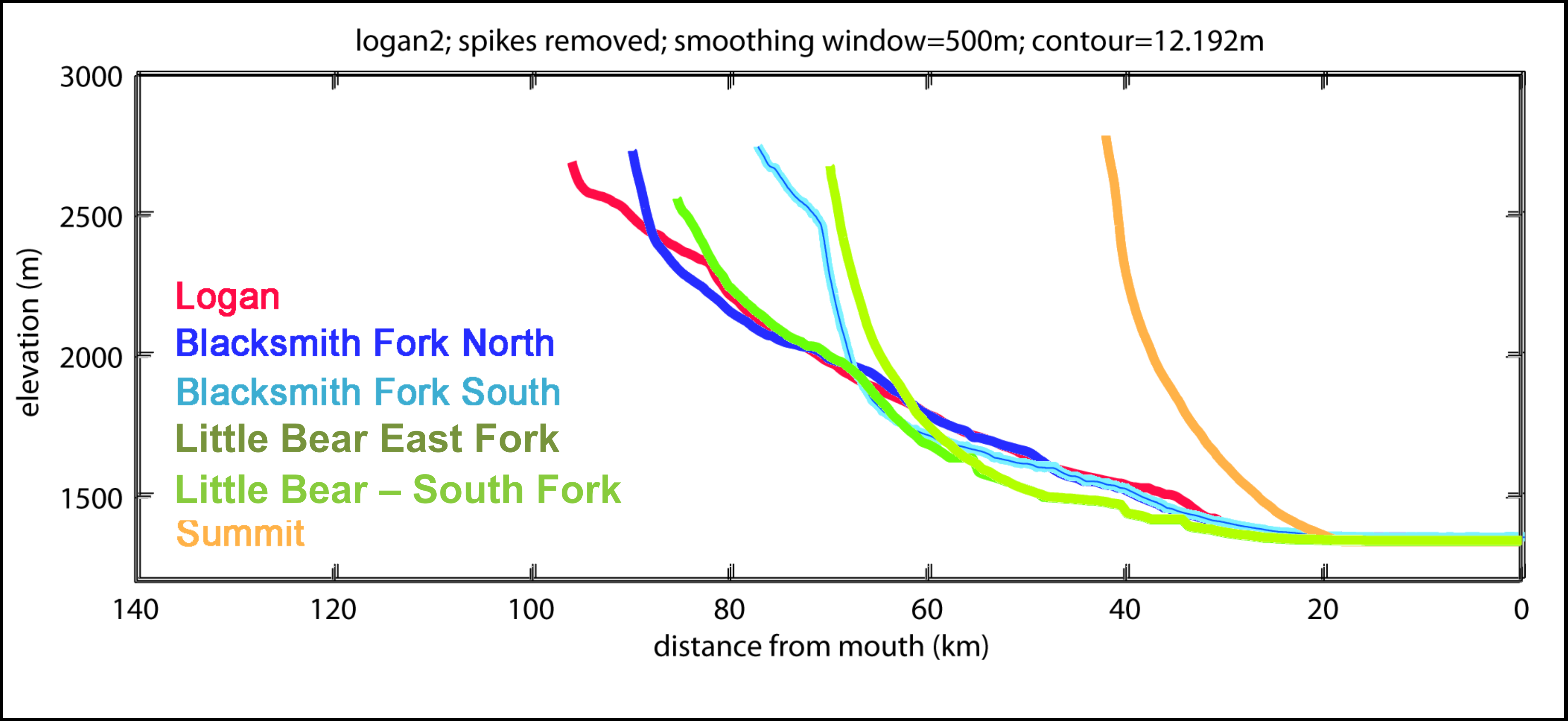








Long profiles of EF, SF Little Bear and other drainages of the Bear River Range



Longitudinal profiles extracted with Stream Profiler Tool: geomorphtools.org

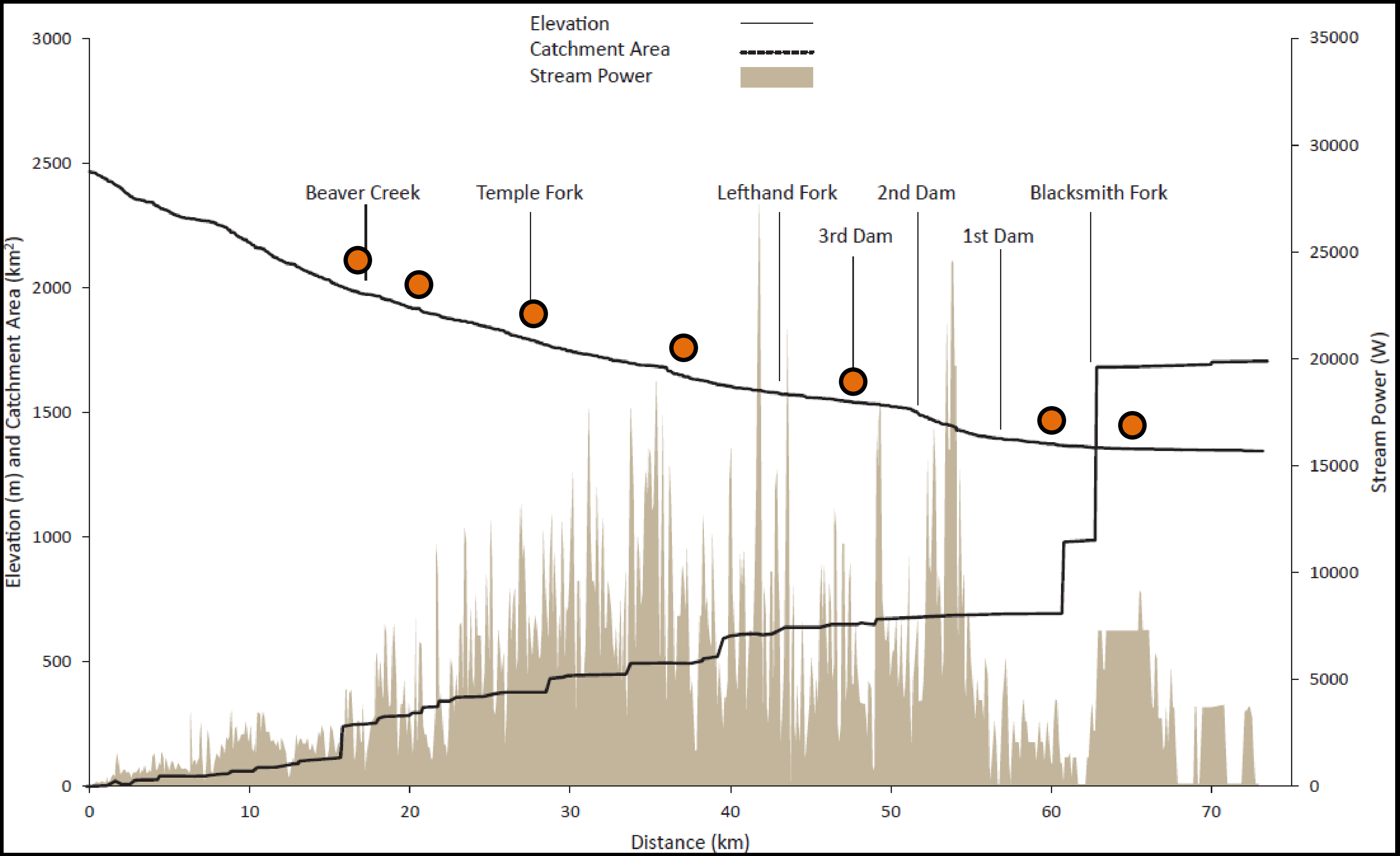


Figure from Gary O'Brien

Your assignment for this afternoon:

Work in groups of 3-4

The Logan River Watershed is being targeted for a major watershed restoration project with the goal of restoring cutthroat and brown trout habitat.

Utah DNR has requested a map illustrating the different reach types that occur along the river. This info will be used to determine which sites to prioritize for further monitoring and restoration.

Your assignment for this afternoon:

1. Obtain paper maps, GIS and/or Google Earth data

2. Peruse the data for 30 min. Identify points/areas of interest along the channel and throughout the watershed.

3. Spend ~30 min delineating distinct reaches of the mainstem Logan River along our tour route. Delineate distinct River Styles and describe each reach wrt:
    1. valley confinement
    2. number of channels, sinuosity
    3. slope and/or discontinuities in the long profile
    4. notable sediment sources and sinks
    5. other relevant attributes (e.g., D50, slope)

Turn in by 5pm:

1. Paper map showing reach breaks
2. Brief descriptions of each River Style

Questions we'll discuss at each stop

(1) Which erosional processes do you see evidence for? What is conveying sediment to the channel? Amount and type of sediment supplied?

(2) Is there a clearly defined bankfull channel? How deep is it?

(3) Which geomorphic units do you see?

(4) Is the bed armored? Does bed material move at channel filling flow? How does τ_o compare to τ_c?

(5) Is there evidence of coarse suspended load (little in the bed, but deposits of fine gravel or sand in sheltered locations or within bars)?

(6) How sensitive is this reach to changes in flow and/or sediment supply?