

Watershed Hydrology & Sediment Dynamics

Sediment Transport in Stream Assessment and Design

Monday, July 31, 2023

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...



G. Parker. Fly River, Papua New Guinea.

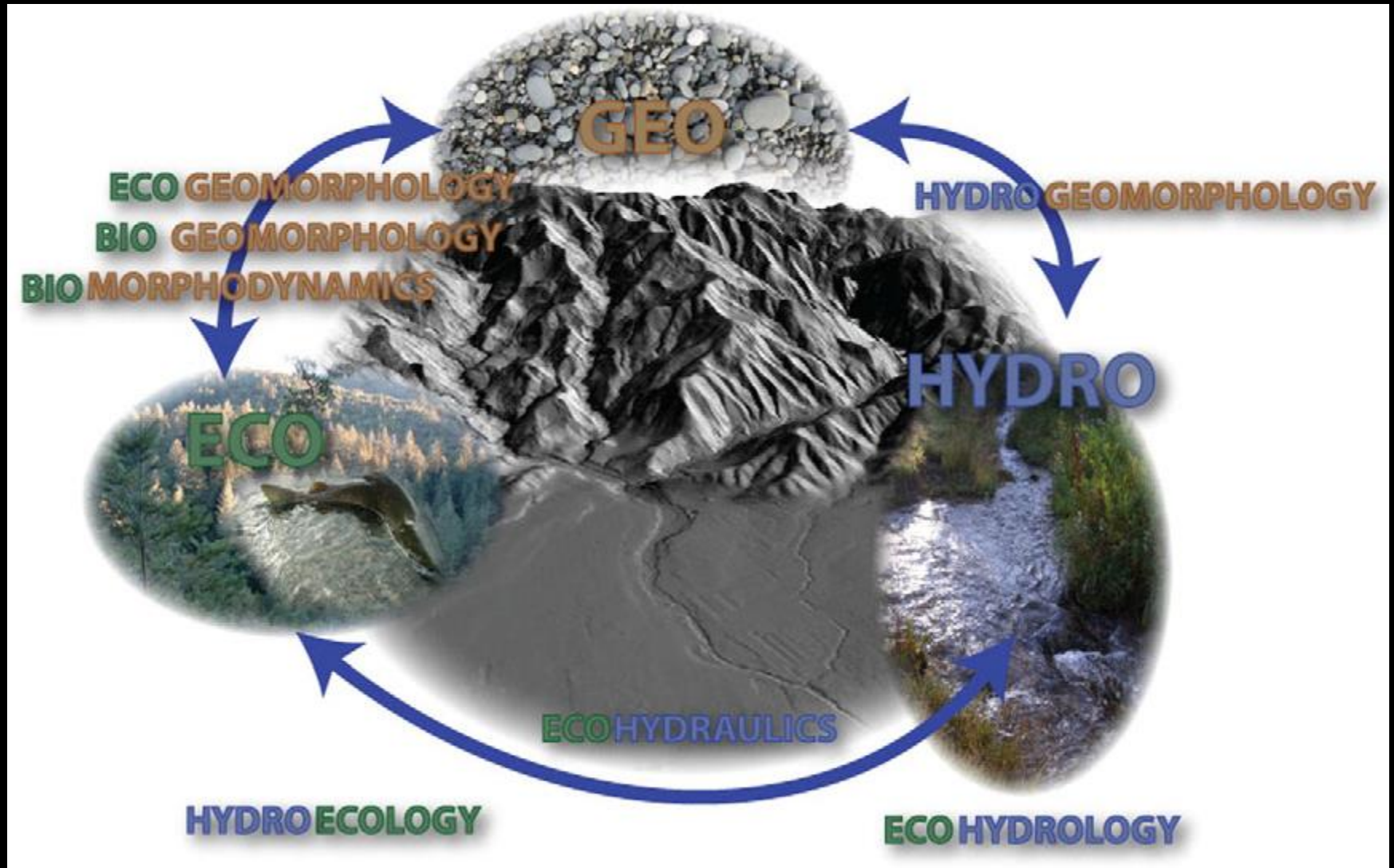


A. Alabyan and A. Sidorchuk. Siberia

J. Imran. Brahmaputra River, Bangladesh.



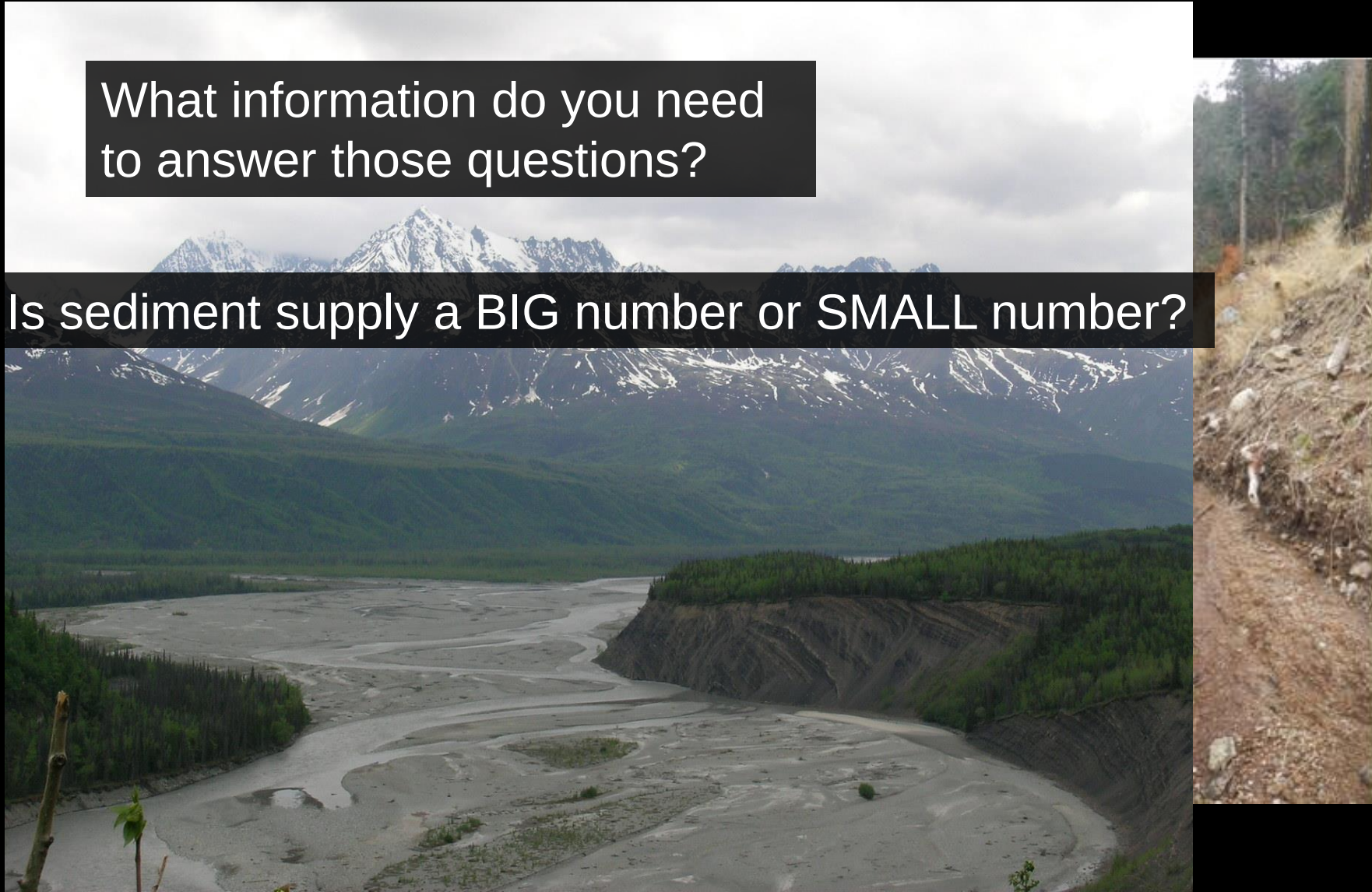
...emerging from complex interactions



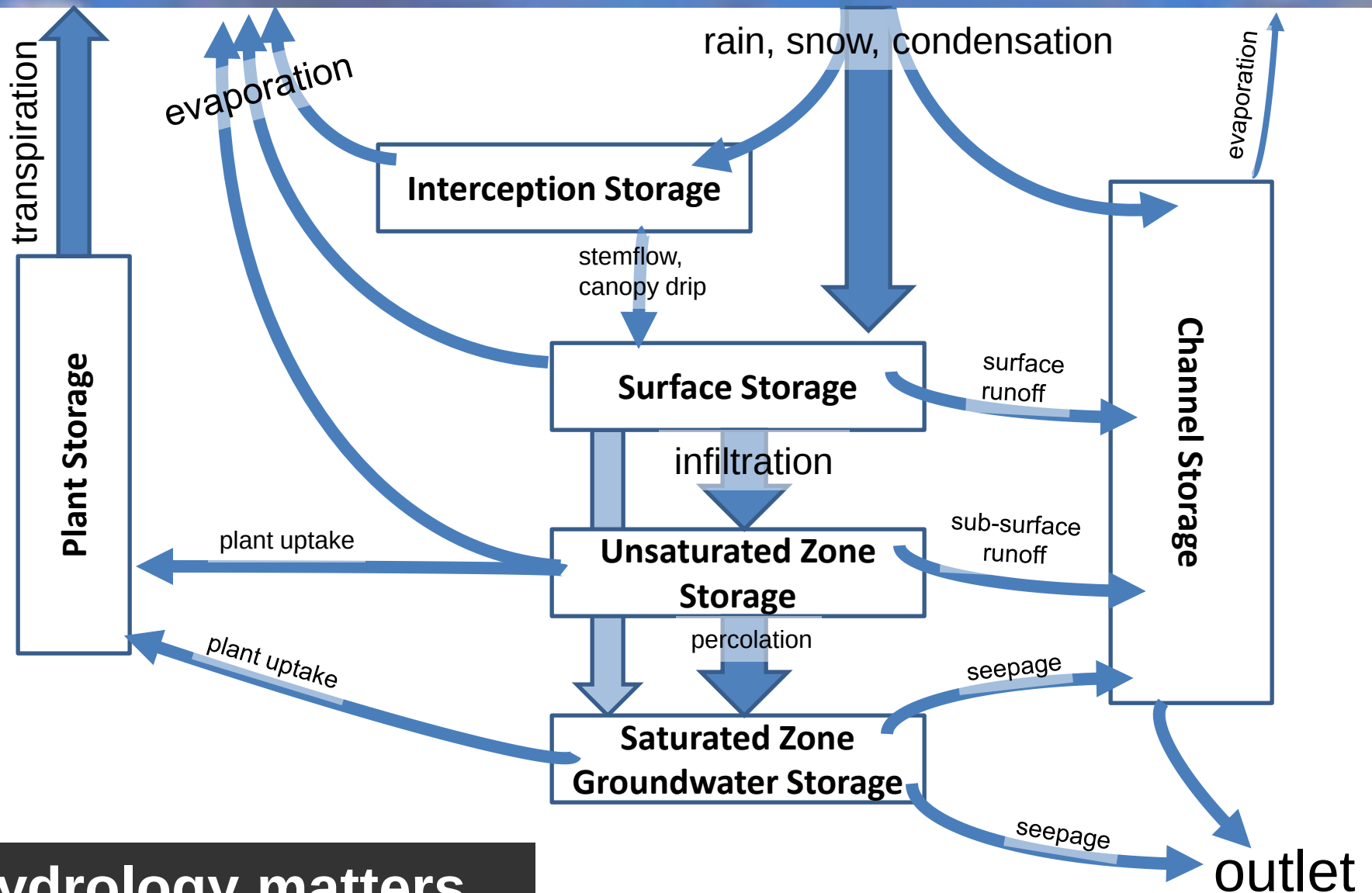
How *much* and what *type* of sediment is being delivered to this channel?

What information do you need to answer those questions?

Is sediment supply a BIG number or SMALL number?



Atmospheric Moisture

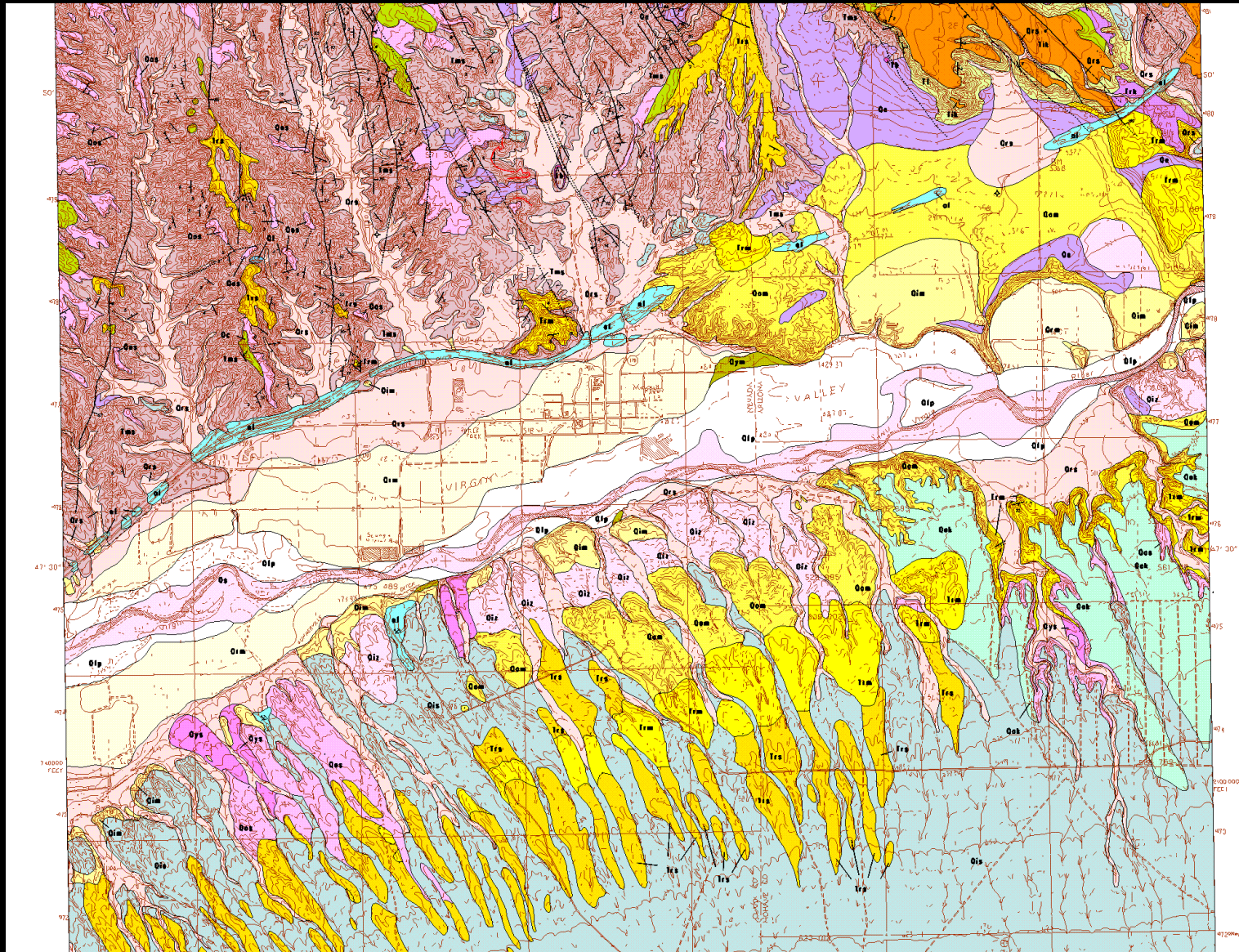


Hydrology matters...

Land use matters...



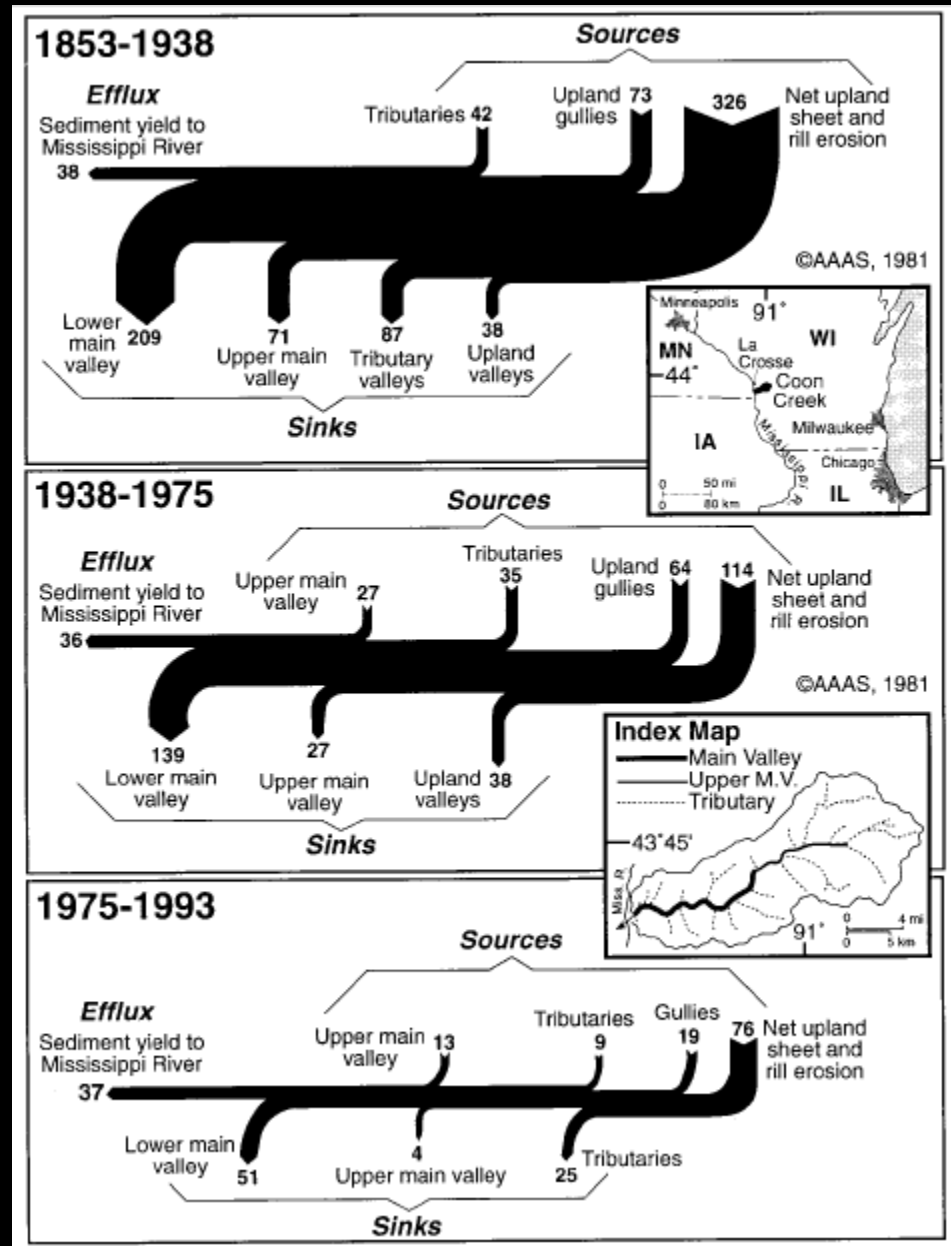
Soils, surficial and bedrock geology matter...



Storage matters...

Natural and human-caused
'legacy effects'

Sediment transport through
watersheds is complicated



Grain size matters

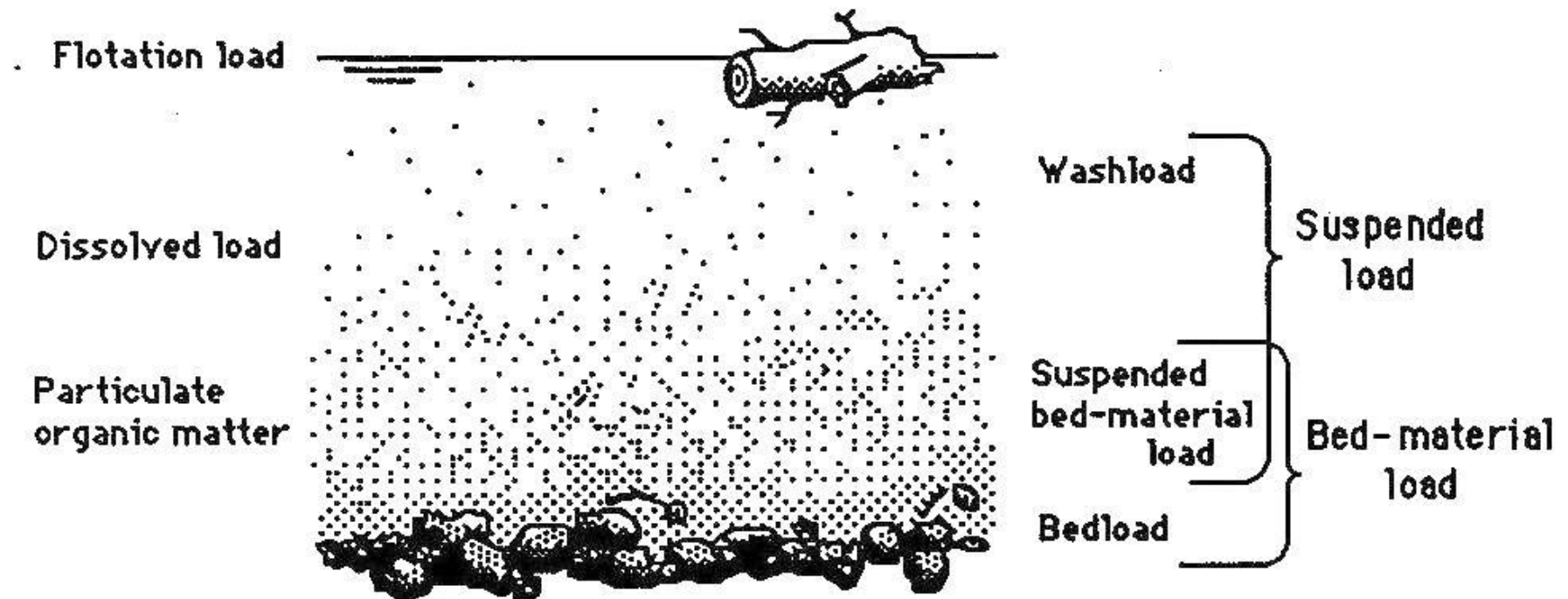


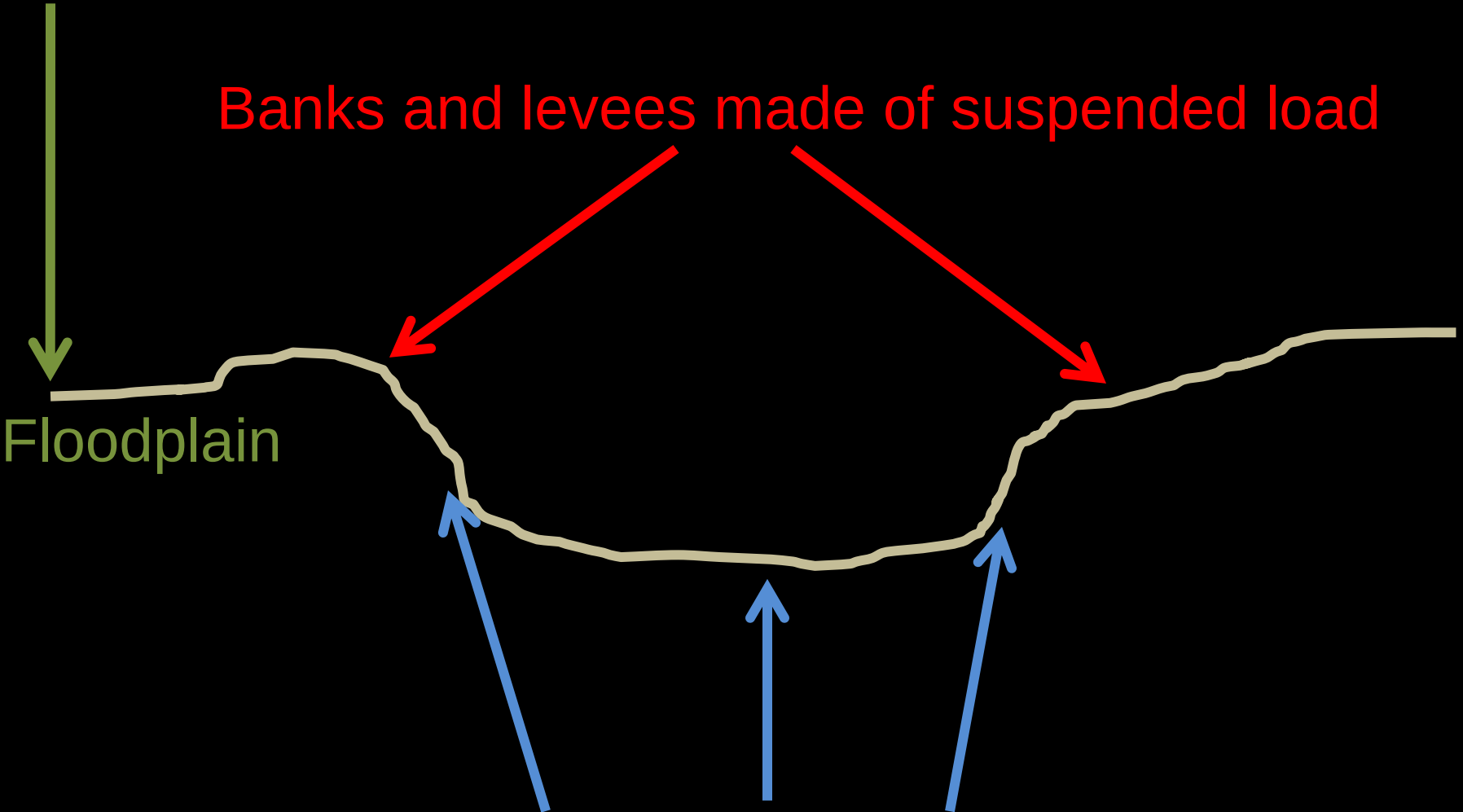
Figure 7.1. Categories of transported materials in a stream

Grain size matters...

Coarse and fine load often have different sources/transport paths

Floodplains preserve old channel deposits + overbank

Banks and levees made of suspended load

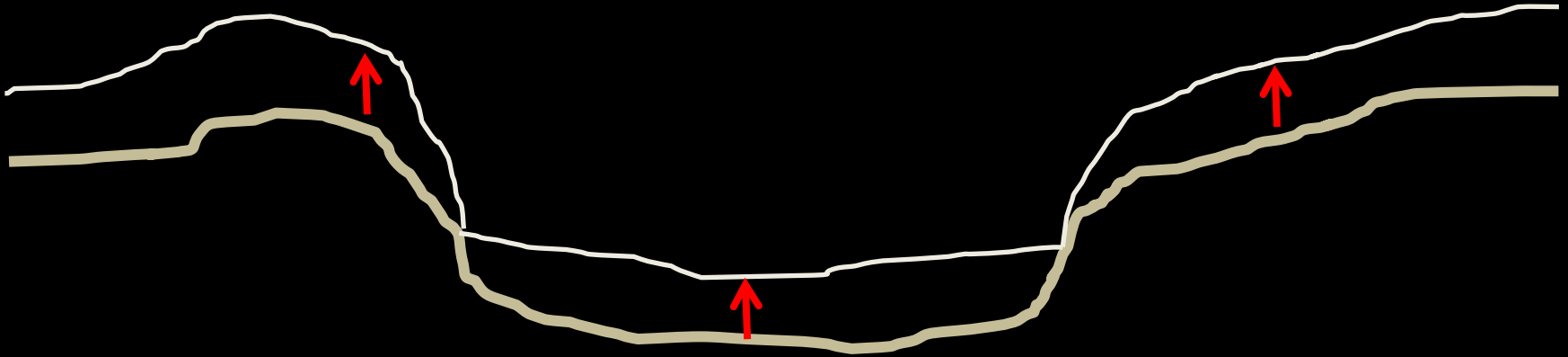


Bed and lower point bars made of bed material load

Grain size matters...

Coarse and fine load often have different sources/transport paths

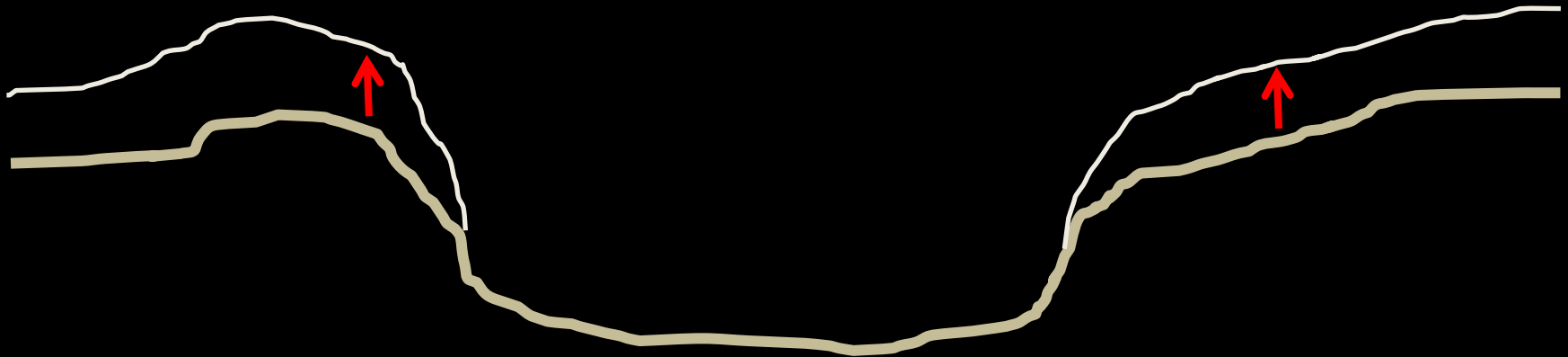
All else held constant,
aggradation on the bed causes...



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

How can we  erosion?

This is not always the right question to ask.



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

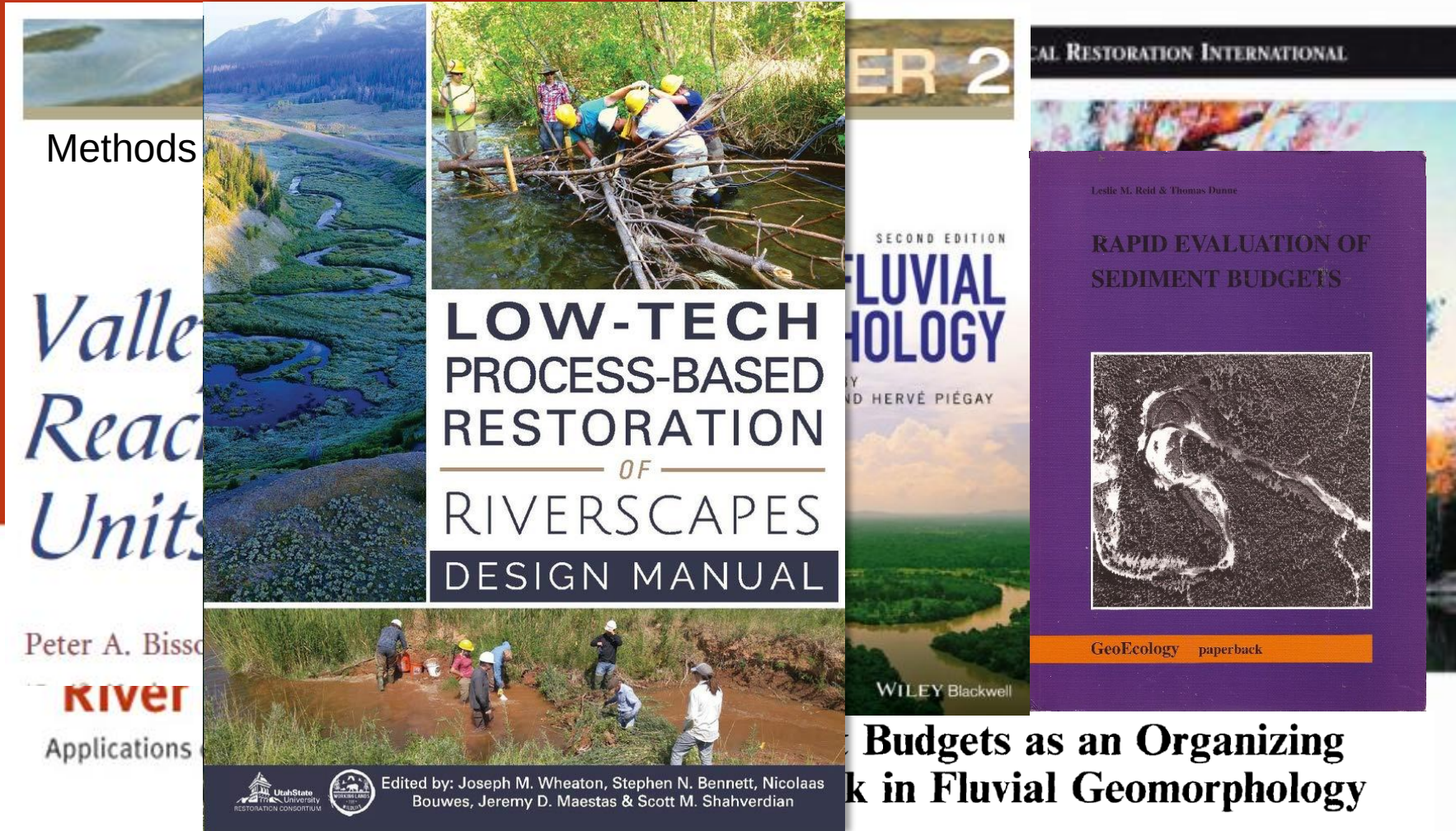
Size matters...boulders, cobbles, gravel, sand, mud play distinct roles

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



LESLIE M. REID¹ AND THOMAS DUNNE²

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²Donald Bren School of Environmental Science and Management and Department of Geological Sciences, University of California, CA, USA

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?

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.

TOMMORROW

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

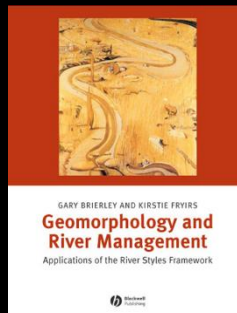
Stage 2 Data Analysis

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

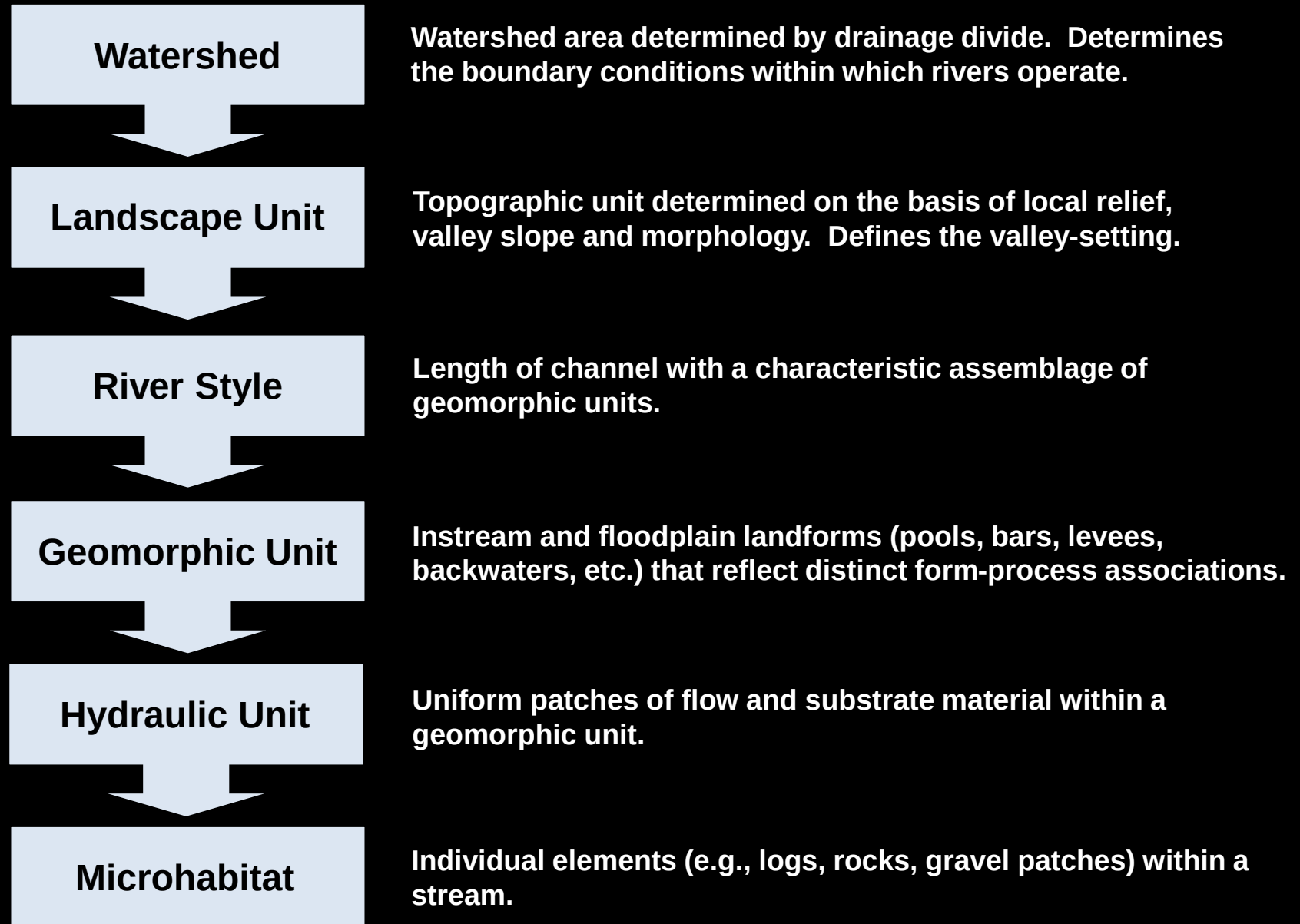
Stage 3 Predict future river structure

Stage 4 Prioritize watershed management issues

Stage 5 Identify target conditions for river



River Styles Hierarchy

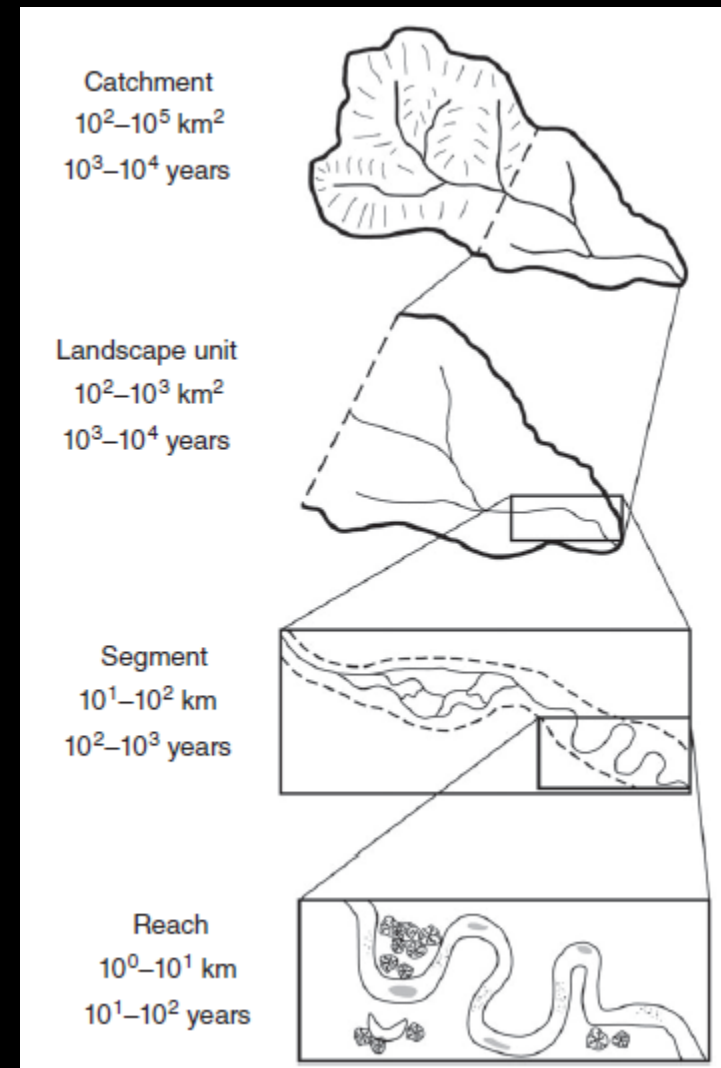


Many other classification schemes out there

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
Reach	Riparian corridor and wood production Channel planform, migration, and features Channel geometry Sediment transport Riparian vegetation, aquatic vegetation, wood

Grabowski et al. 2014



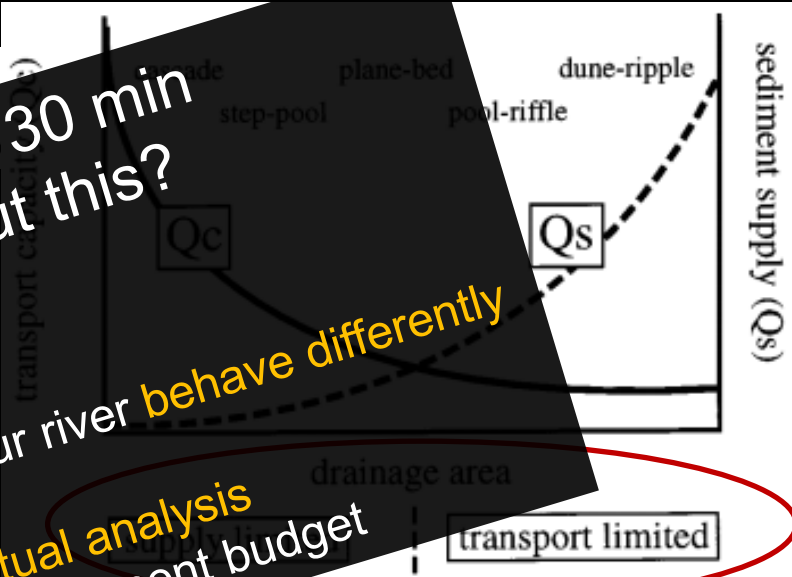
Many other classification schemes out there

Channel-reach morphology in mountain drainage basins

Montgomery and Buffington, 1997

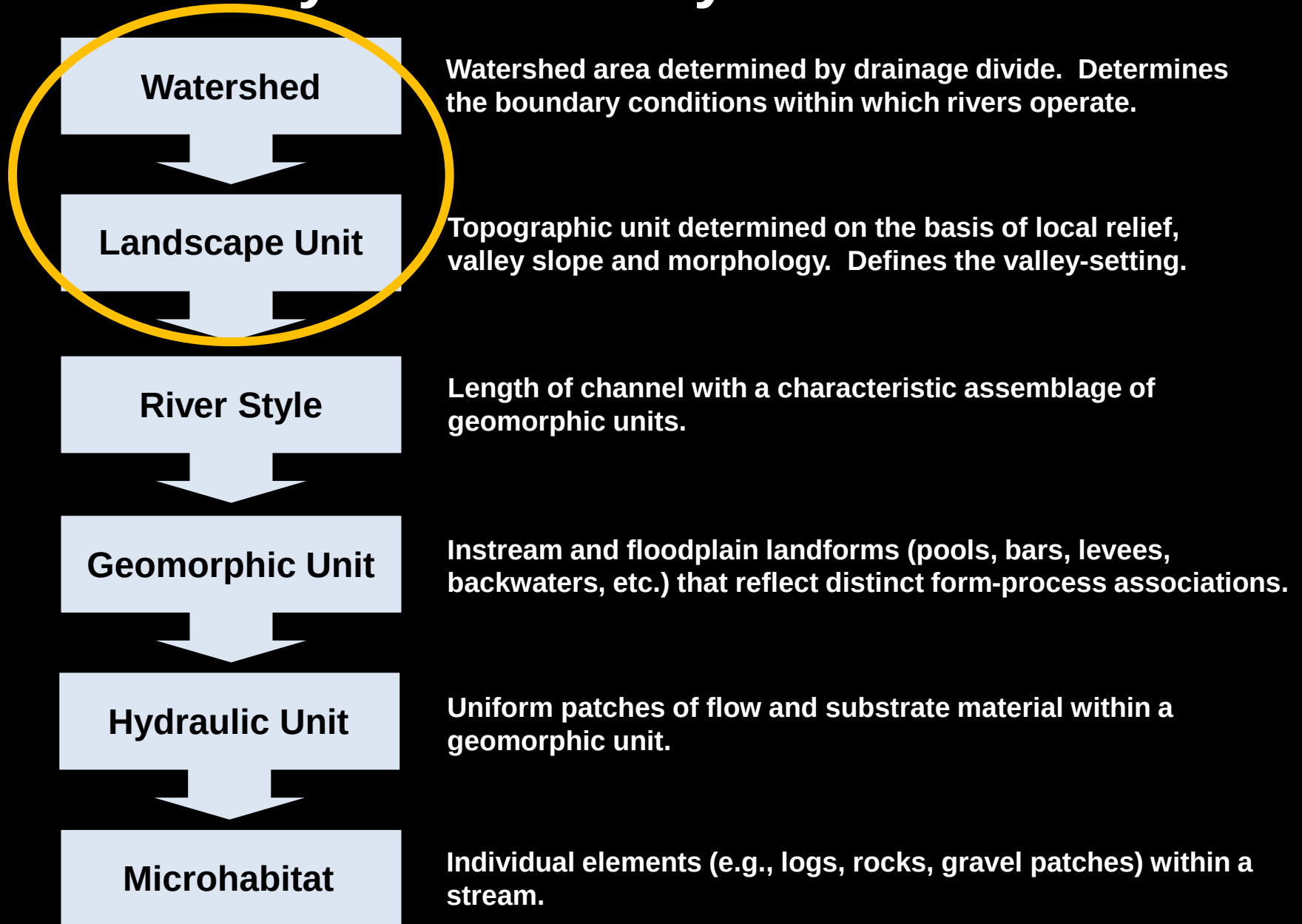
Why are we going to spend the next 30 min + most of the afternoon talking about this?

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



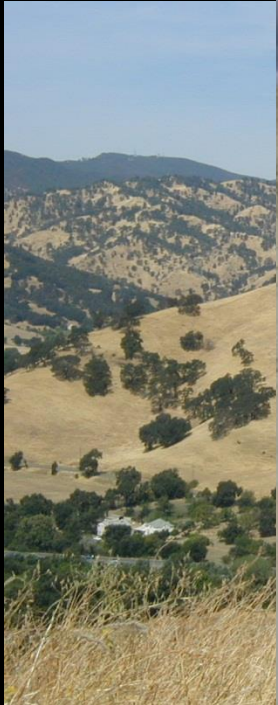
CHANNEL TYPE							
	Step pool	Cascade	Bedrock	Colluvial			
Typical bed material	Cobble-boulder	Boulder	Rock	Variable			
Bedform pattern	Vertically oscillatory	Random	Irregular	Variable			
Dominant roughness elements	Bedforms (steps, pools), grains, banks	Grains, banks	Boundaries (bed and banks)	Grains			
Dominant sediment sources	Fluvial, bank failure	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Hillslope, debris flows			
Sediment storage elements	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

River Styles Hierarchy



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?



River Styles Hierarchy

Watershed

Watershed area determined by drainage divide. Determines the boundary conditions within which rivers operate.

Landscape Unit

Topographic unit determined on the basis of local relief, valley slope and morphology. Defines the valley-setting.

River Style

Length of channel with a characteristic assemblage of geomorphic units.

Geomorphic Unit

Instream and floodplain landforms (pools, bars, levees, backwaters, etc.) that reflect distinct form-process associations.

Hydraulic Unit

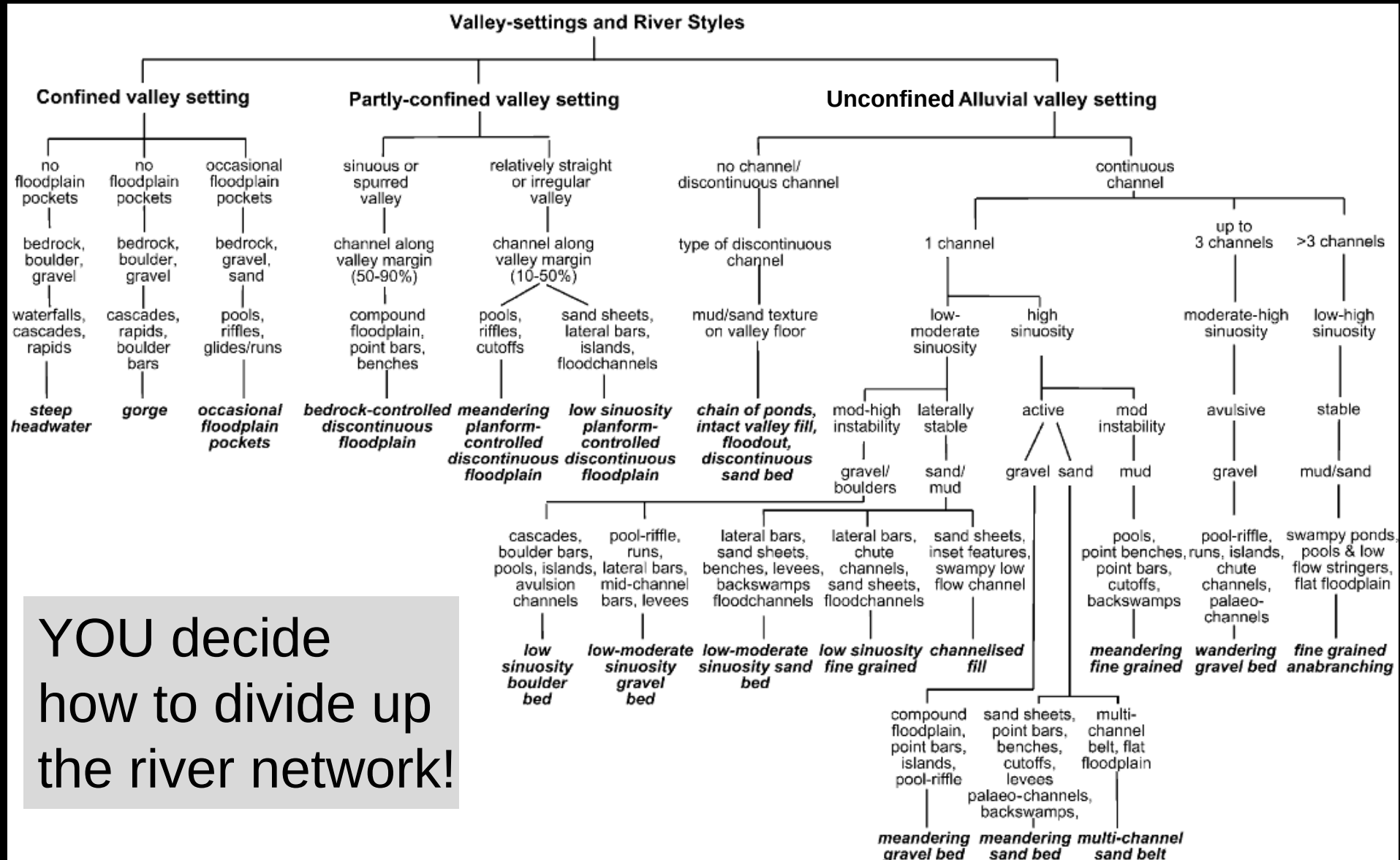
Uniform patches of flow and substrate material within a geomorphic unit.

Microhabitat

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

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!

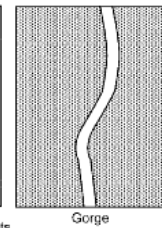
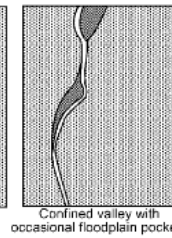
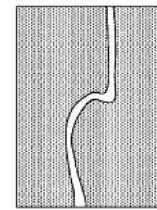
Visual representation of NSW River Styles

Which river styles are you working on?

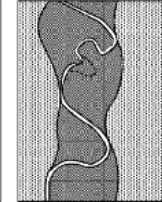
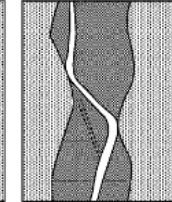
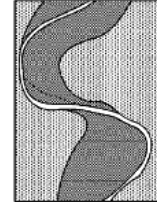
These are each different
'process domains'

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

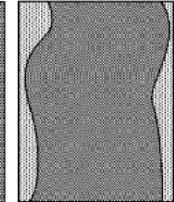
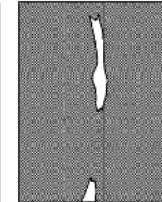
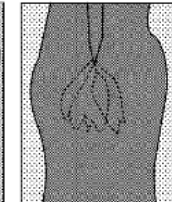
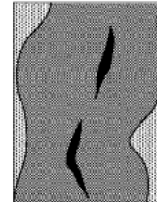
Confined valley setting



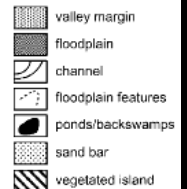
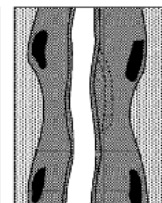
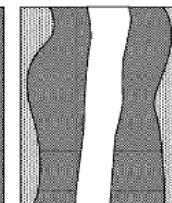
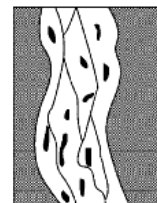
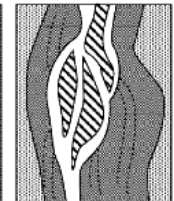
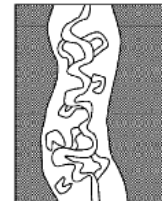
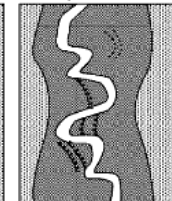
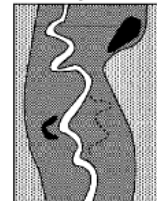
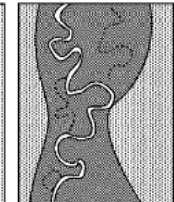
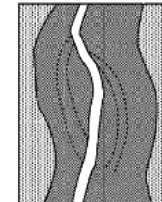
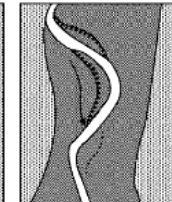
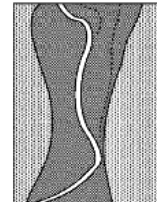
Partly-confined valley setting



Alluvial valley setting (Discontinuous channel)

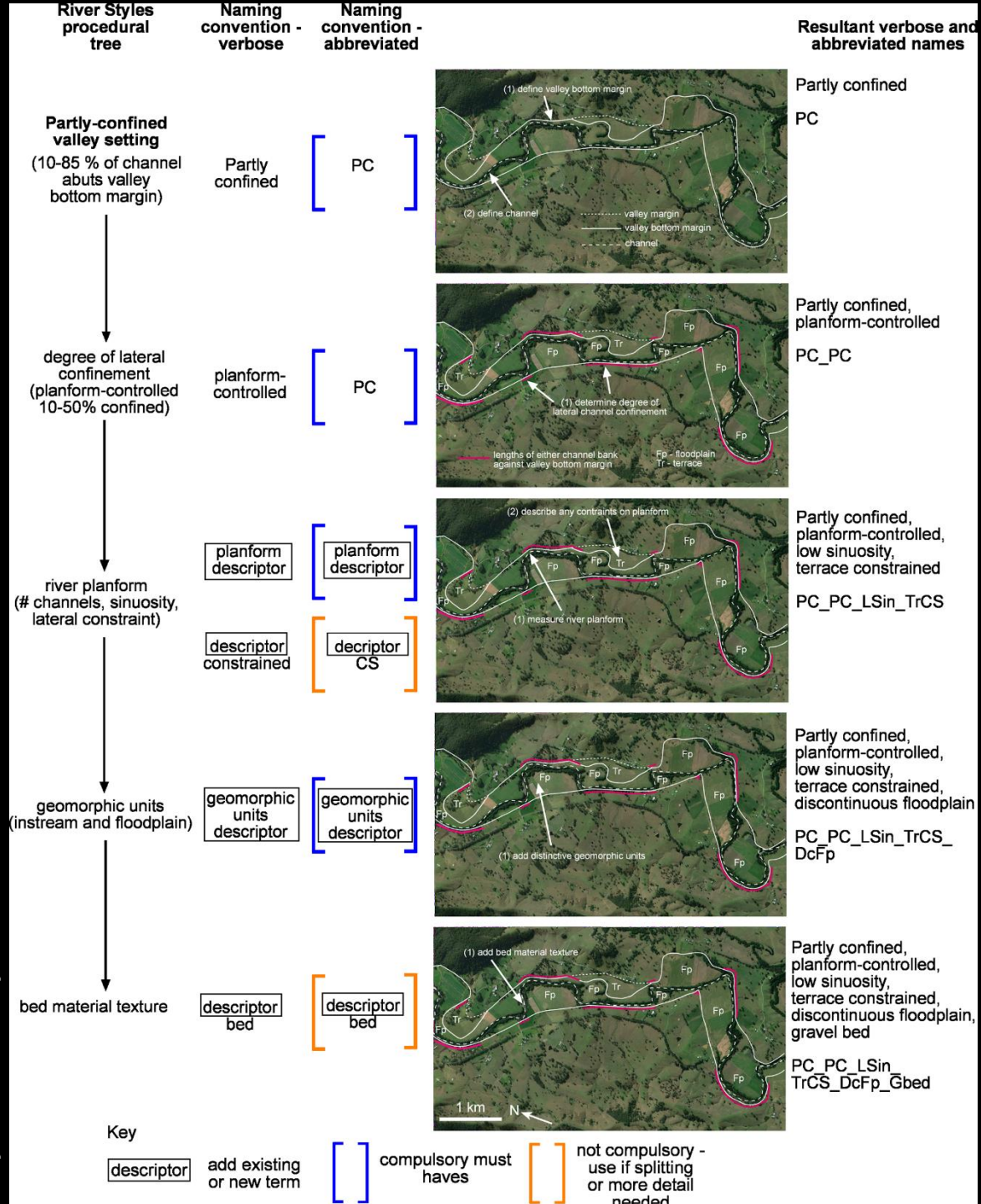


Alluvial valley setting (Continuous channel)



What's in a name?

Flyirs 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

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

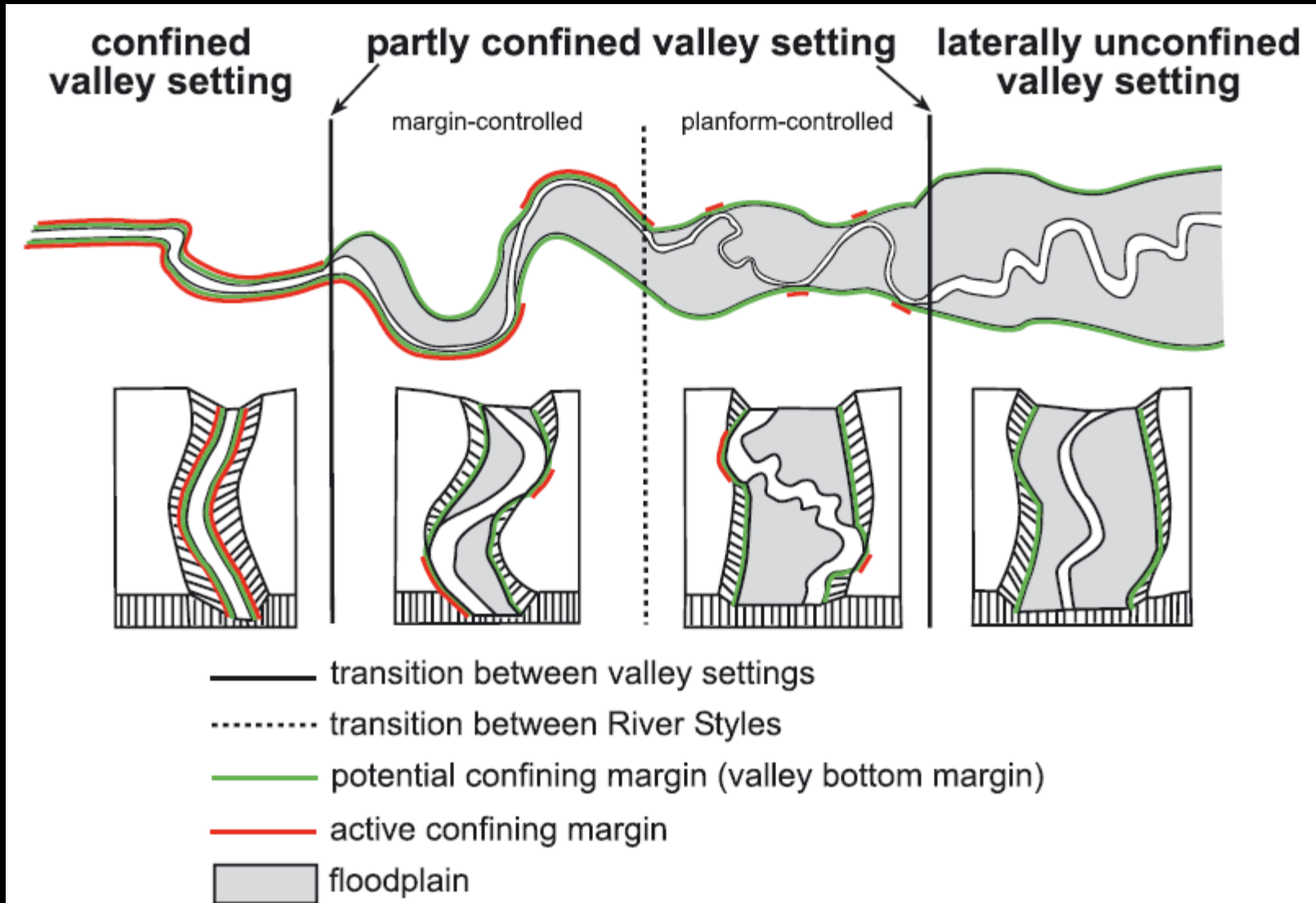
90-50%: margin controlled
10-40%: planform controlled



Unconfined

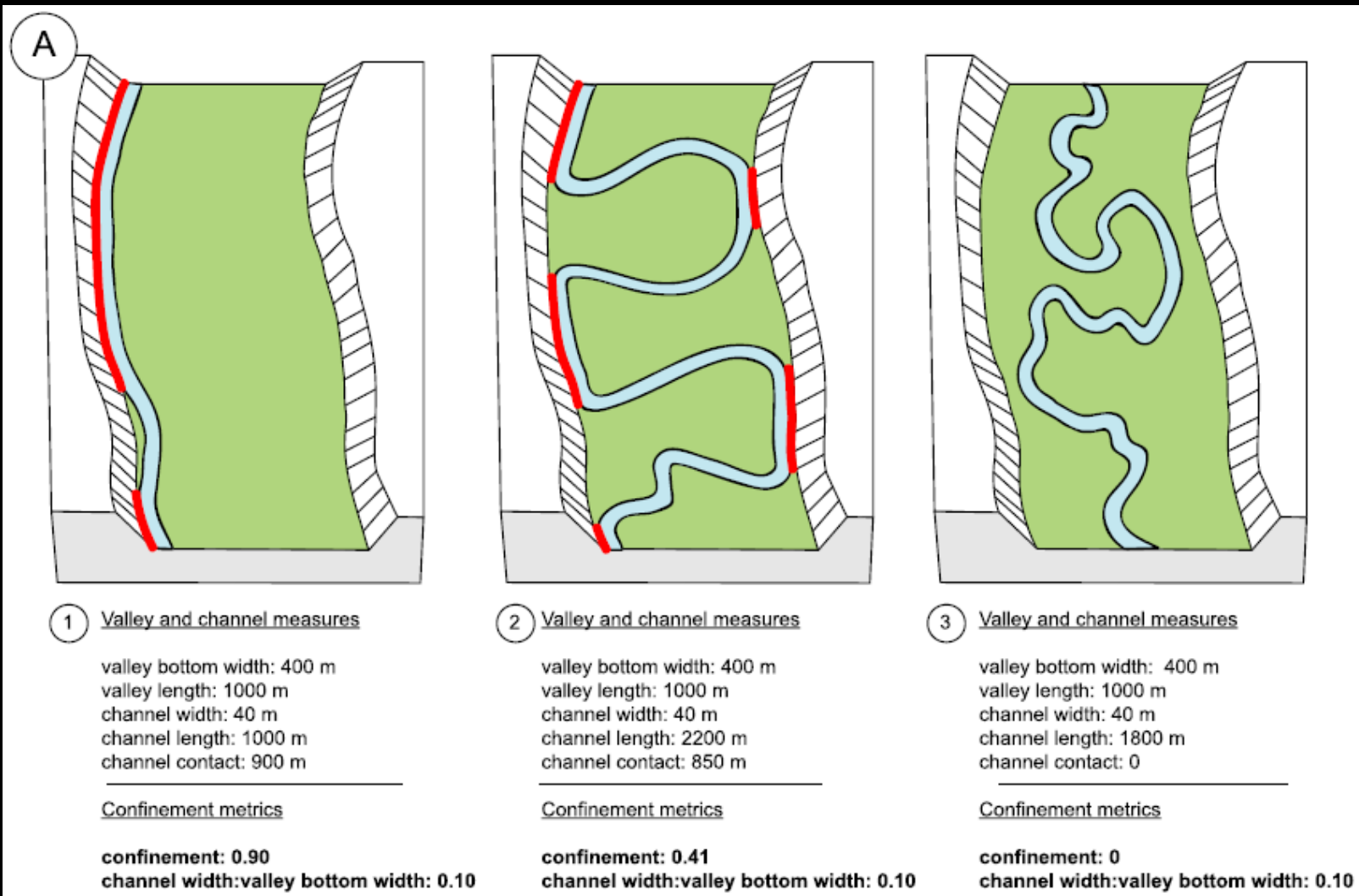
<10% interacting with cm

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

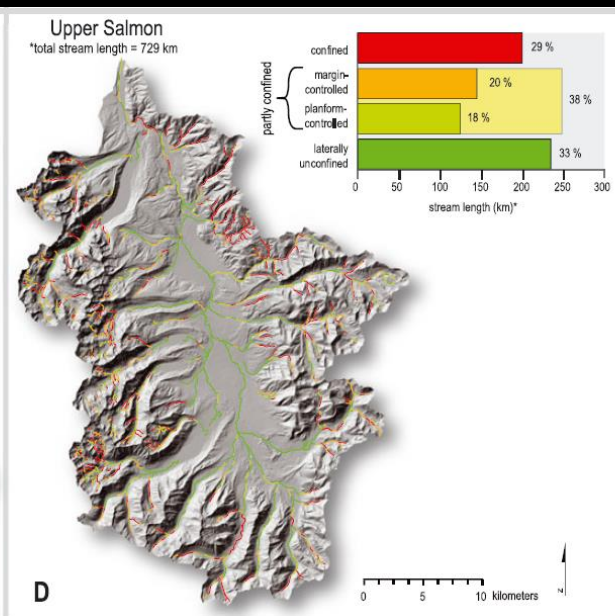
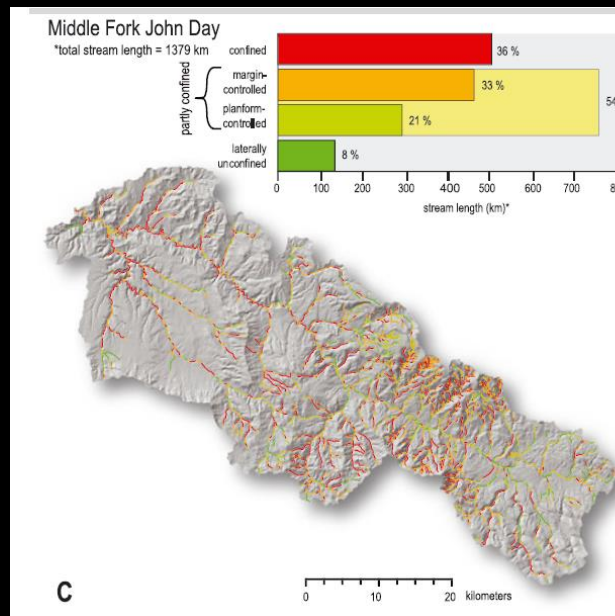
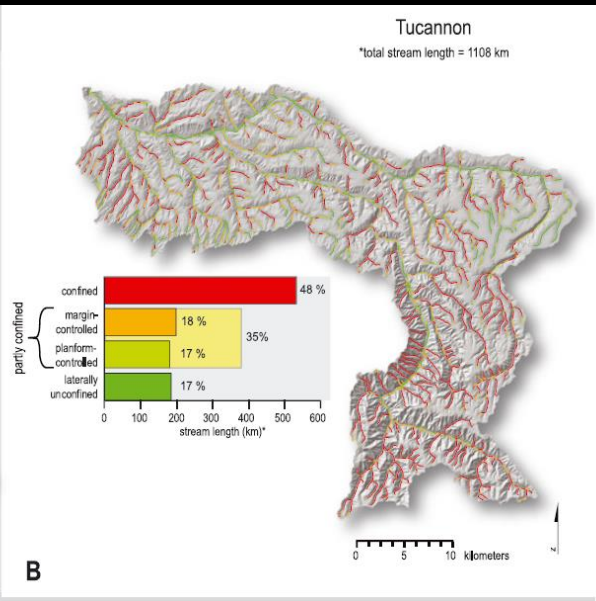
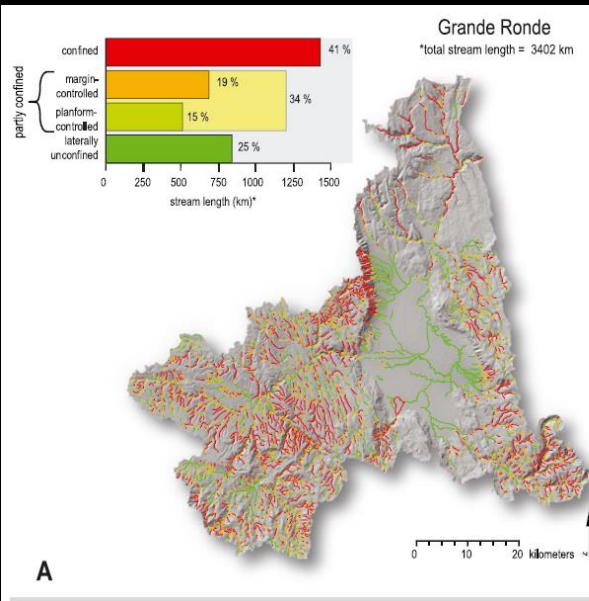


Confinement tells you more than any other metric about channel constraints and adjustment capacity

All have the same channel/valley ratio!



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



River Styles Hierarchy

Watershed

Watershed area determined by drainage divide. Determines the boundary conditions within which rivers operate.

Landscape Unit

Topographic unit determined on the basis of local relief, valley slope and morphology. Defines the valley-setting.

River Style

Length of channel with a characteristic assemblage of geomorphic units.

Geomorphic Unit

Instream and floodplain landforms (pools, bars, levees, backwaters, etc.) that reflect distinct form-process associations.

Hydraulic Unit

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

Microhabitat

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

Second tier characteristics for classification

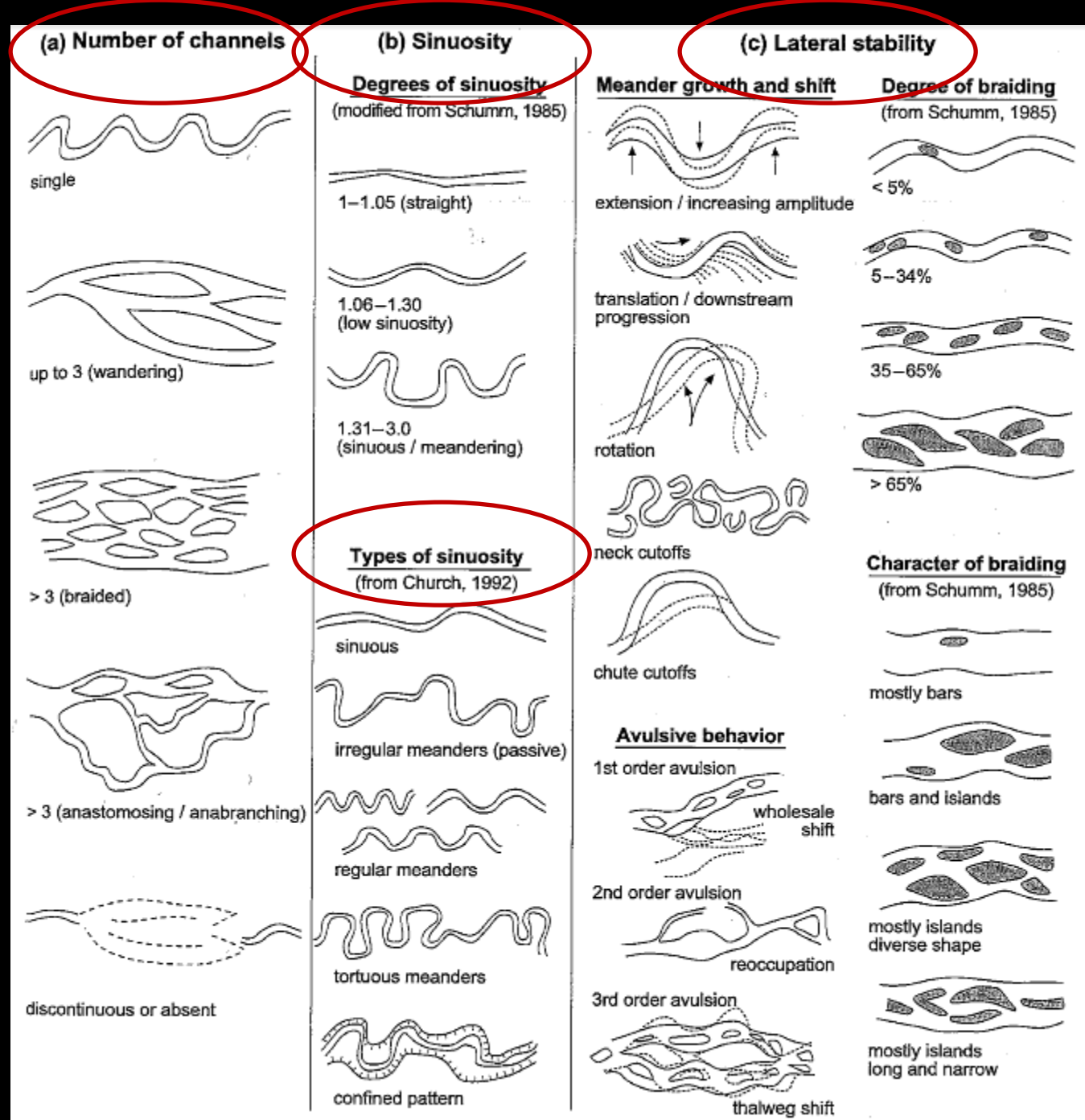
Indicators of channel behavior

Assemblage of geomorphic units that make up a reach

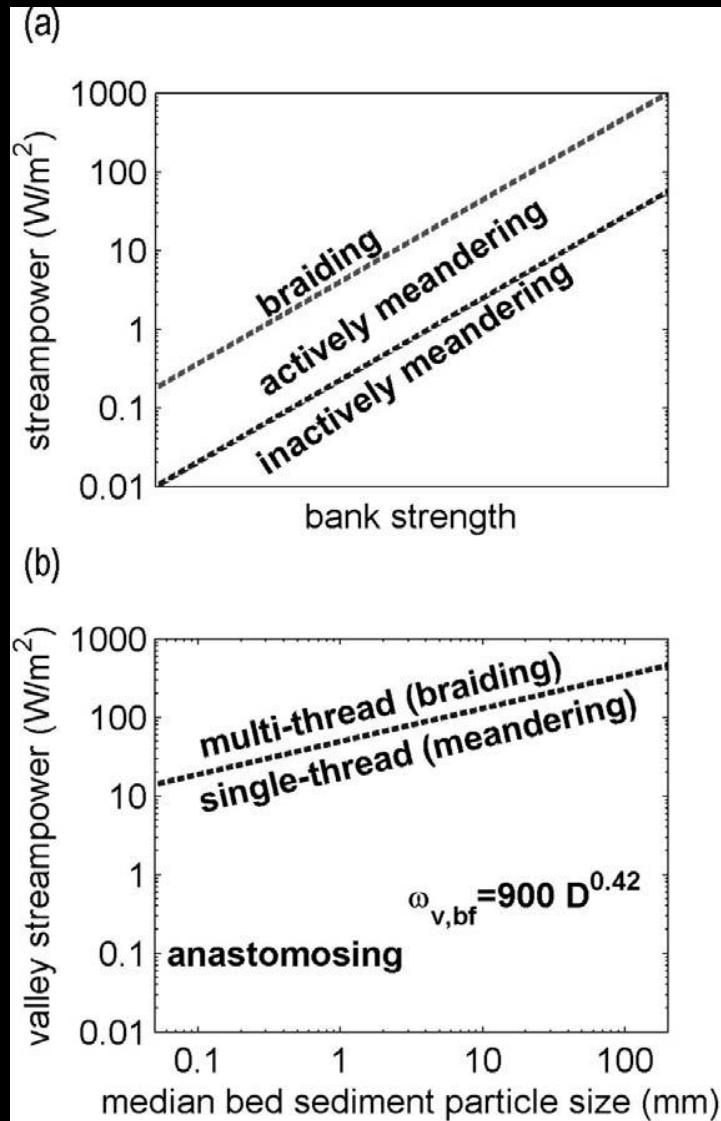
Channel planform

Bed material texture

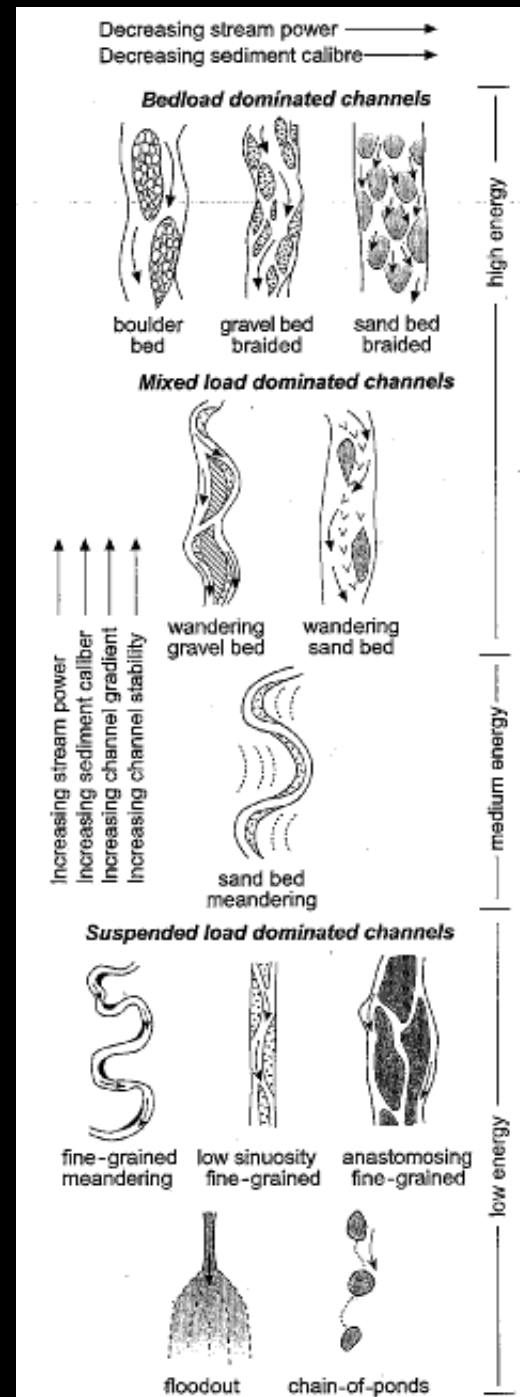
Metrics of channel planform



Interpretations from channel planform

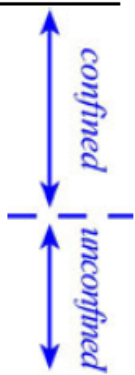
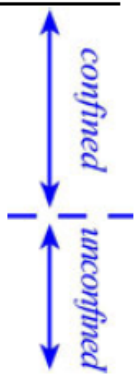


Kleinhans, 2010



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	+	+	+/+	

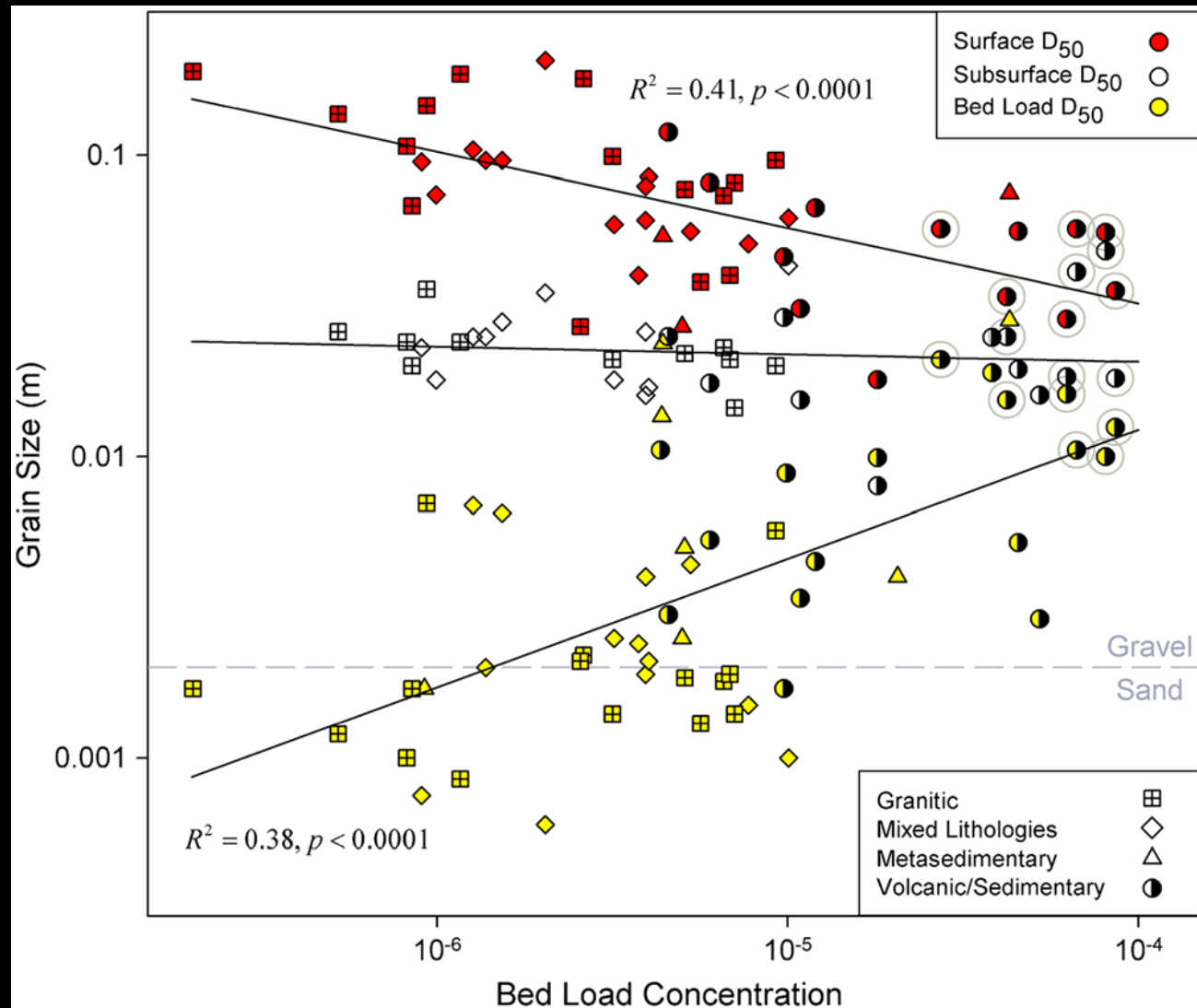
^a Modified from [Montgomery and Buffington \(1997\)](#). Response potential for each channel type is discussed elsewhere (Montgomery and Buffington, 1997; 1998; Buffington *et al.*, 2003).

^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.

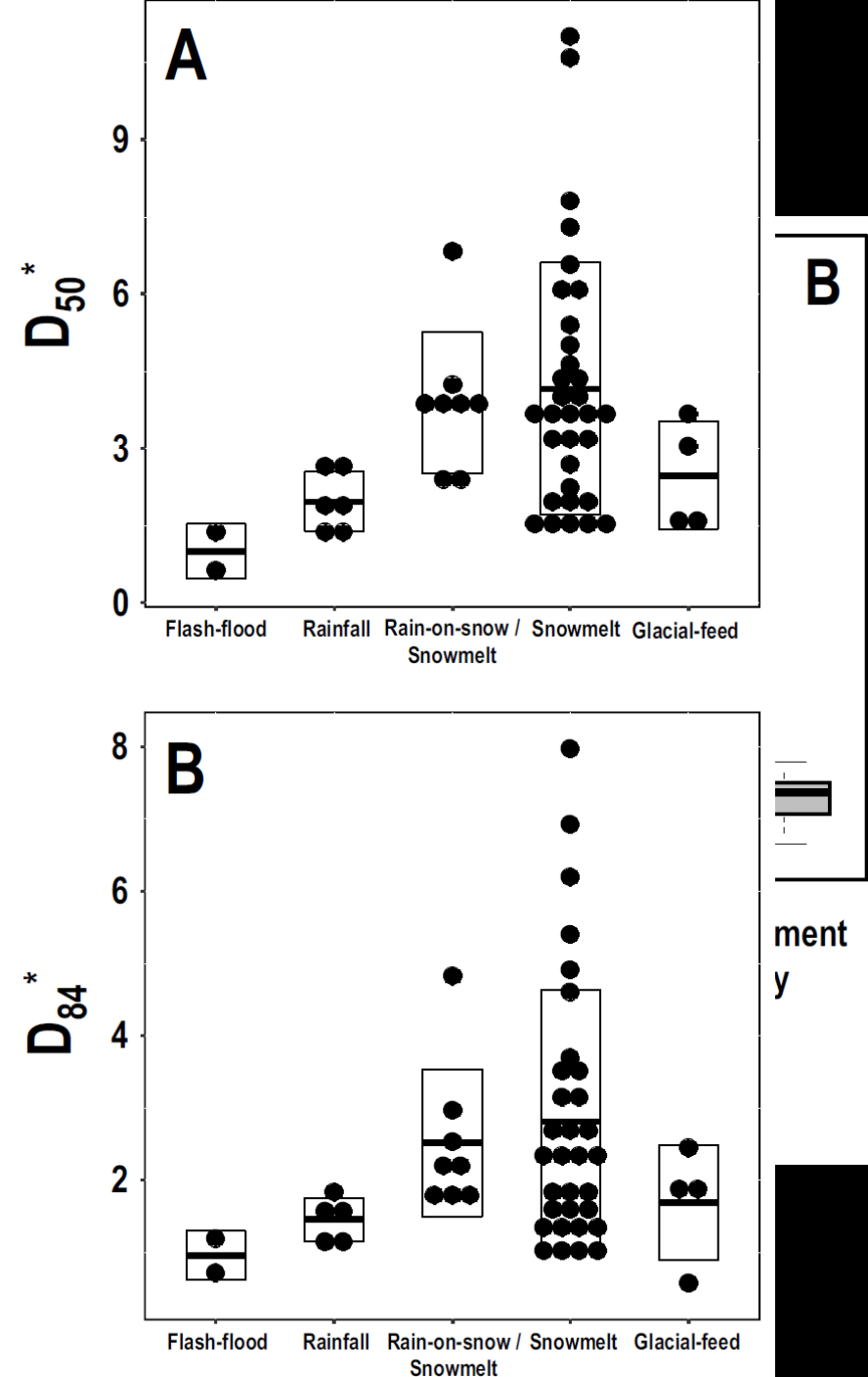
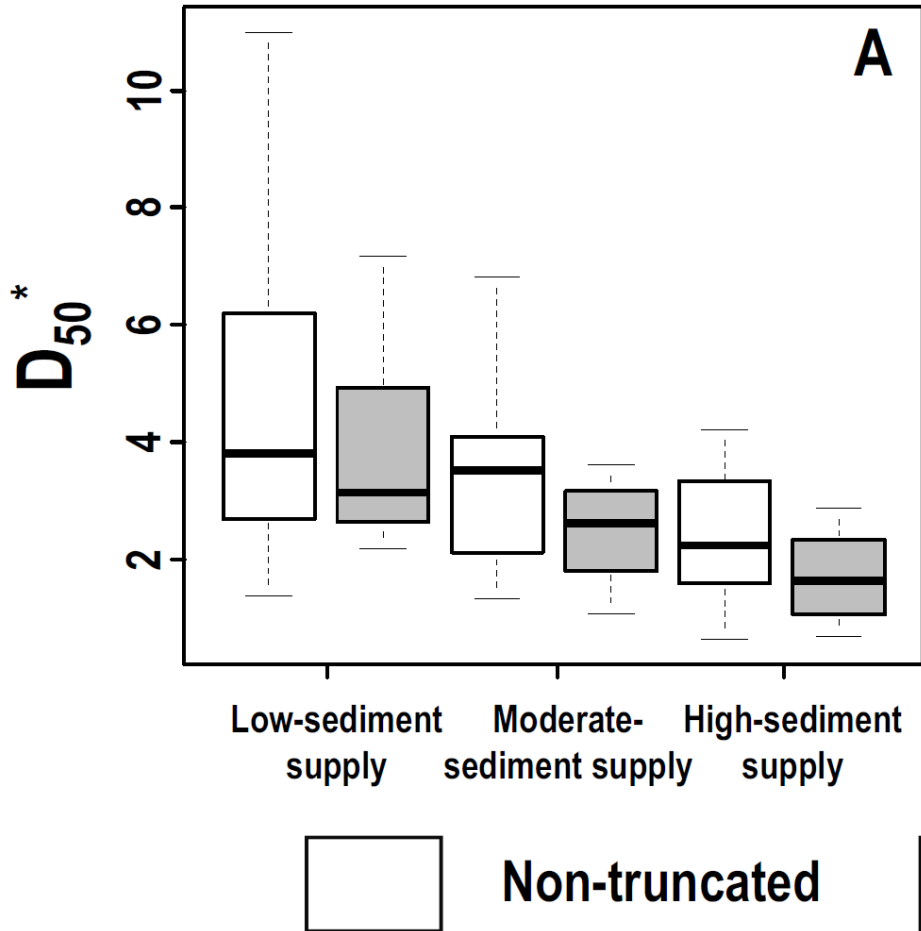
^c Fluvial incision/deposition is possible, depending on the degree of colluvial fill.

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

Armoring allows gravel bed rivers to adjust transport rates to changes in sediment supply



Armoring tends to increase D_{50}^* in low sediment supply conditions



Tools for geomorphic assessments

<https://riverscapes.xyz/>

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
<i>Confinement and valley setting</i>		
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)
<i>River planform</i>		
Fluvial corridor toolkit (FCT)	https://github.com/EVS-GIS/Fluvial-Corridor-Toolbox-ArcGIS	Roux et al. (2015)
Geomorphic network and analysis toolkit (GNAT)	http://gnat.riverscapes.xyz/ http://brat.riverscapes.xyz/	Macfarlane, Gilbert, et al. (2017); Macfarlane, Wheaton, et al. (2017)
Beaver restoration assessment tool (BRAT)		
<i>Geomorphic units</i>		
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)
<i>Bed material texture</i>		
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)
<i>River behavior</i>		
Morphological change—Geomorphic change detection (GCD)	http://gcd.riverscapes.xyz/	Wheaton, Brasington, Darby, and Sear (2010); Wheaton et al. (2013)

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, Heimbarg, 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)
<i>Downstream patterns of rivers and controls</i>		
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



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 COMMENTARY¹

Thomas E. Lisle, John M. Buffington, Peter R. Wilcock, and Kristin Bunte²

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?

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.

TOMMORROW

Reach 1

Laterally unconfined, low gradient channel

Steep hillslopes deliver sediment to low gradient valley floor

Weak tuff and rhyolite bed



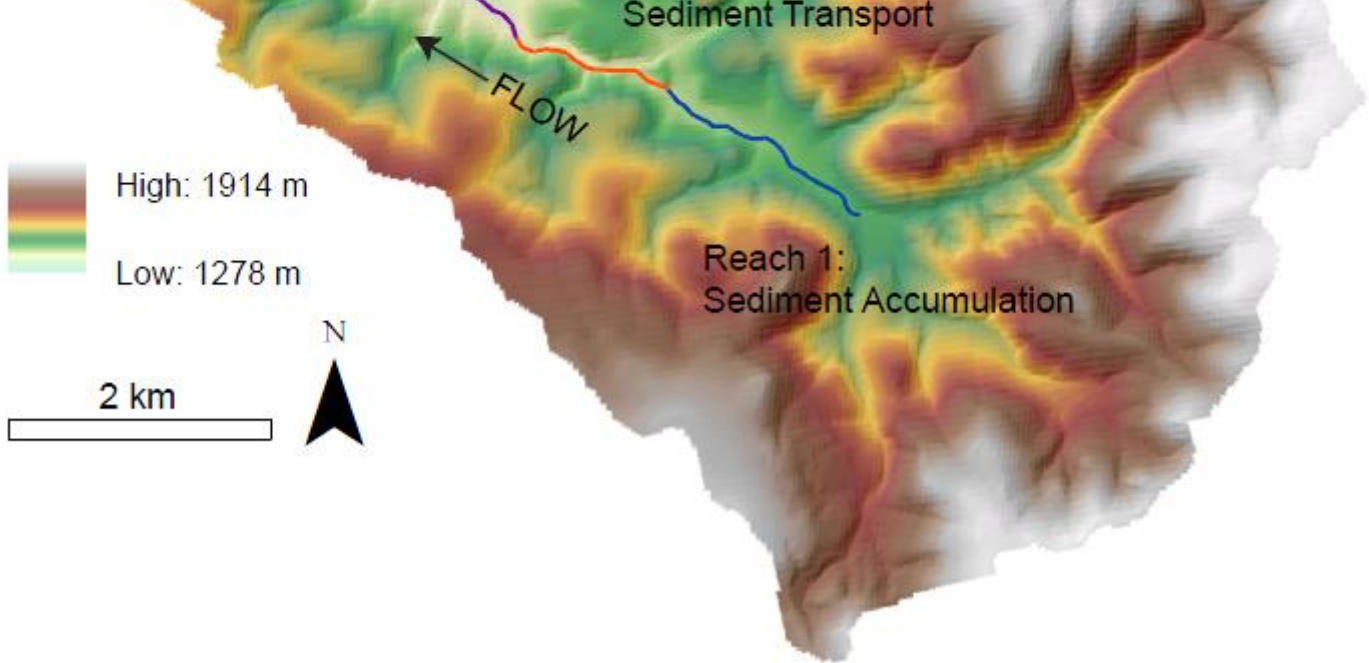
Example: North Fork Cable Creek, Oregon



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

NORTH FORK CABLE CREEK, OREGON

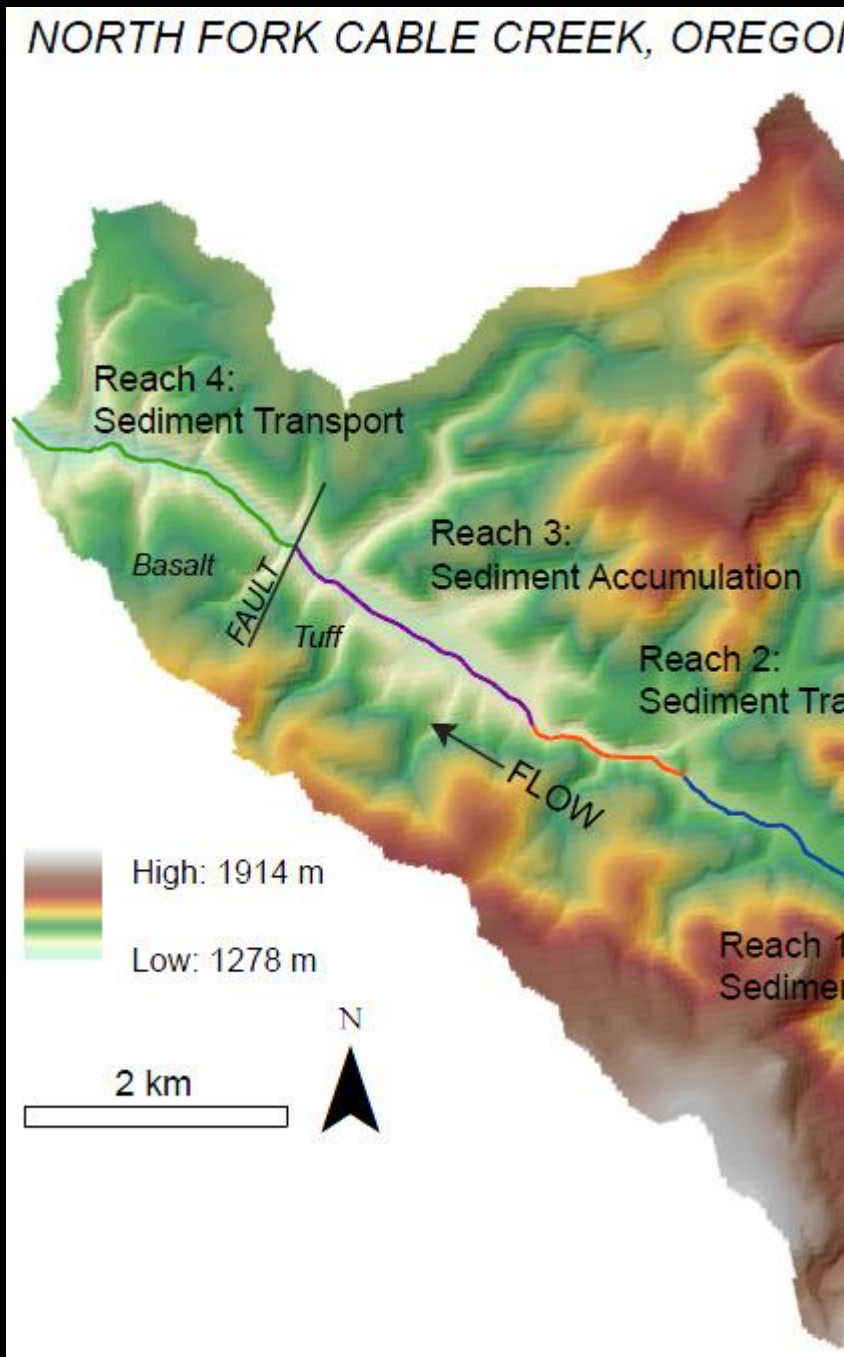


Reach 4

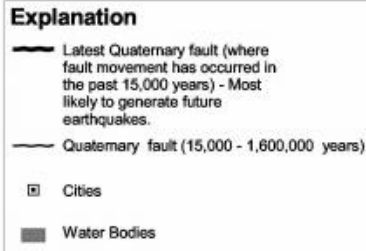
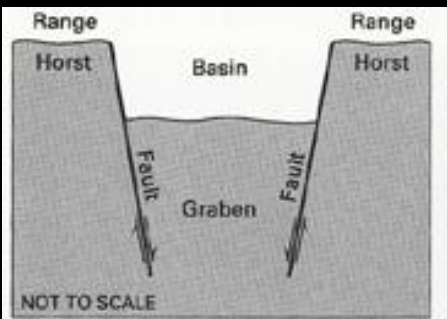
Partly confined, margin controlled

Channel crosses fault and enters onto hard Columbia River Basalt

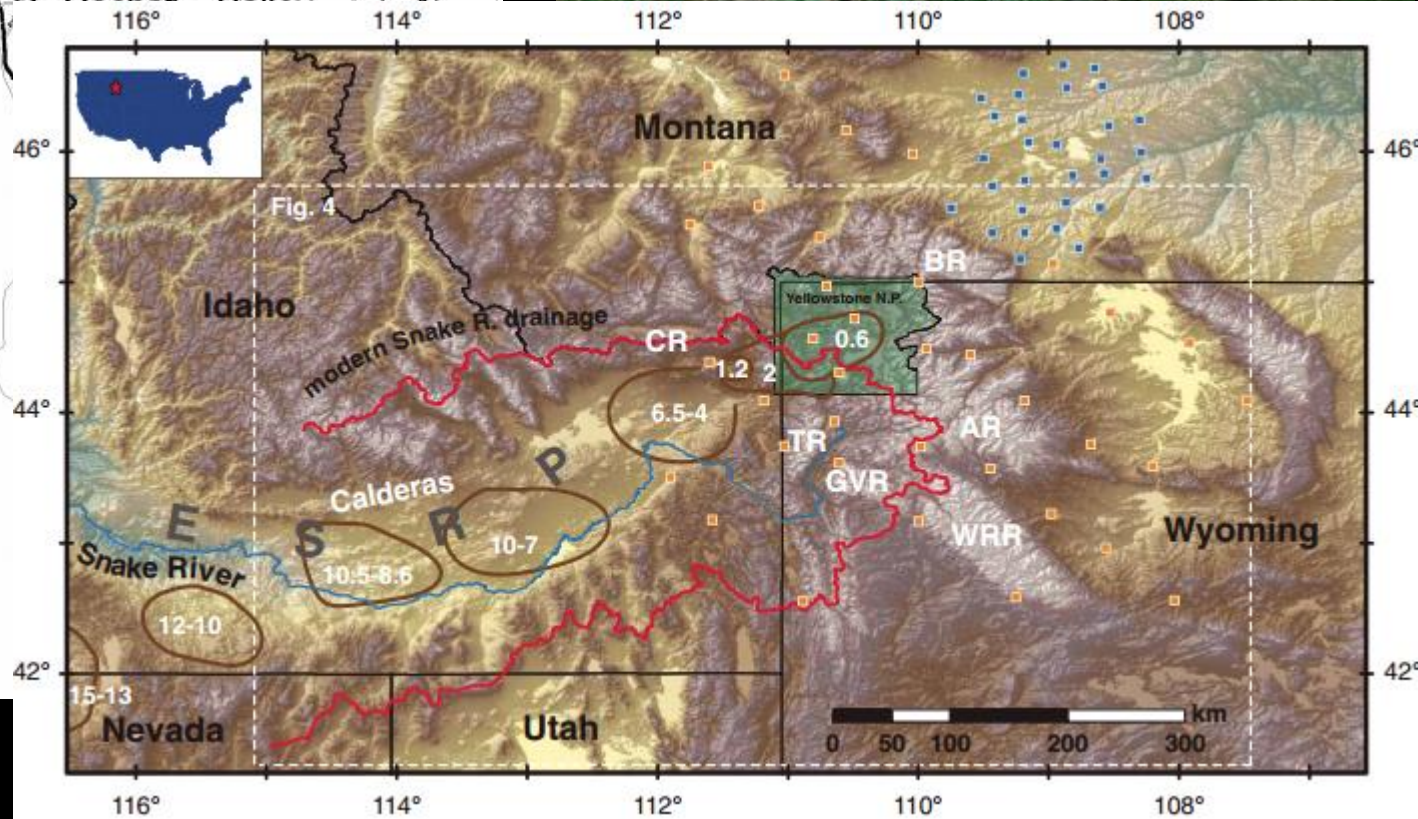
Step-pool to pool-riffle morphology



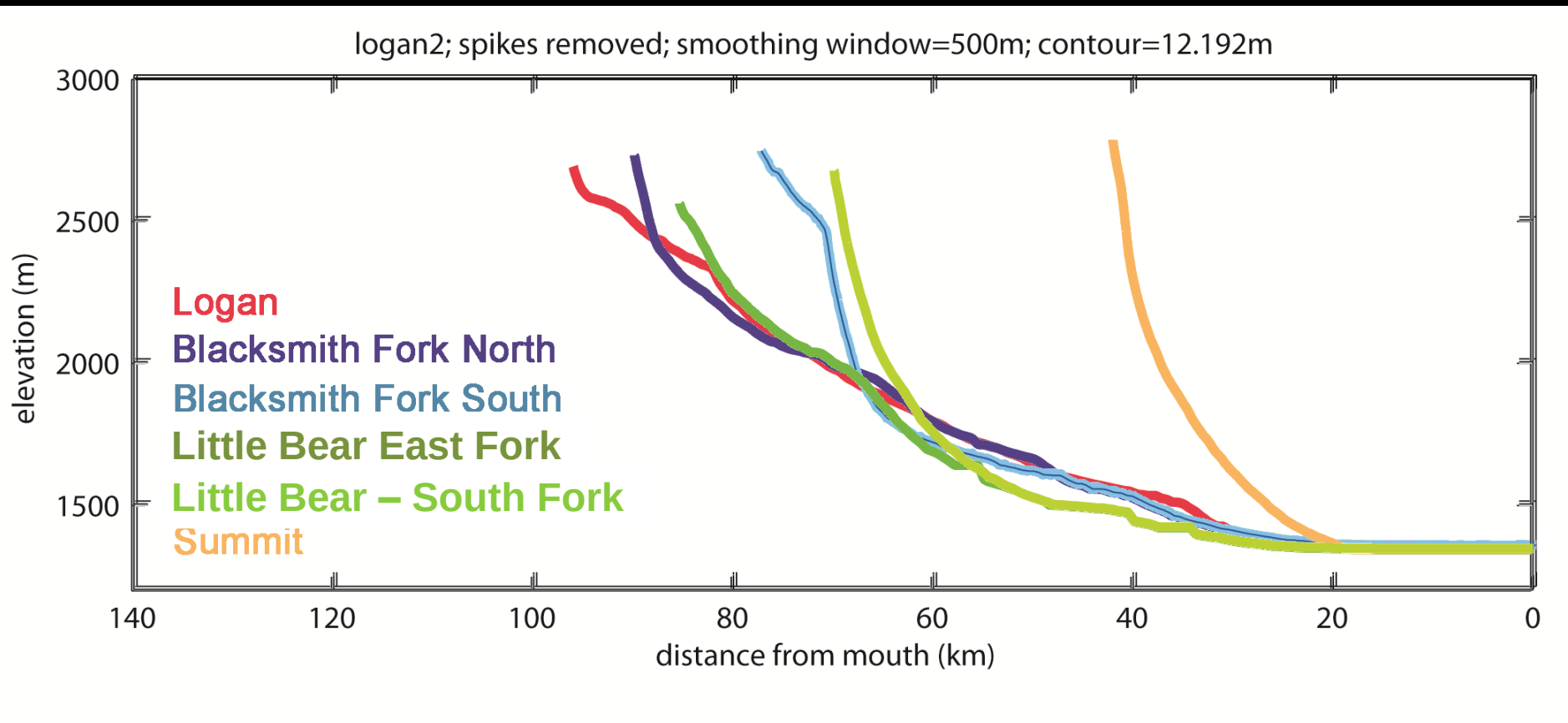
Some history on the landscape we'll be examining this afternoon



Map Location



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



Longitudinal profiles extracted with Stream Profiler Tool: geomorphtools.org

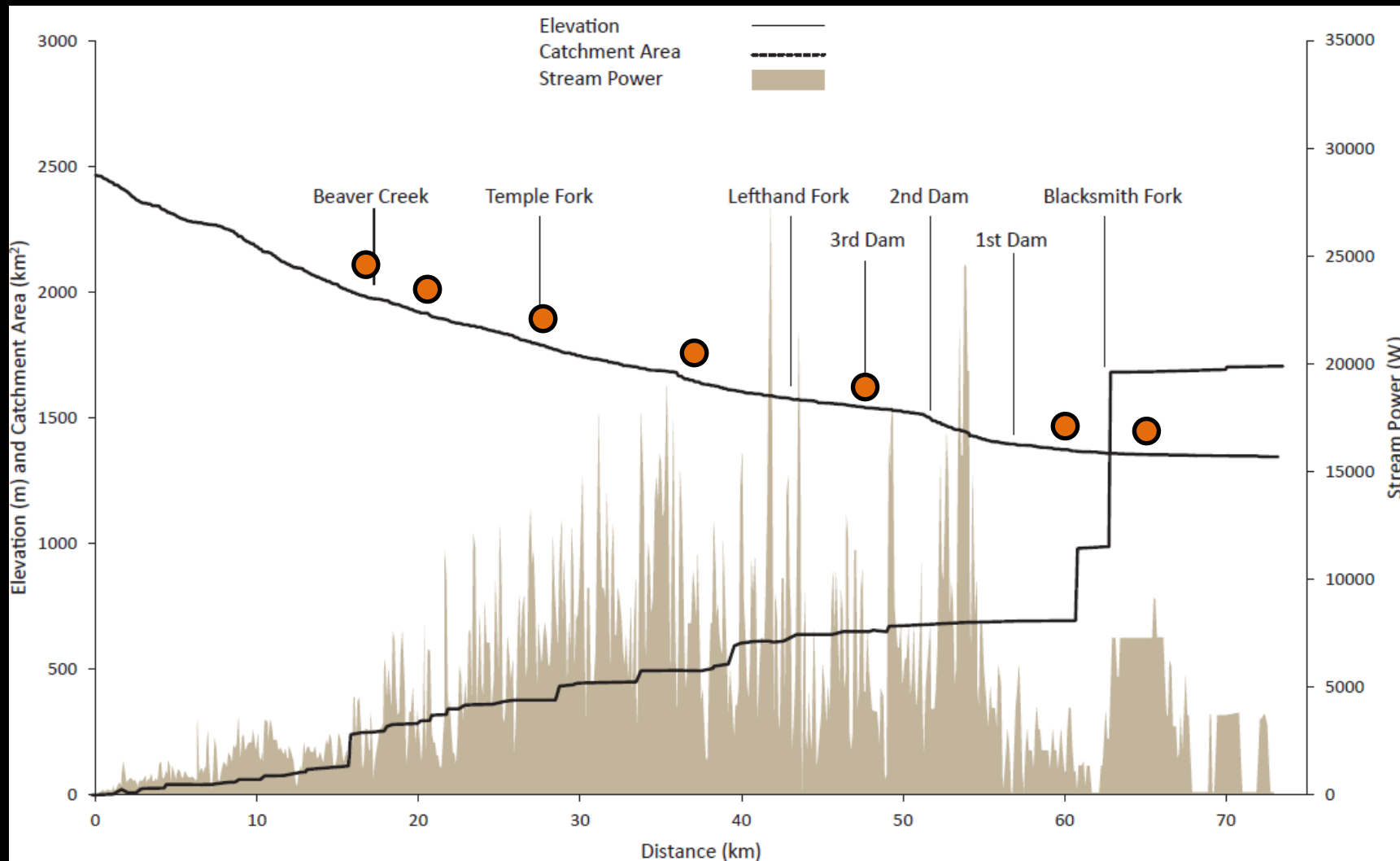


Figure from Gary O'Brien

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. Answers to questions at each stop and 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?