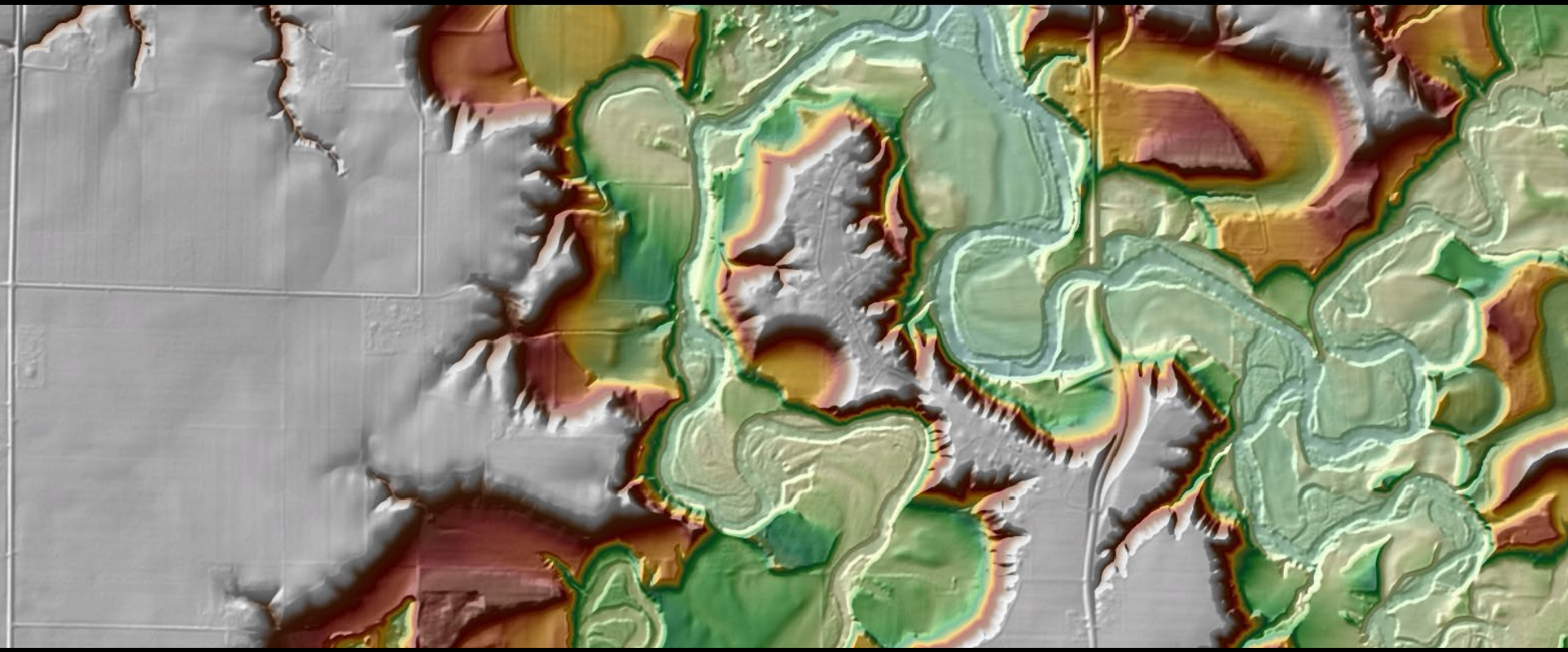
Watershed Context Tools and Techniques

Sediment Transport in Stream Assessment and Design
Tuesday, August 1, 2023
Patrick Belmont



Roadmap

YESTERDAY

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?

TODAY

Watershed Sediment Budget

Tools and techniques for robust constraints on sources and sinks.

Case studies in sediment supply, transport, and morphodynamics

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.

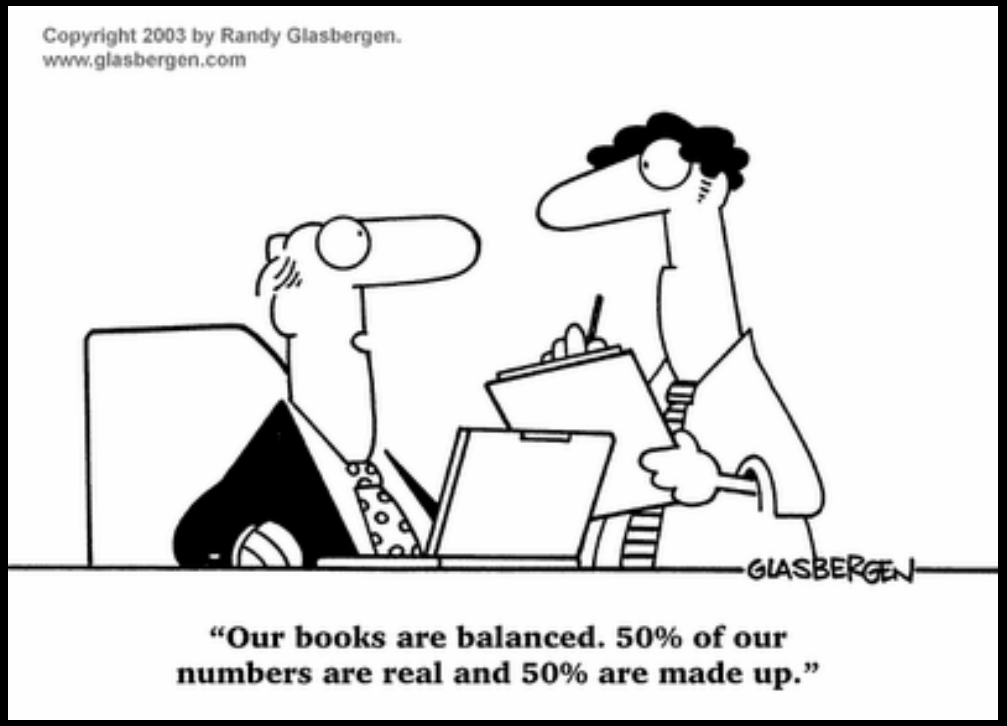
A bit of hydrology

Targeted modeling and metrics. Stationarity Assumption?

Reservoir and pond sedimentation rates

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

Sediment budget: An accounting tool



Inputs from watershed to channel

Output measured at channel outlet

Change in channel storage

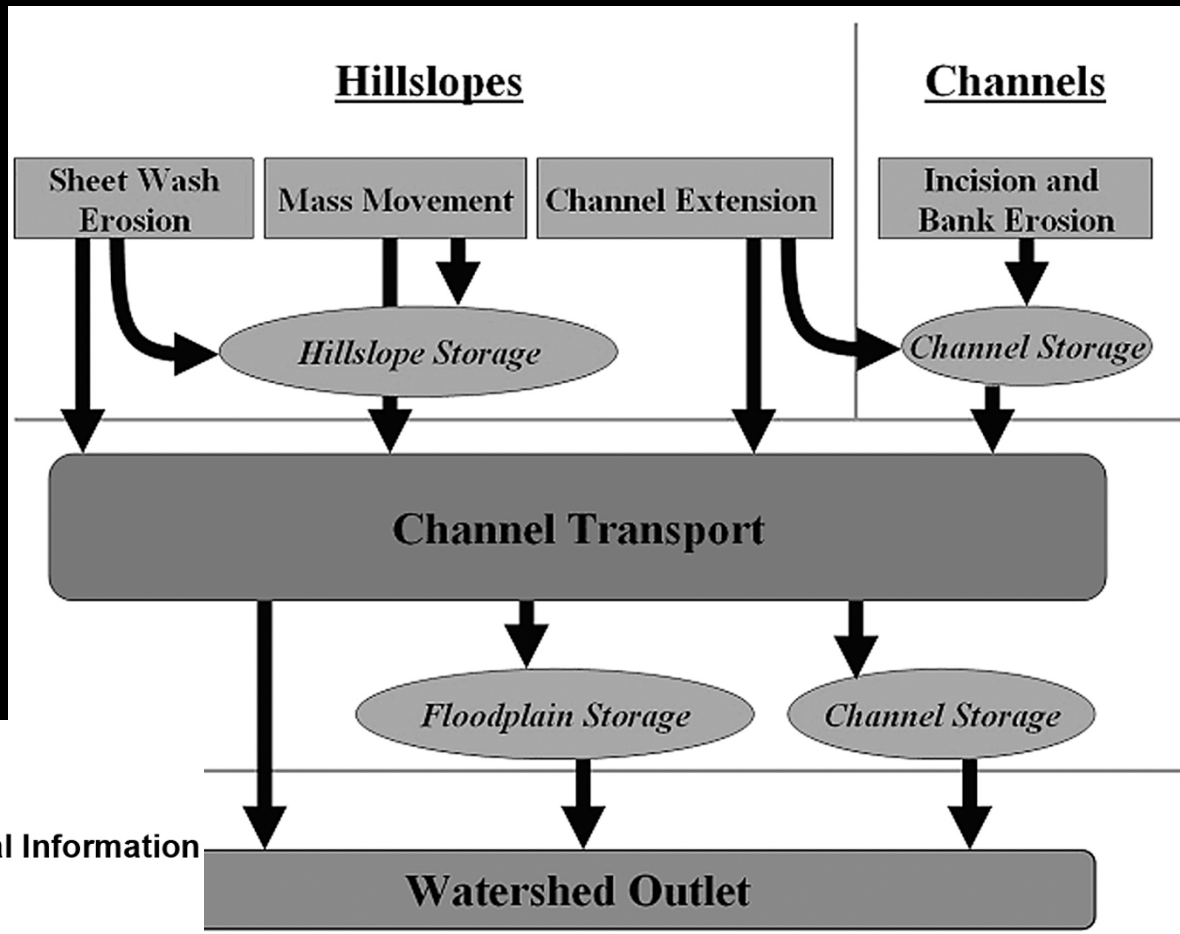
$$I - O = \Delta S$$

Over a specified time period

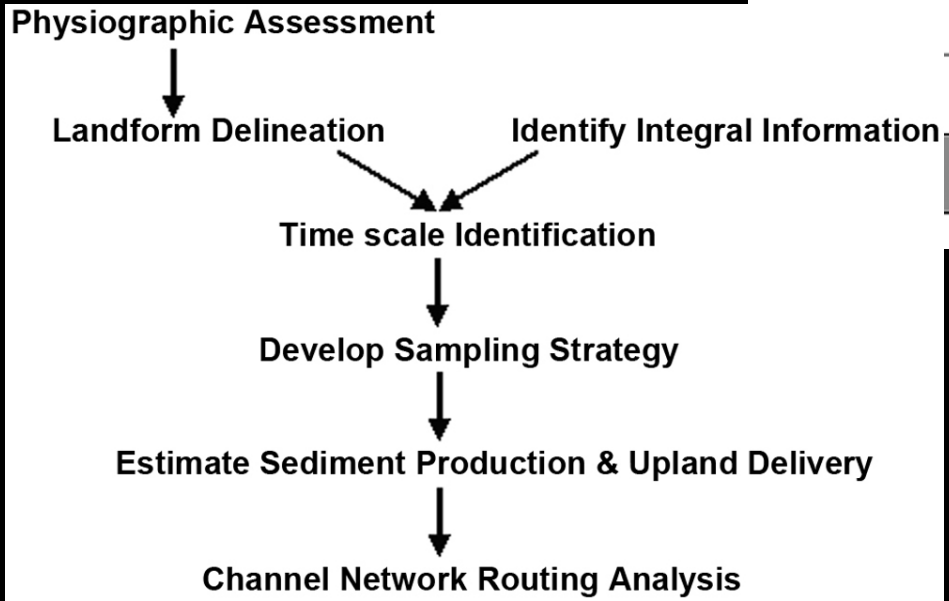
Sediment budget: Sources and sinks with uncertainty

Typically need several different tools to constrain each of these

Redundancy in measurements is good practice



Smith et al., 2011



Four keys to constraining a budget

(1) specificity regarding location, mechanism, and rates of sediment erosion

(2) accurate treatment of changes in sediment storage

(3) redundant measurements for all sediment fluxes

(4) appropriate methods for up-scaling local observations

Smith et al., 2011

Common techniques for developing budgets

Technique	Used to Measure Erosion or Deposition	Watershed Elements Quantified	Time Scales	Applicable Spatial Scales	References
Monitoring suspended sediment loads	erosion and deposition	watersheds and tributaries, channel reaches	years, decades, individual storm events	km	*Milliman and Meade* [1983], *Parker* [1988], *Fitzpatrick et al.* [1999], *Syvitski et al.* [2003], *Gellis et al.* [2006]
Aerial photography and LIDAR[a]	erosion and deposition	stream banks, roads, land use/land cover	years, decades, individual storm events	m, km	*Bartley et al.* [2008], *Keen et al.* [2008], *Pizzuto et al.* [2007], *Piégay et al.* [2005], *Thoma et al.* [2005], *Gellis* [2002], *Evans et al.* [2006], *Lawler* [1993]
Aerial photography[a]	erosion	mass movements	years, decades, individual storm events	km	*Wallbrink et al.* [2002], *Larsen and Santiago-Roman* [2001], *Dietrich et al.* [1982]
Historical maps	erosion and deposition	channels, channel bars	years, decades	m, km	*Kesel et al.* [1992]
Erosion pins	erosion and deposition	sheetwash	years, days, individual storm events	cm, m	*Leopold et al.* [1966], *Visser et al.* [2007]
Field surveying, historical surveys, and inventorying	erosion and deposition	channels, gullies, channel bars	years, decades, individual storm events	m, km	*Leopold et al.* [1966], *Munro et al.* [2008], *Marzolff and Ries* [2007], *Gellis et al.* [2001b], *Wijdenes and Bryan* [2001], *Kesel et al.* [1992], *Trimble* [1983]
Radionuclide inventories (^{137}Cs, ^{210}Pb)	erosion and deposition	upslope areas of varying land use and land cover	decades	km	*Campbell et al.* [1988], *Ritchie and McHenry* [1990], *Walling and Bradley* [1990], *Walling and Quine* [1991], *Walling and He* [1999b], *Nagle et al.* [2000], *Wallbrink et al.* [2002], *Walling et al.* [2003b], *Zapata* [2002]
Radionuclides as time horizon markers (^{137}Cs, ^{210}Pb)	deposition	floodplains, lake and pond sediment	decades	km	*Amos et al.* [2009], *Ritchie et al.* [2004], *Terry et al.* [2002], *Walling and He* [1997b], *Walling et al.* [2001]
Dendrochronology	erosion and deposition	channels, floodplains	decades, years	m, km	*Allmindinger et al.* [2007], *Hupp and Bazemore* [1993], *Dietrich et al.* [1982]
Clay pads	deposition	floodplains	years, individual storm events	m	*Gellis et al.* [2009], *Hupp and Bazemore* [1993]
Bank pins	erosion and deposition	stream banks	years, days, individual storm events	cm, m	*Thorne* [1981], *Bartley et al.* [2006], *Lawler* [1993]
Sediment traps	erosion	upslope areas of varying land use and land cover	years, days, individual storm events	m, km	*Gellis et al.* [2006], *Larsen et al.* [1999]
Resuspension cylinder	deposition	channel storage	days, individual storm events	M	*Lambert and Walling* [1988]
Sediment fingerprinting	erosion	watershed areas under varying land cover or geologic type	years, individual storm events	km	*Walling and Woodward* [1995], *Collins et al.* [1997], *Motha et al.* [2003], *Walling* [2005]
Ponds and lakes	deposition	lake bottoms and deltas	decades, years	km	*Leopold et al.* [1966]
Sediment models[b]	erosion and deposition	hillslopes, channels	decades, years, days, individual storm events	m, km	*Fu et al.* [2010], *Evans et al.* [2006], *Croke and Nethery* [2006], *Aksoy and Kavvas* [2005], *Chen and Lai* [2005], *Merritt et al.* [2003], *Bhuyan et al.* [2002]

Basic questions you want to answer

What are the grain sizes of interest?

Where do those exist in the watershed?

What geomorphic processes convey them to the channel?

Contributions from near-channel sources or hillslope/watershed sources?

Near channel:
river migration, incision, widening processes

Hillslope/watershed:
creep, rill erosion, debris flows, landslide processes

Where are erosion/deposition hotspots? Natural or human influenced?

Erosion relatively steady or pulsed?

Where are the disconnects in the sediment routing system?

Basic questions you want to answer

What are the grain sizes of interest?

Where do those exist in the watershed?

What geomorphic processes convey them to the channel?

Washload

Hillslope soils →

Floodplain/Terraces →

Trails/Roads →



Basic questions you want to answer

What are the grain sizes of interest?

Where do those exist in the watershed?

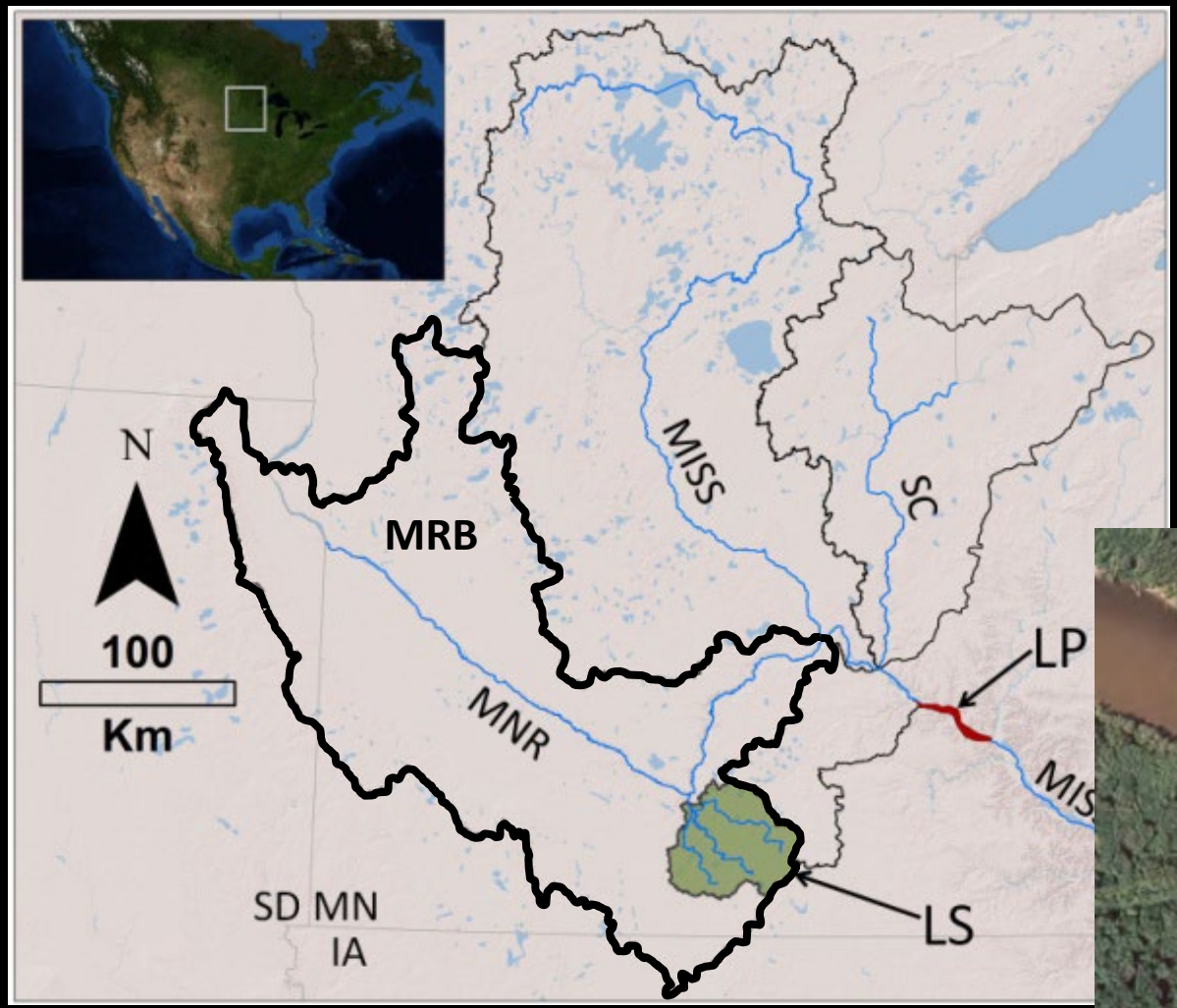
What geomorphic processes convey them to the channel?

Bed material

Hillslopes →

Trails/Roads →

Sediment, nutrient problems in the upper Mississippi River



Minnesota River Basin:
336 impairments for sediment, nutrients, aquatic life

MRB is primary source of sediment and nutrients for the upper Mississippi



Corn and soybeans



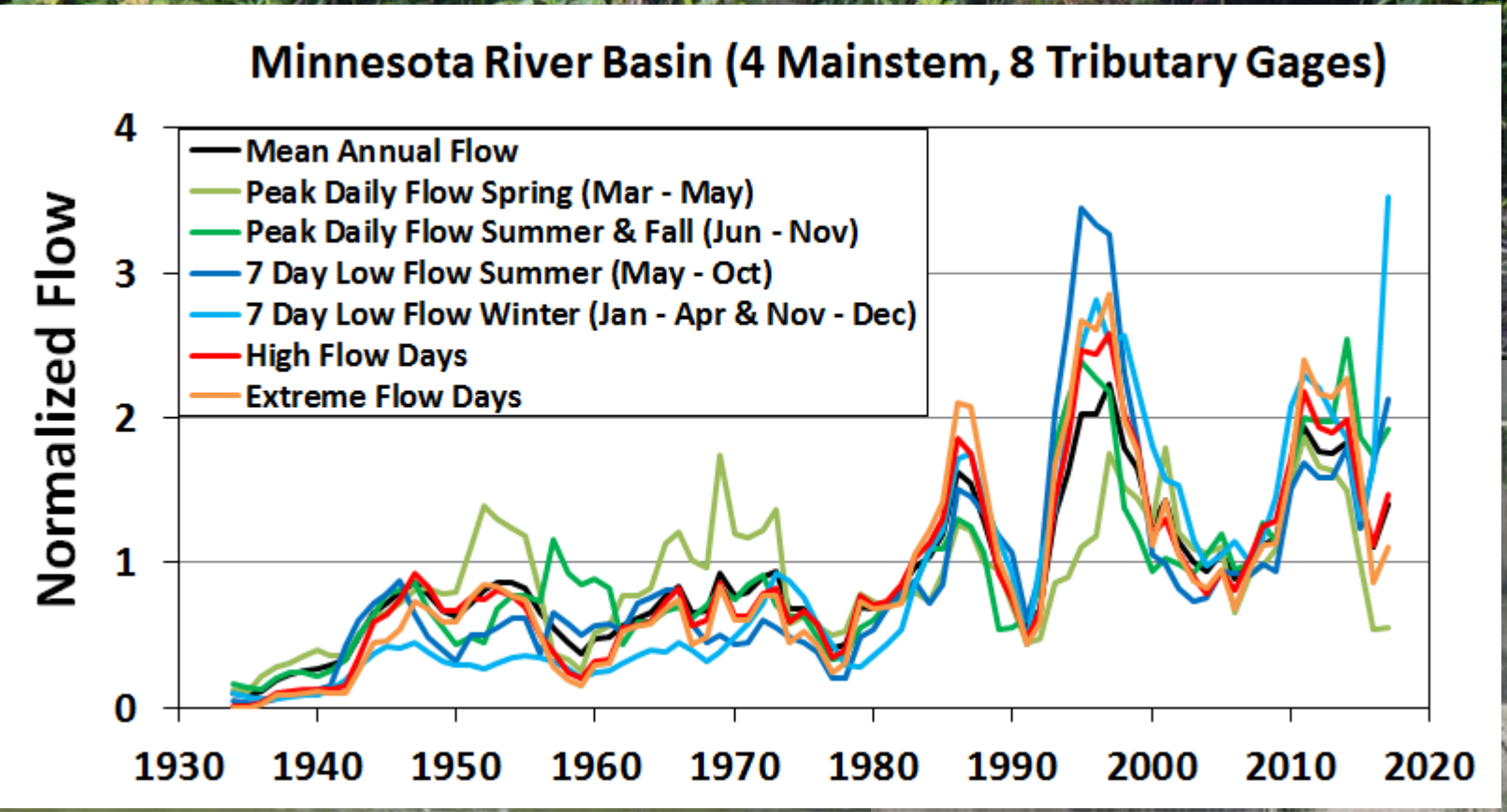
The cause of the problem is obvious, right?





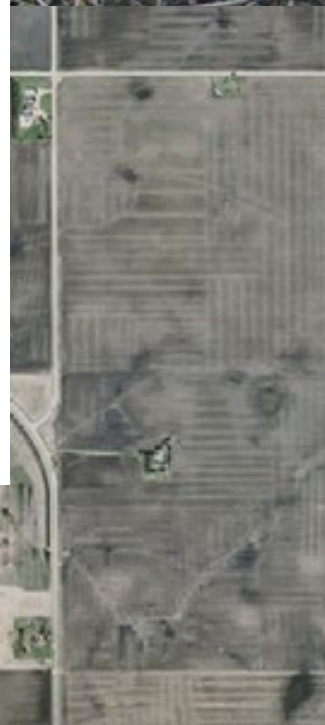


Artificial drainage



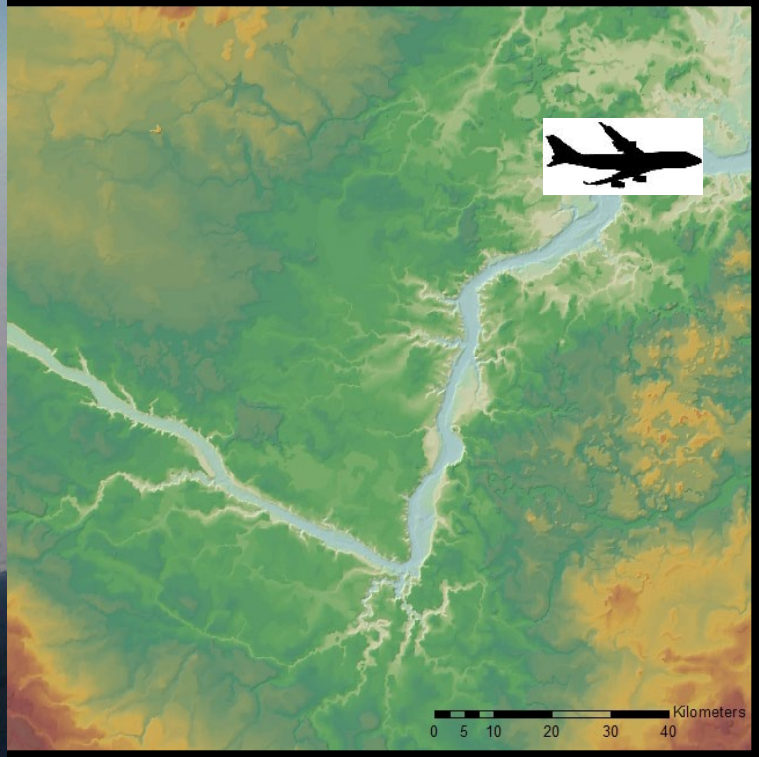




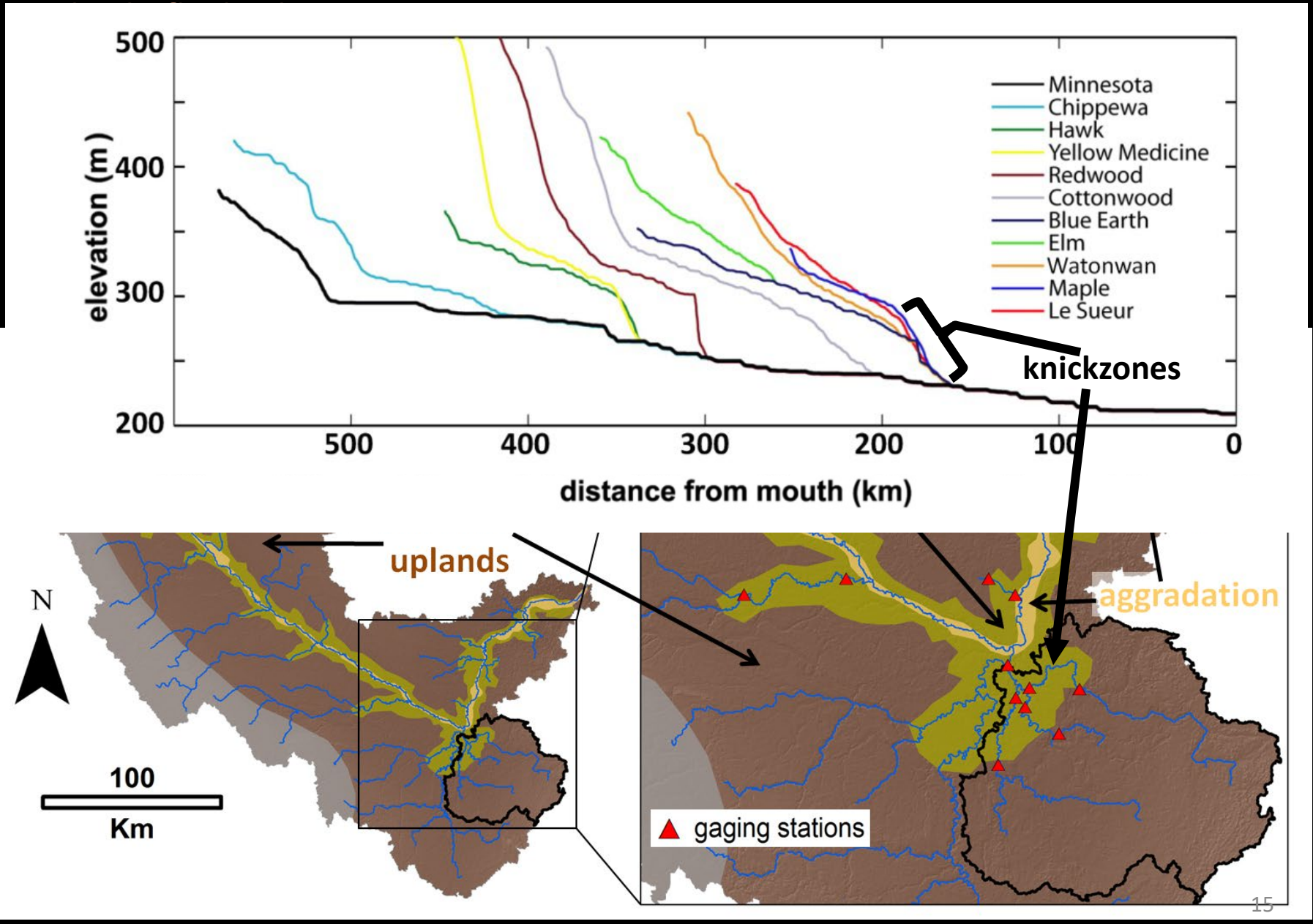


Landscape Evolution Context

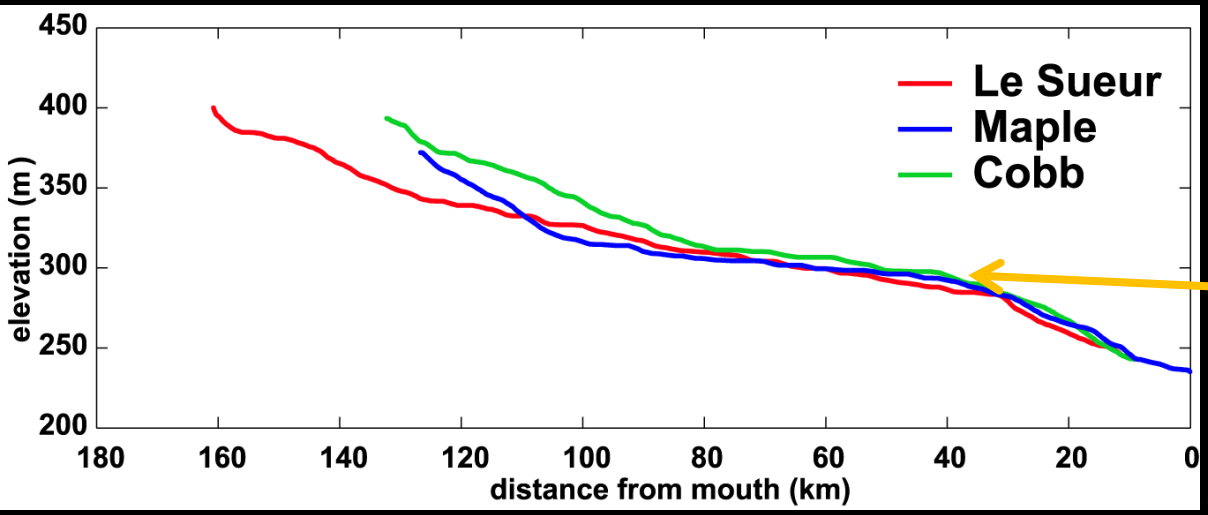




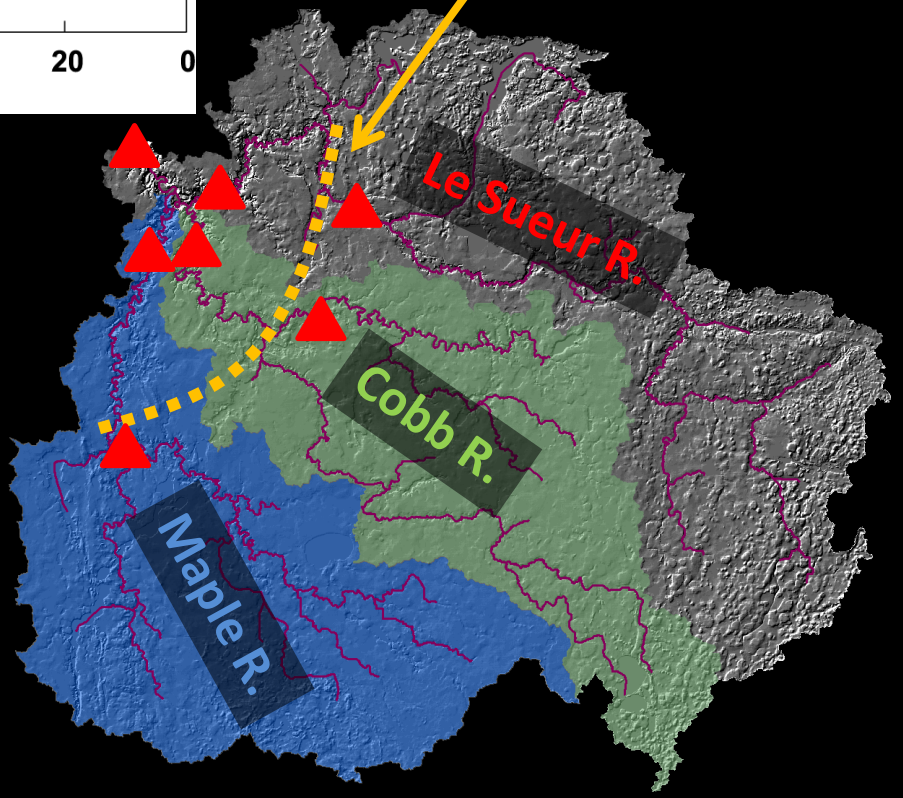
Identify the landscape units...



Le Sueur River Longitudinal Profiles



upper extent of knickzone



13.4 ka: 60 m baselevel fall

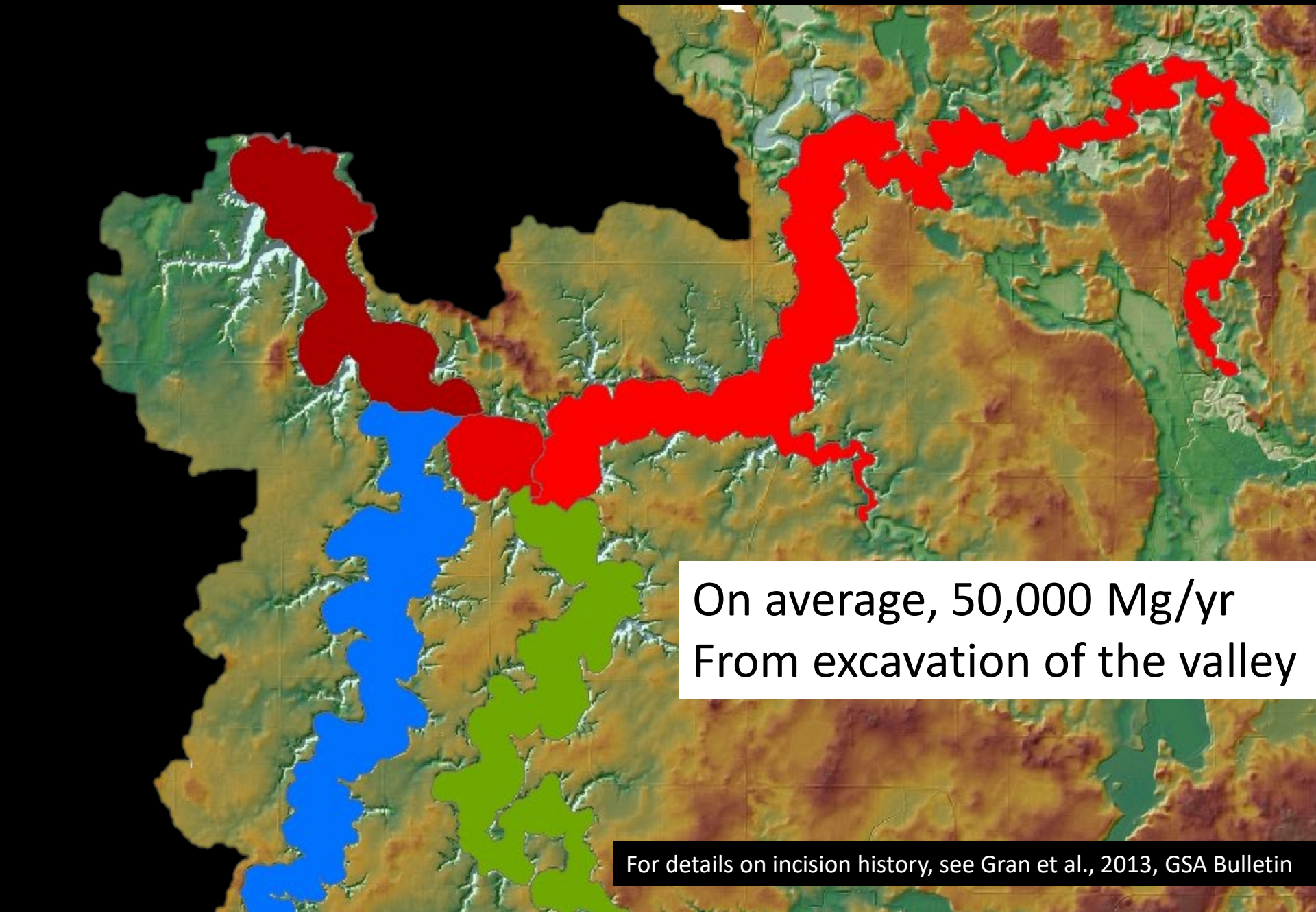
Rapid Holocene incision in lower 40 km
Big bluffs and ravines within knickzone

Widespread agriculture began ~ 1830

Extensive artificial drainage began ~ 1950

Sediment loads increase ~ 3x in knickzone

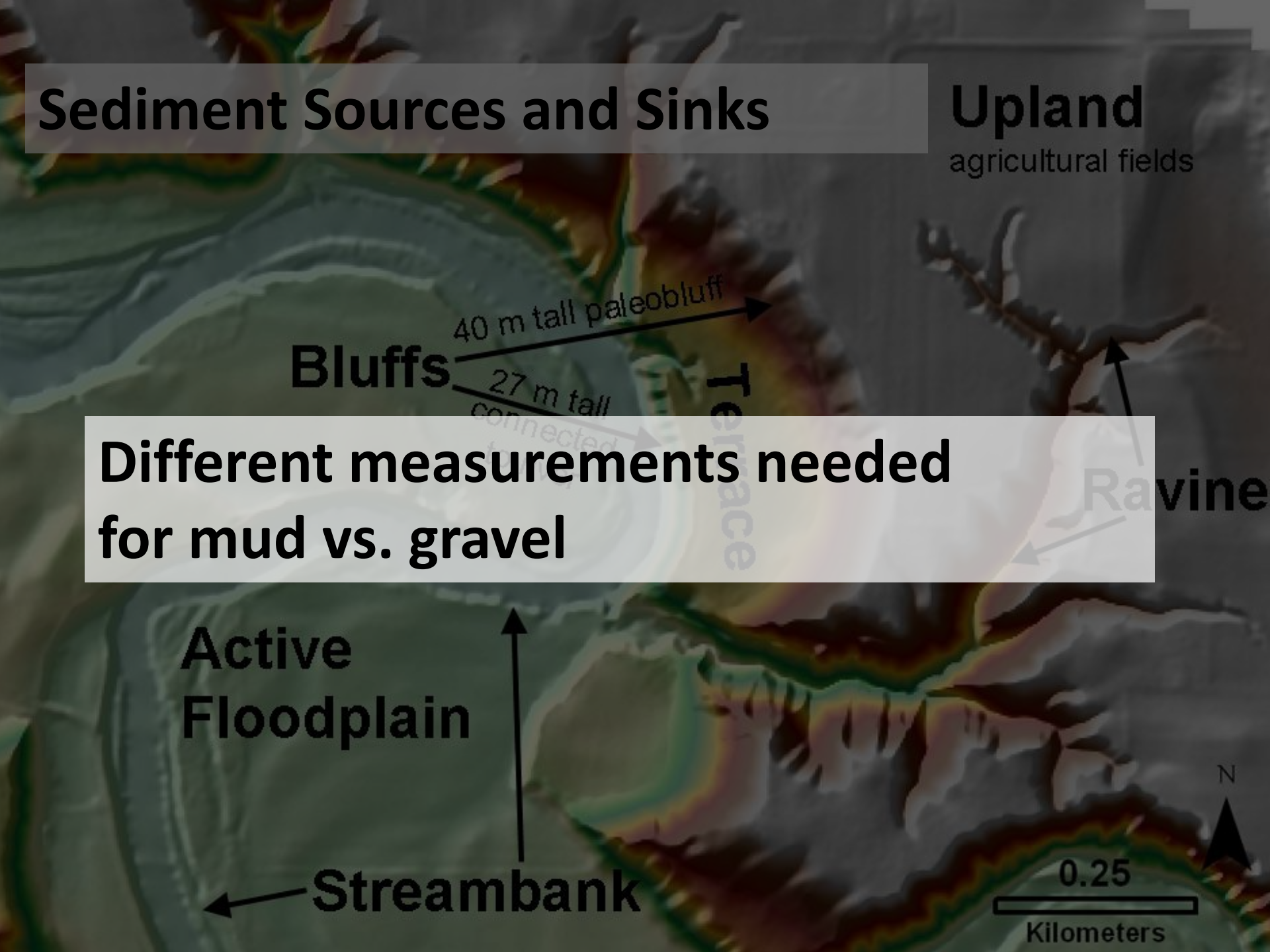
Volume excavated over the past 13,400 years?



On average, 50,000 Mg/yr
From excavation of the valley

For details on incision history, see Gran et al., 2013, GSA Bulletin

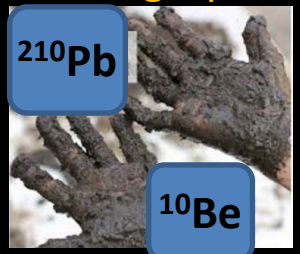
Sediment Sources and Sinks



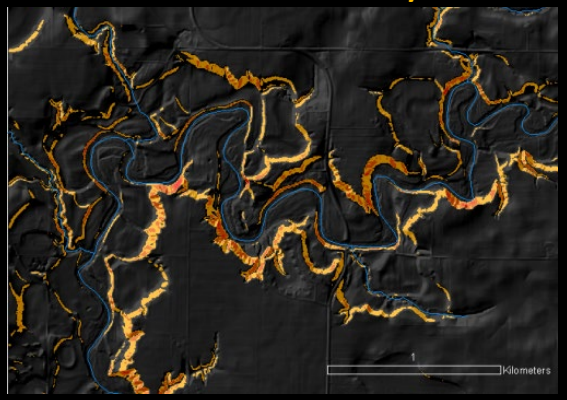
Different measurements needed for mud vs. gravel

Many tools available…

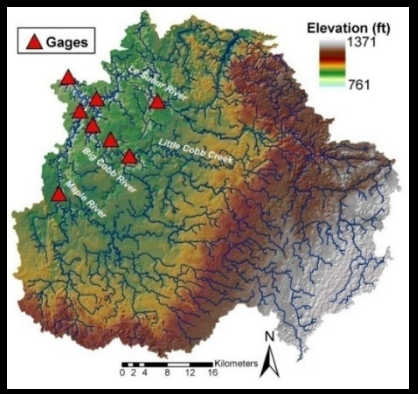
Sediment fingerprinting



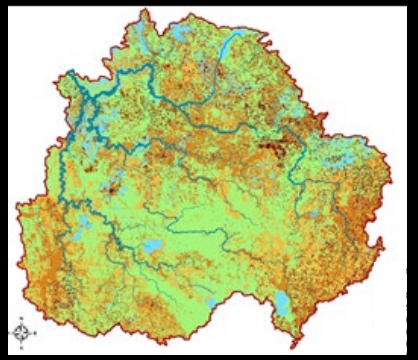
Aerial Lidar analysis



Gages galore!



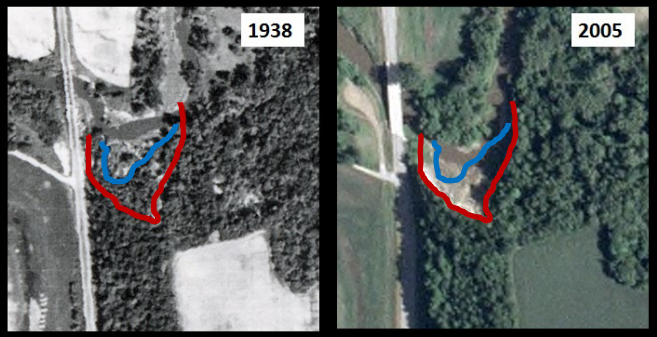
Modeled
Soil erosion rates



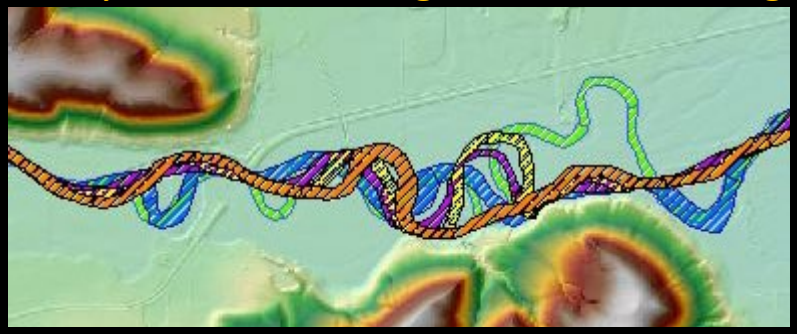
50+Field surveys



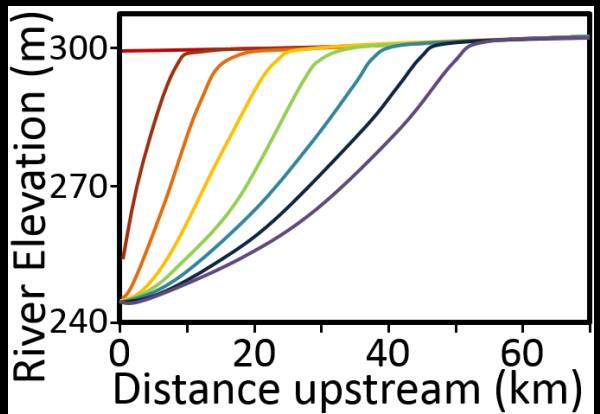
70 years of bluff erosion rates



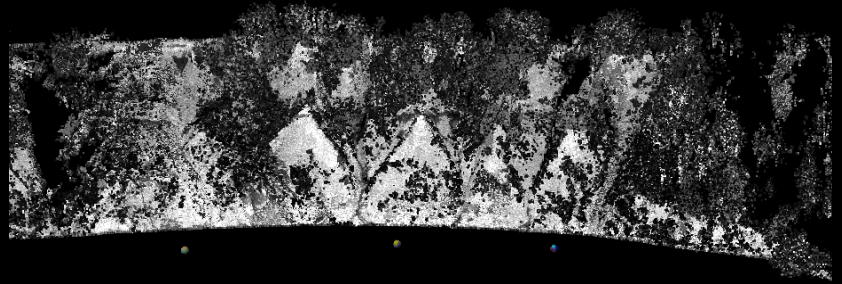
70 years of river migration & widening



14C & OSL-Dates for incision history



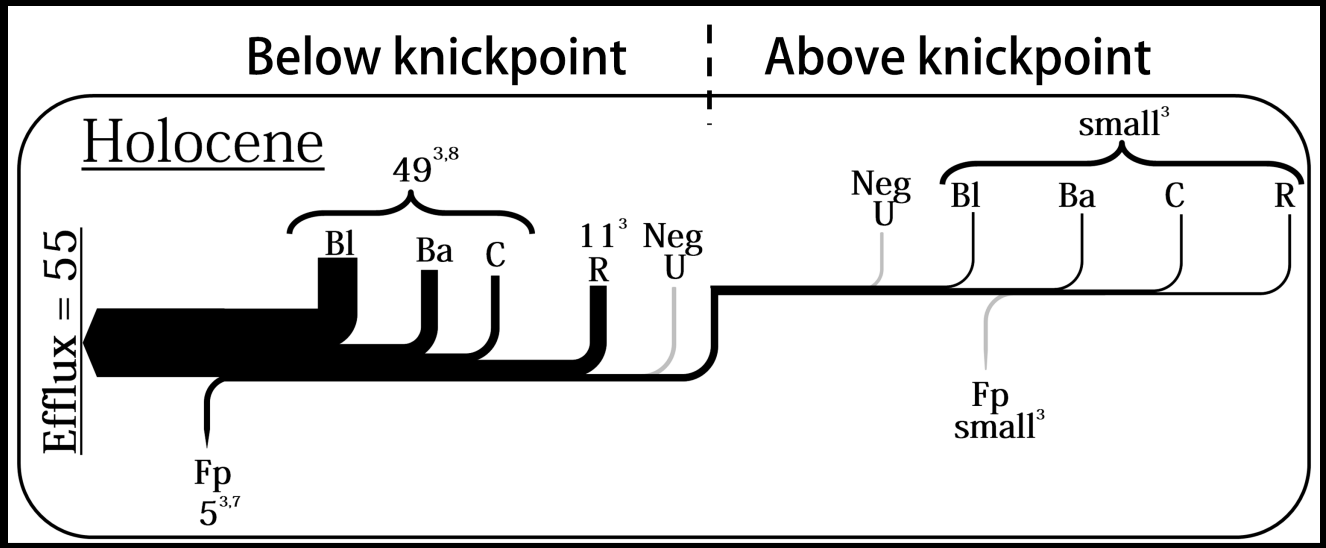
4 years of terrestrial lidar



Le Sueur Sediment (mud) Budget

Sources

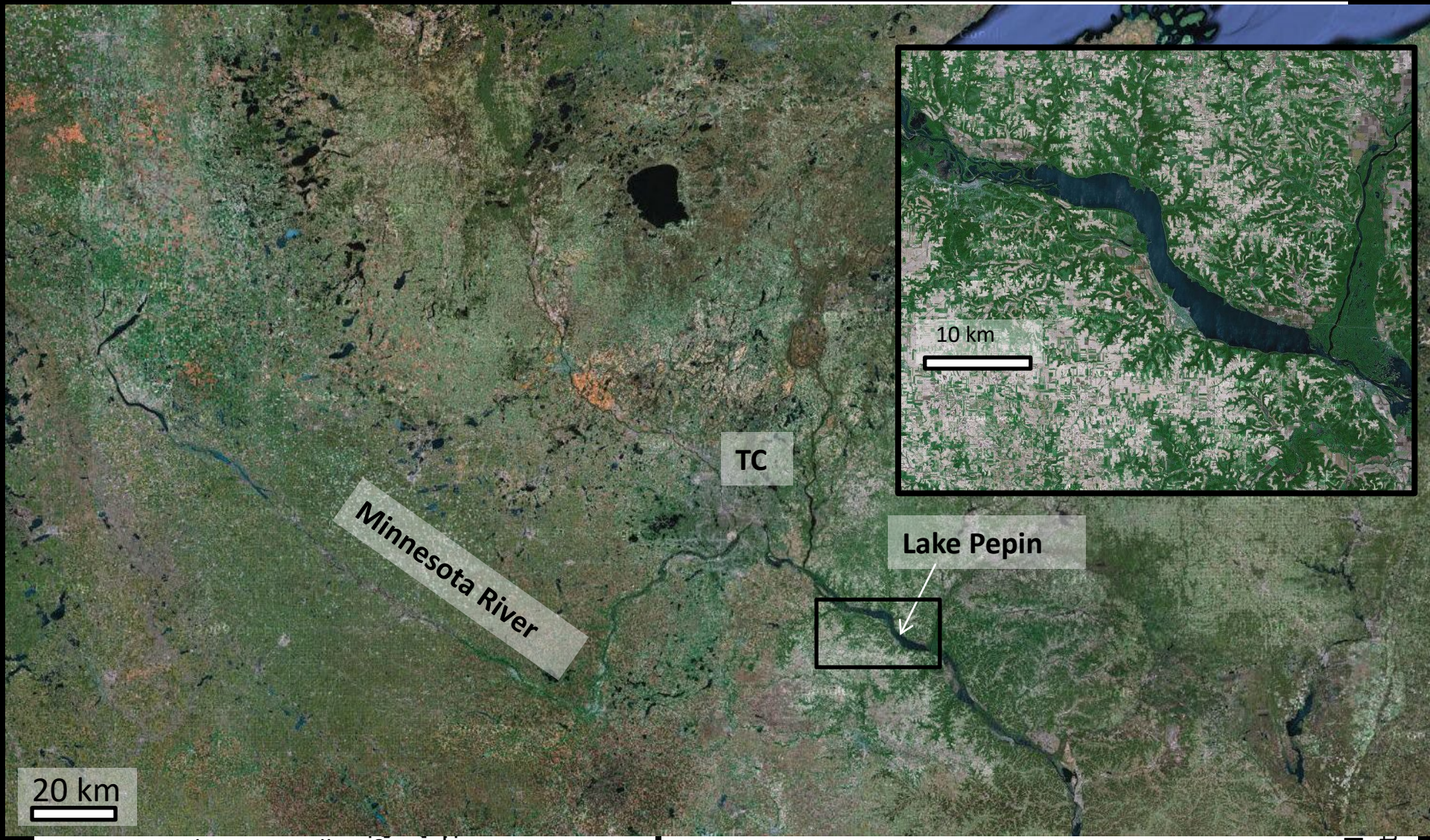
U: Uplands
F_p: Floodplain
Bl: Bluffs
Ba: Banks
C: Channel incision
R: Ravines



Constraints

1. Gaging data
2. Geochemical tracers
3. Aerial lidar analysis
4. Terrestrial lidar scans
5. Air photo analysis
6. Numerical modeling
7. Field surveys
8. Optically Stimulated Luminescence and ^{14}C dating

Large shift in sediment sources



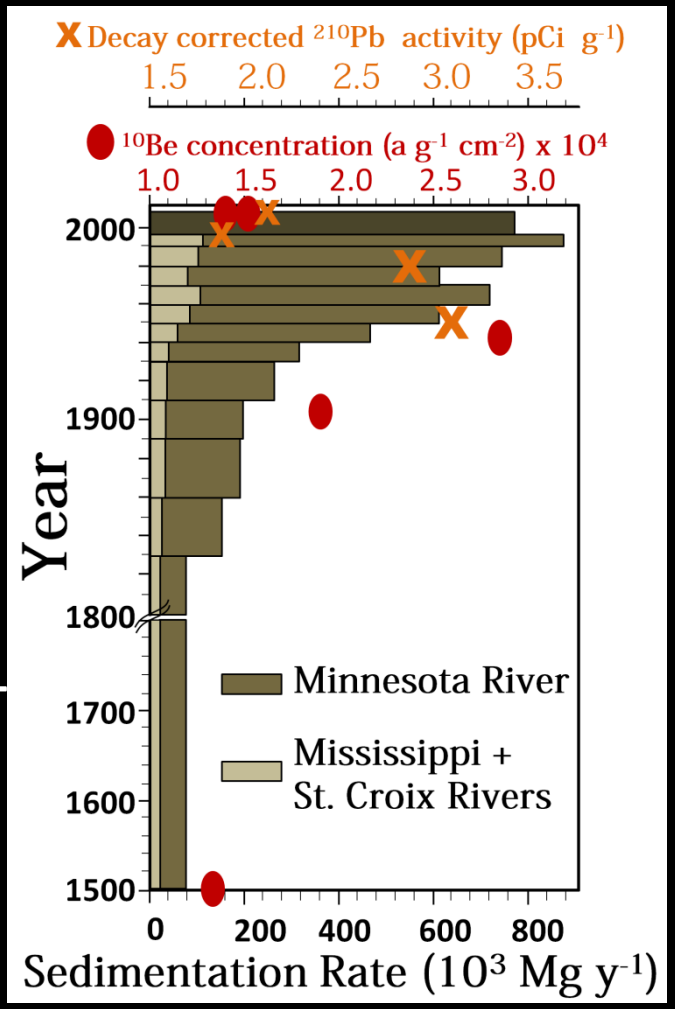
Engstrom et al., 2009; Kelley & Nater. 2000

0 1,000,000 2,000,000 3,000,000

Annual Total Suspended Solids - Mg

Shift between upland and near-channel sediment sources in the Upper Mississippi Basin

Lake Pepin Sediment Core



Belmont et al., 2011

Sediment Fingerprinting Results

Mid 20th Century: Conservation reduces upland erosion, but hydrology amplifies erosion of near-channel sources…sediment loading remains high

Mid 20th Century: Poor land management causes pulse of upland soil erosion

Pre-settlement: primarily near-channel sources



Uplands:
Gravel contributions == negligible



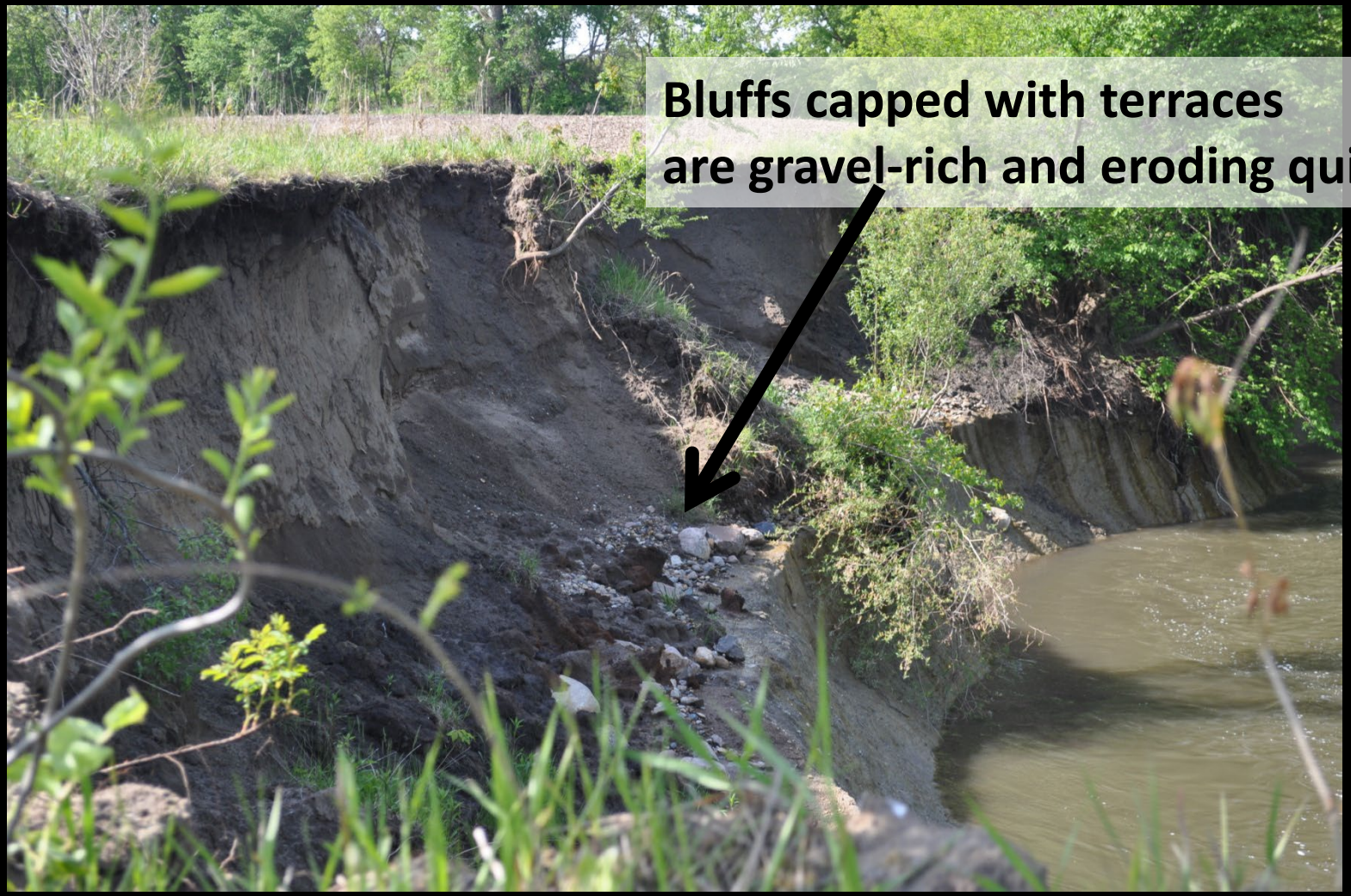


Bluffs: Gravel contributions

Mostly fine-grained, but
grapes, oranges, and watermelons distributed randomly
Less than 1% of till fabric

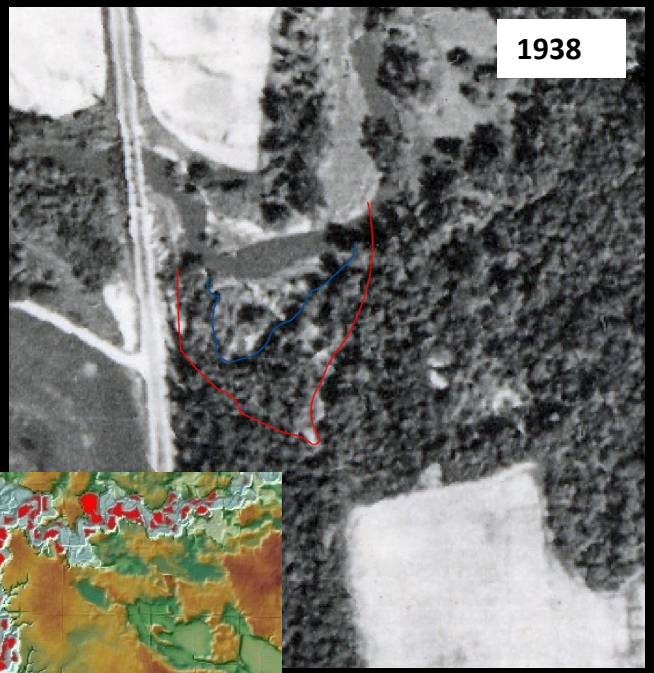


Bluffs: Gravel contributions

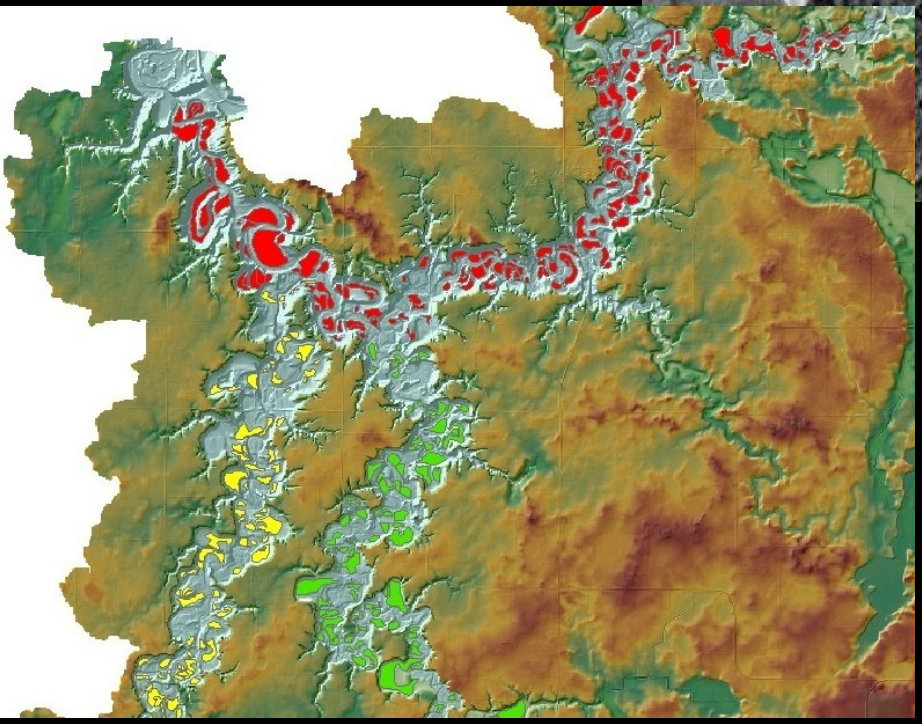


Bluffs: Historic Air Photo Analysis

67 year bluff retreat: segregate bluffs with terraces…







70 – 90% gravel load?

Ravines:
Gravel contributions



10 - 30% gravel load

2009 Gaging Stations

- ditch
- ravine
- river

10

Kilometers

Closing the budget, considering uncertainty

	Est. Rate (Mg/yr)	Uncertainty (±Mg/yr)
Soil creep	65	20
Debris flows	15	10
Landslides	35	10
Channel widening	5	2
Net floodplain deposition	(20)	10
Total	100	

Observed load (2005-2015) = 80 Mg/yr

Budget components over-estimate by 20 Mg/yr

Basic questions you want to answer

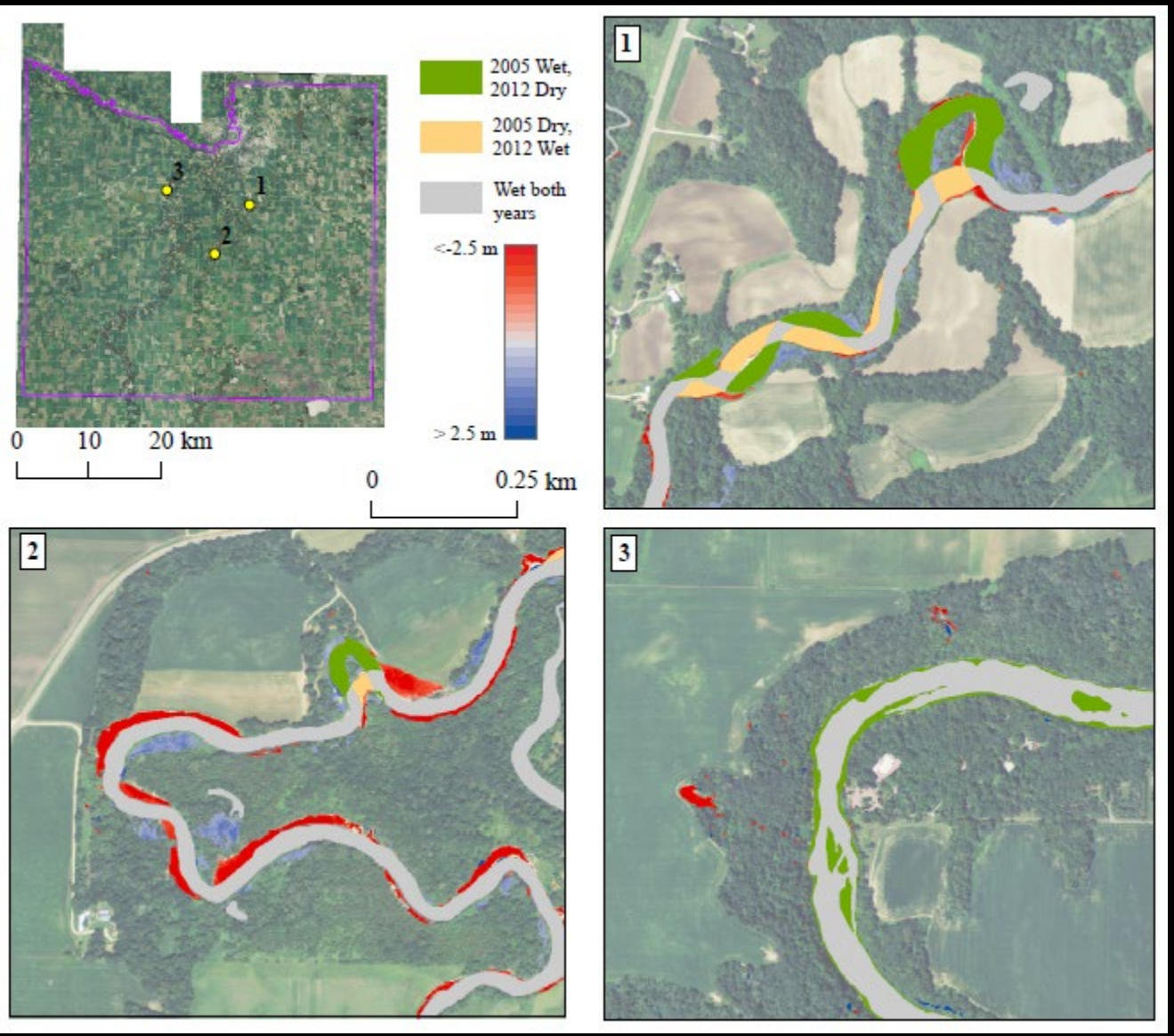
What are the grain sizes of interest?

Where do those exist in the watershed?

What geomorphic processes convey them to the channel?

How to map the relevant landforms and measure/constrain rates?

Geomorphic change detection from lidar



Change detection from 1m DEMs over 2000 km^2

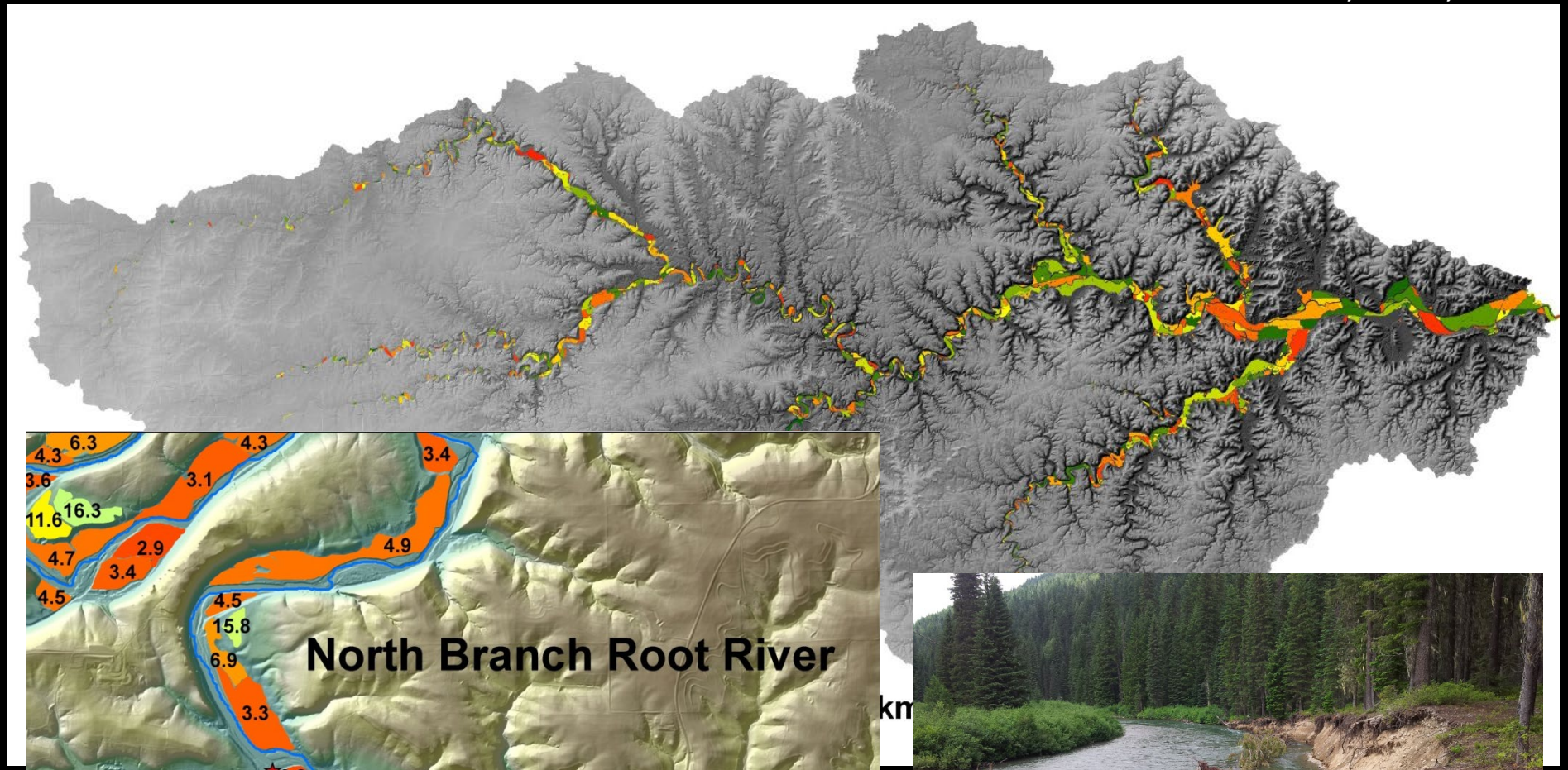
Spatially variable uncertainty

New methods to:
Account for veg uncertainty
Eliminate errors in legacy data

Schaffrath et al., 2015, see also Wheaton et al., 2010 and Passalacqua et al., 2015

TerEx Tool: maps terraces, measures heights

See Stout and Belmont, 2013, ESPL

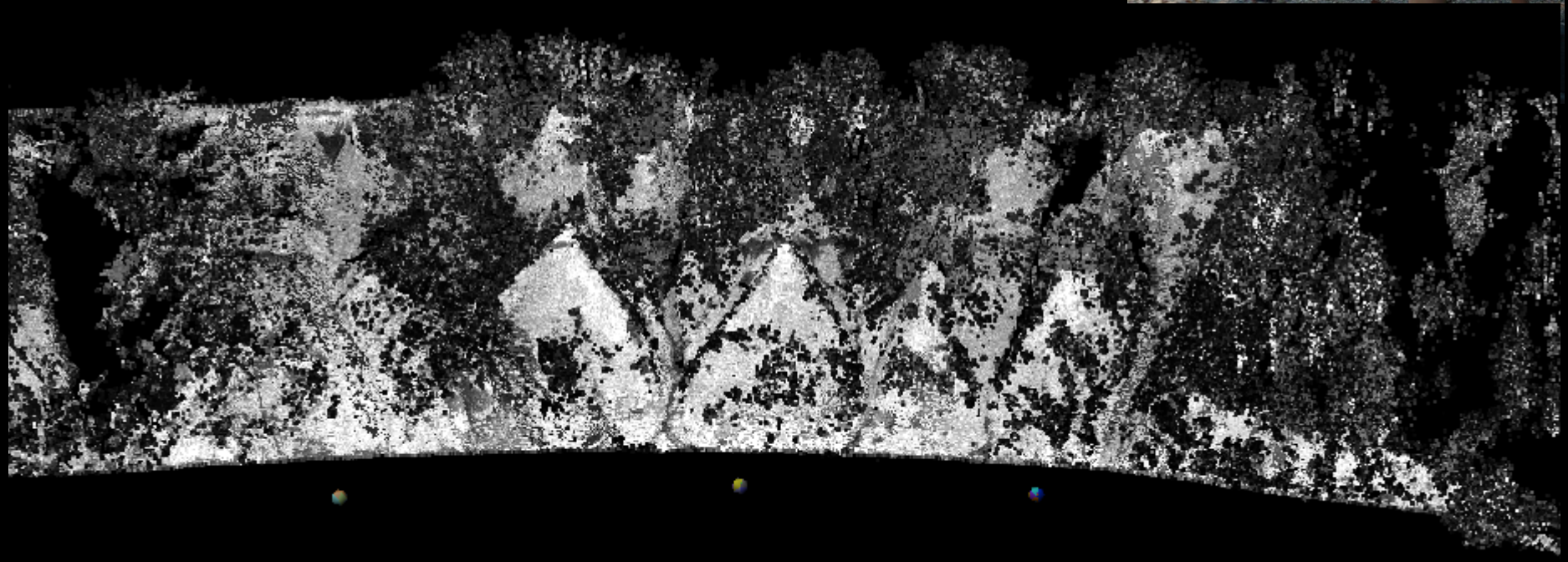




Terrestrial lidar scans

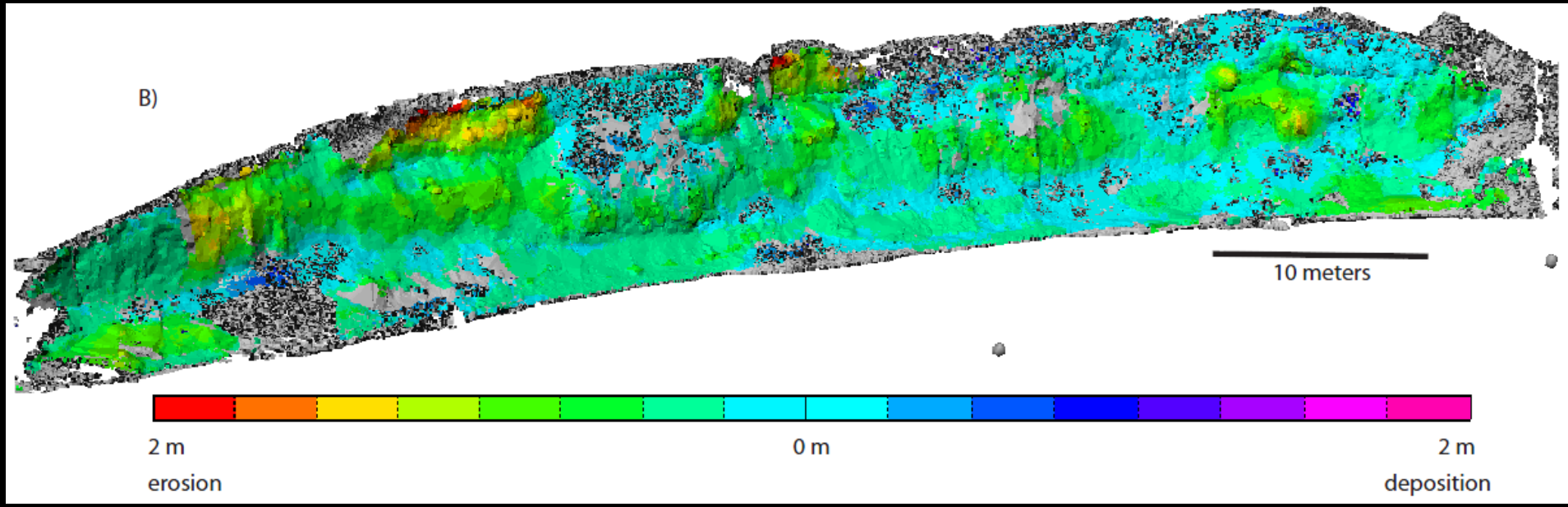
Sub-cm precision annual erosion rates





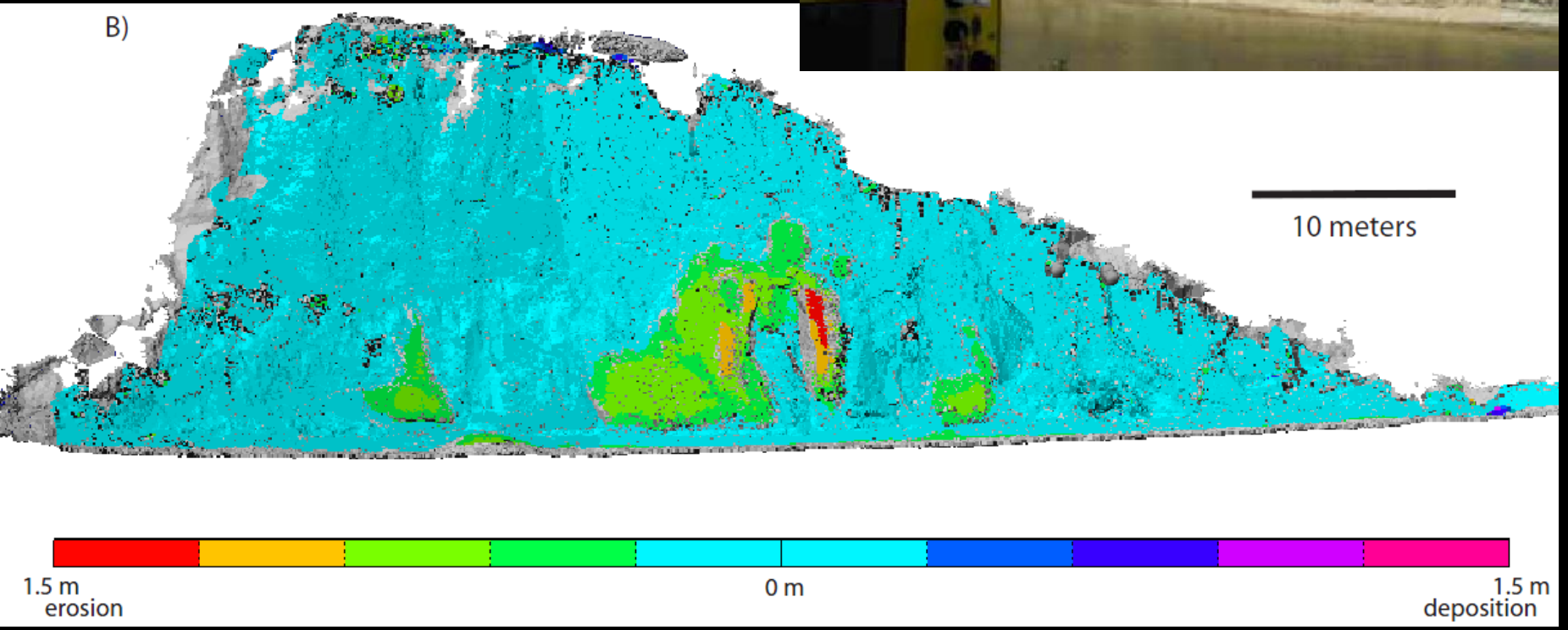
Terrestrial lidar scans





Terrestrial lidar scans





See Day et al., 2013 ESPL; Wheaton et al., 2010 ESPL

Structure from Motion Photogrammetry

I. Acquire Photos

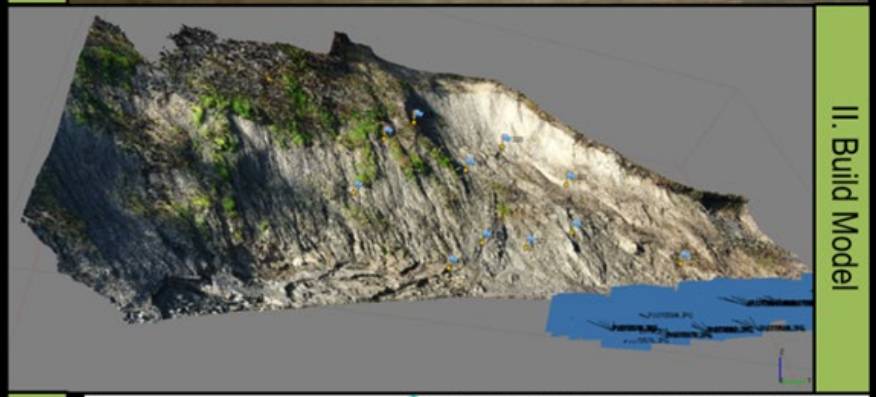








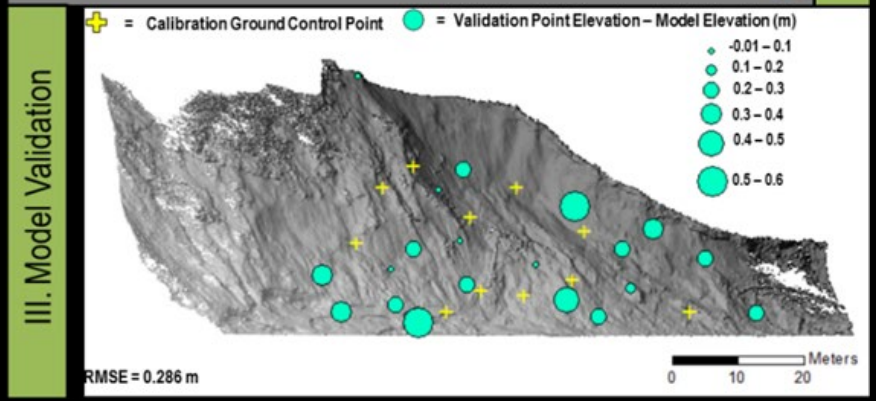
II. Build Model



2 sites monitored for 3 years



III. Model Validation





Kelly et al., 2018

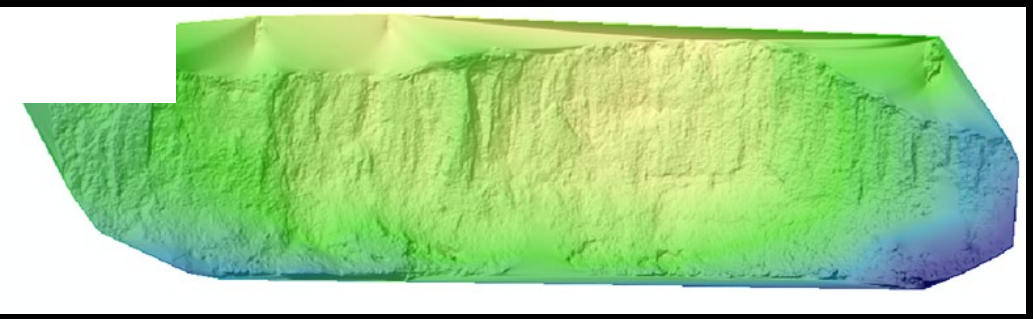
SfM Photogrammetry and GCD



Use ordinary photographs

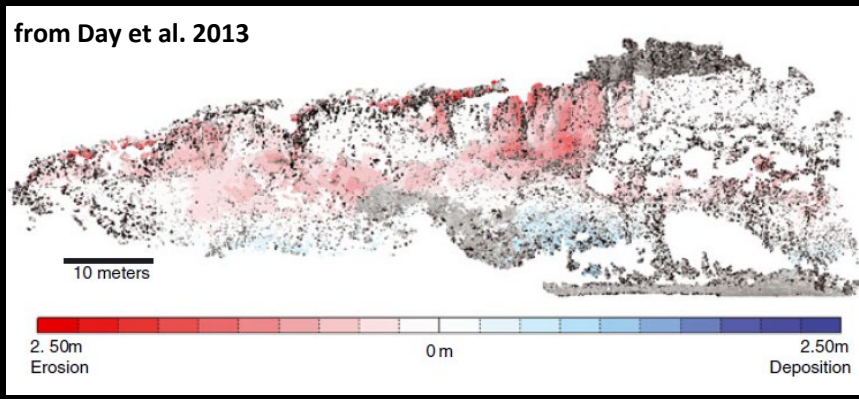


and SfM software (Agisoft),



to generate point clouds and derive elevation models

Use GCD to quantify erosion and deposition



Using daily photos, we can identify the processes that triggered each failure:





Shallow landslide triggered by heavy rains

Kelly and Belmont, 2018

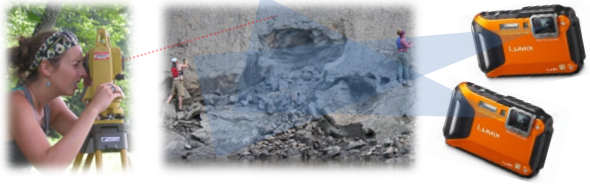
SfM Photogrammetry and GCD

I. Data Acquisition June (2013)2015 – May 2017

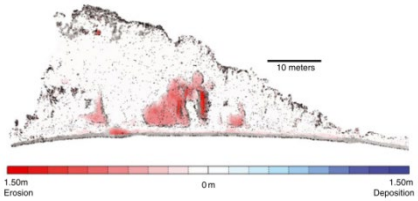
> 12,000 Daily Photographs
20 Sites



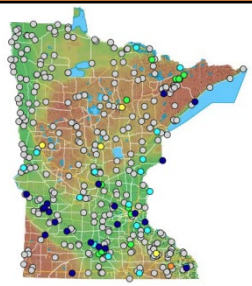
7 Repeat Photograph Surveys
2 Sites



Repeat TLS Surveys
17 Sites – Day et al. 2013



USGS and MNDNR
Daily Streamflow

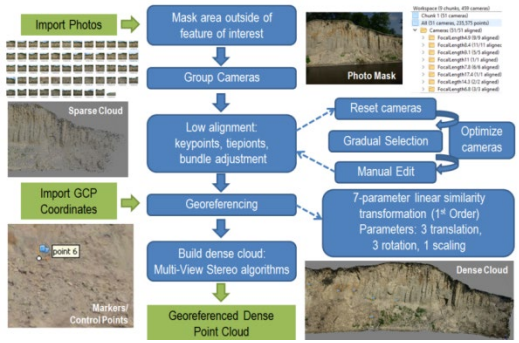


II. Data Analysis

Failures:
- *2705 total*
- *347 large (> 1 m^2)*
- *169 large, bluff face*

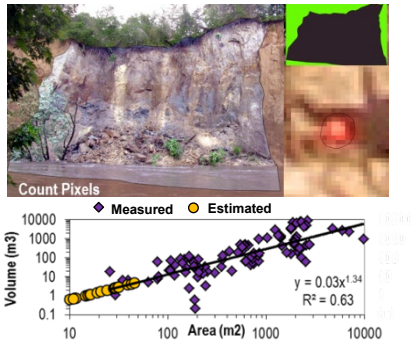


1. Counted and Classified Failure Events



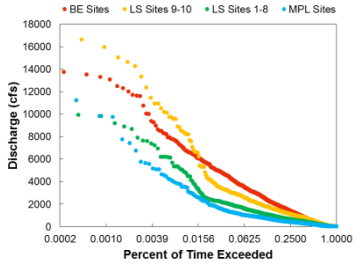
2. Measured Erosion: SfM-MVS Workflow and GCD

(Westoby et al. 2012; Smith et al. 2016; Wheaton et al. 2010)



3. Estimated Erosion: Volume ~ Area Relation

(Hovious et al. 1997)



4. Normalized Discharge and Computed Flow Duration Curves

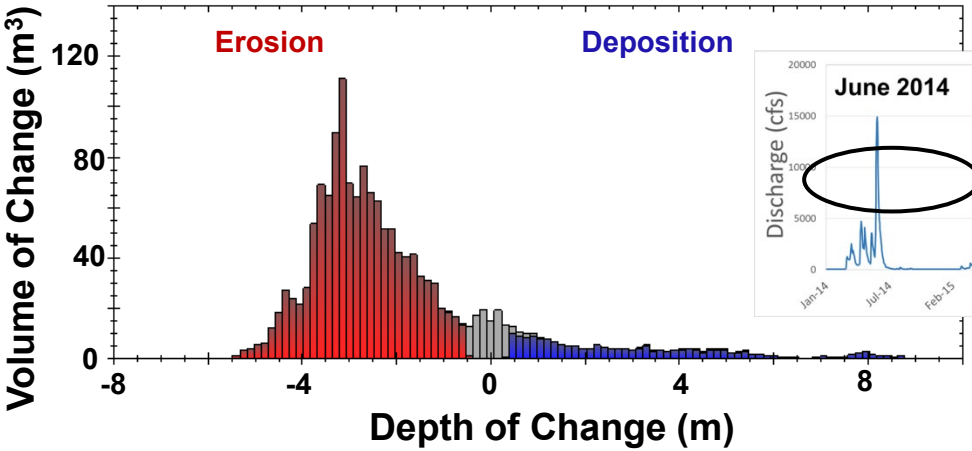
SfM Geomorphic Change Detection: LS10 – 20-year flood

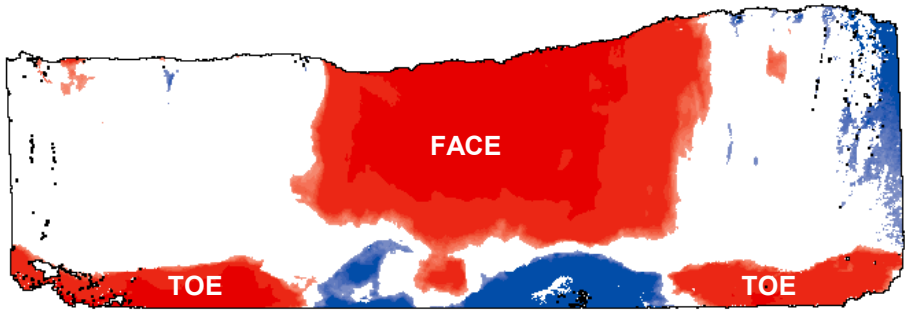
June 17, 2014



June 18, 2014







90 m

Net Change: 1100 m³ erosion

Depth of Change (m)

>2.5 m Erosion

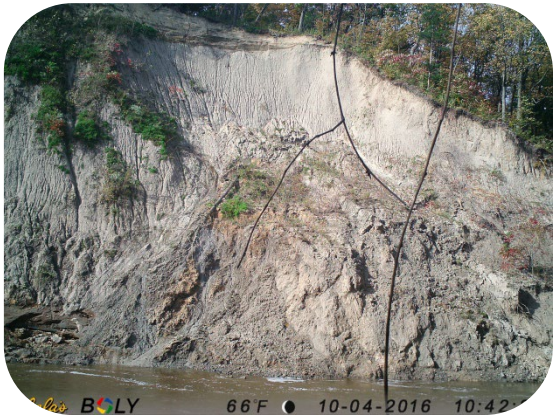
0 m

Deposition 2.5 m

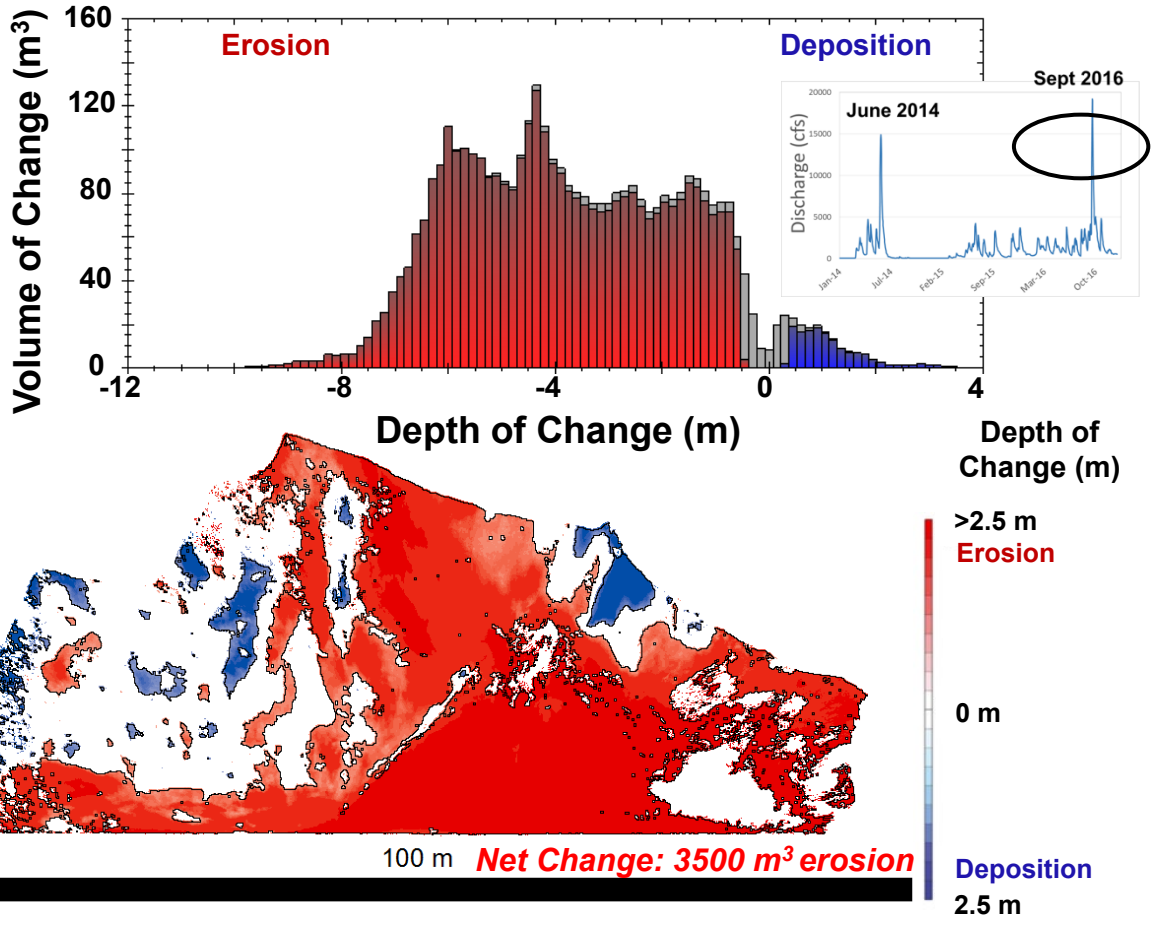
Flow Direction

SfM Geomorphic Change Detection: LS9 – 40-year flood

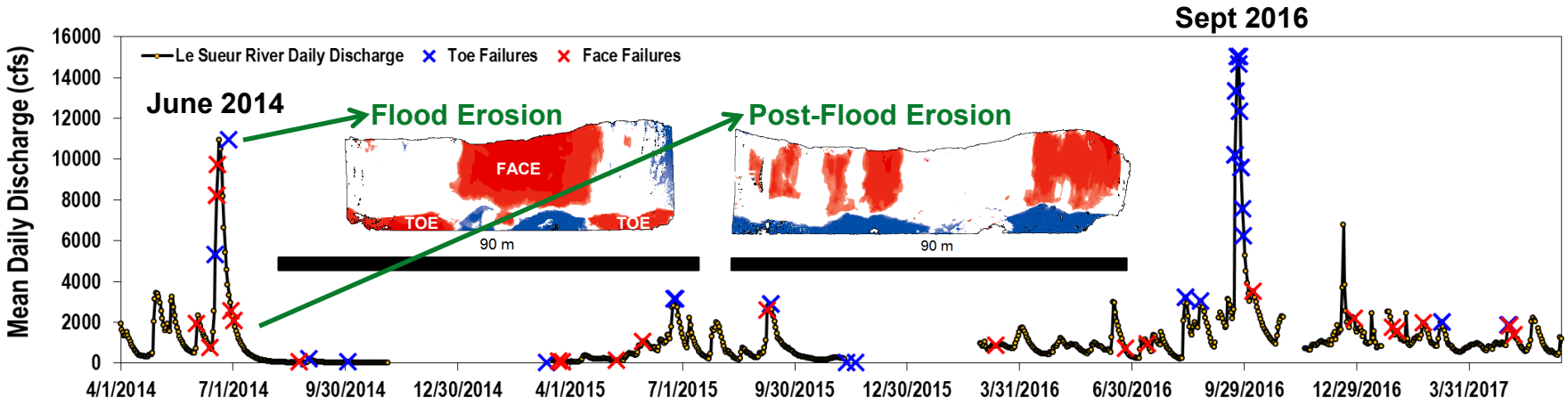




Flow Direction



Q: When and why do bluffs erode?



A: Two events accounted for:

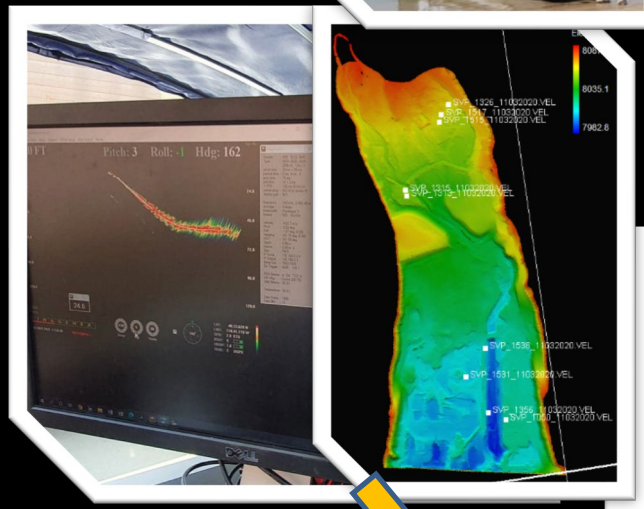
	June 2014		September 2016			
LS9:	23%	+	74%	=	97%	of total site erosion over 3 years!
LS10:	26%	+	53%	=	79%	

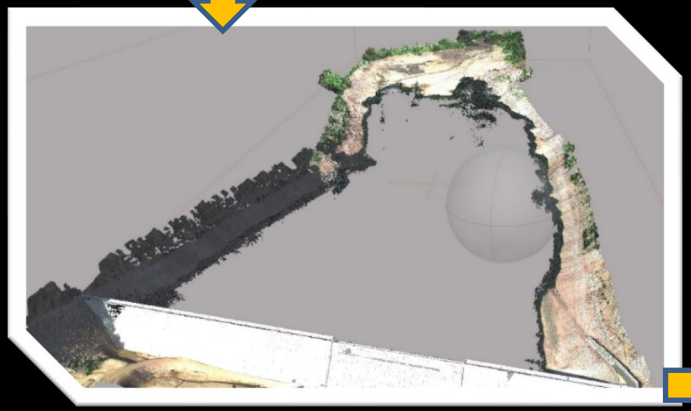
Reservoir mapping with SfM and multibeam sonar





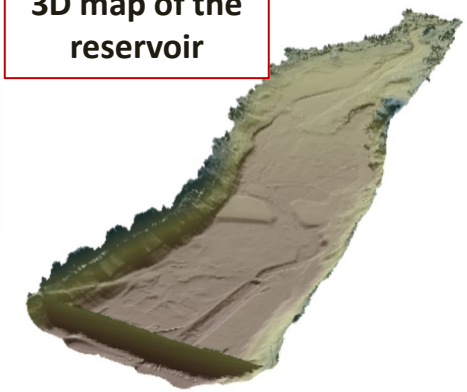
Multi beam sonar collects topography below the water





Drone uses 6 wavelength bands to capture topography above the water line

3D map of the reservoir



Basic questions you want to answer

What are the grain sizes of interest?

Where do those exist in the watershed?

What geomorphic processes convey them to the channel?

Contributions from near-channel sources or hillslope/watershed sources?

Near channel:
river migration, incision, widening processes

Hillslope/watershed:
creep, rill erosion, debris flows, landslide processes

Where are erosion/deposition hotspots? Natural or human influenced?

Erosion relatively steady or pulsed?

Where are the disconnects in the sediment routing system?

Channel and Floodplains

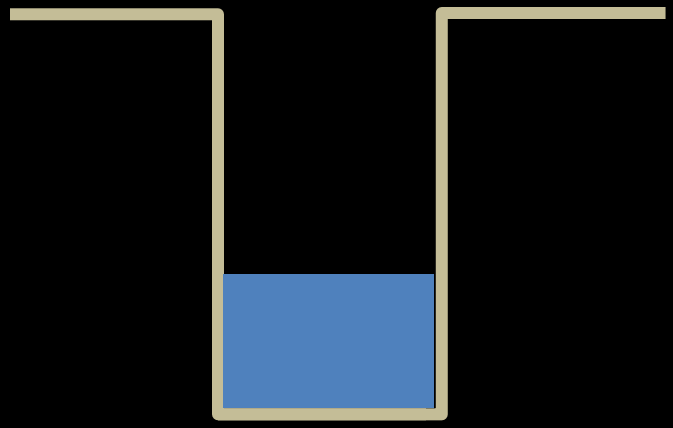
When are they net sources?

A) When the stream is entrenched

B) When cut bank is higher than depositing bank

C) Transient periods of channel widening

Is this stream entrenched?



Why do streams become entrenched?

Channel and Floodplains

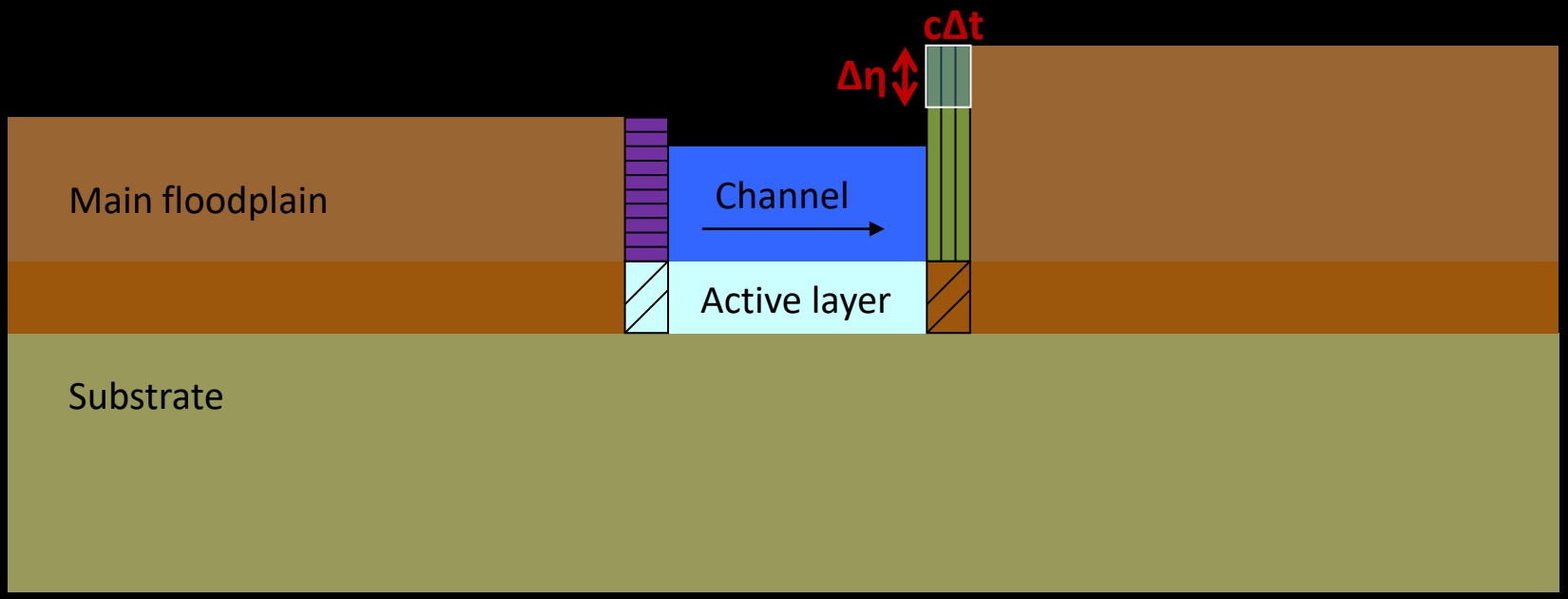
When are they net sources?

A) When the stream is entrenched

B) When cut bank is higher than depositing bank

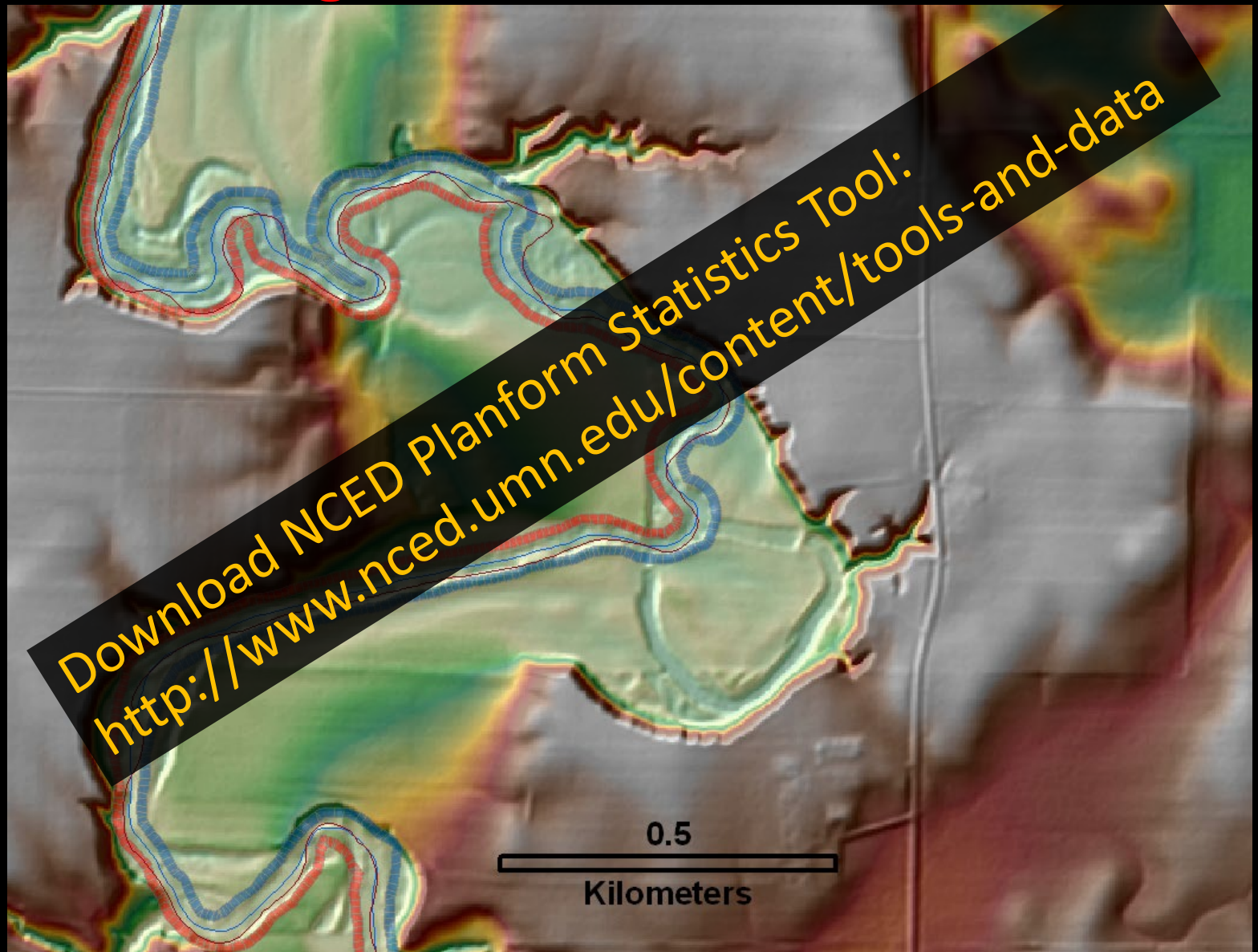
C) Transient periods of channel widening

Under what conditions would this happen?



Conservation of channel geometry

Measuring difference in bank heights and meander migration rate



Channel and Floodplains

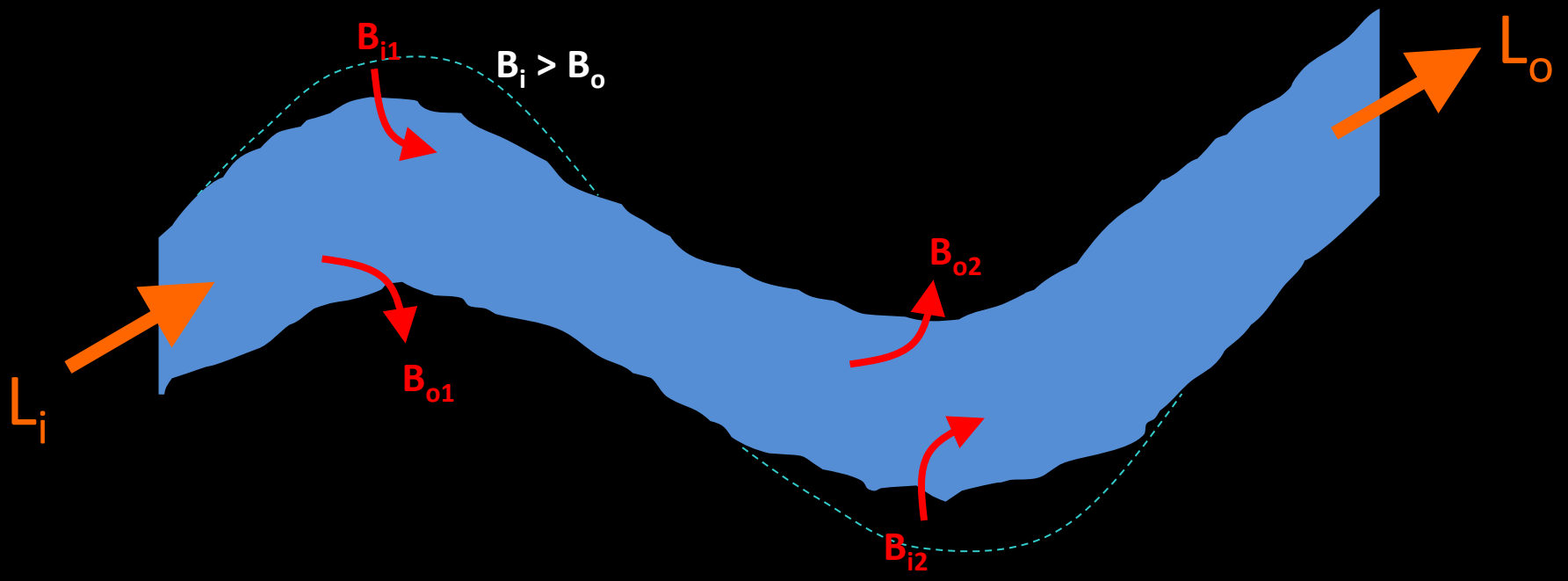
When are they net sources?

A) When the stream is entrenched

B) When cut bank is higher than depositing bank

C) Transient periods of channel widening

$$L_o = L_i + \Sigma B_i - \Sigma B_o$$



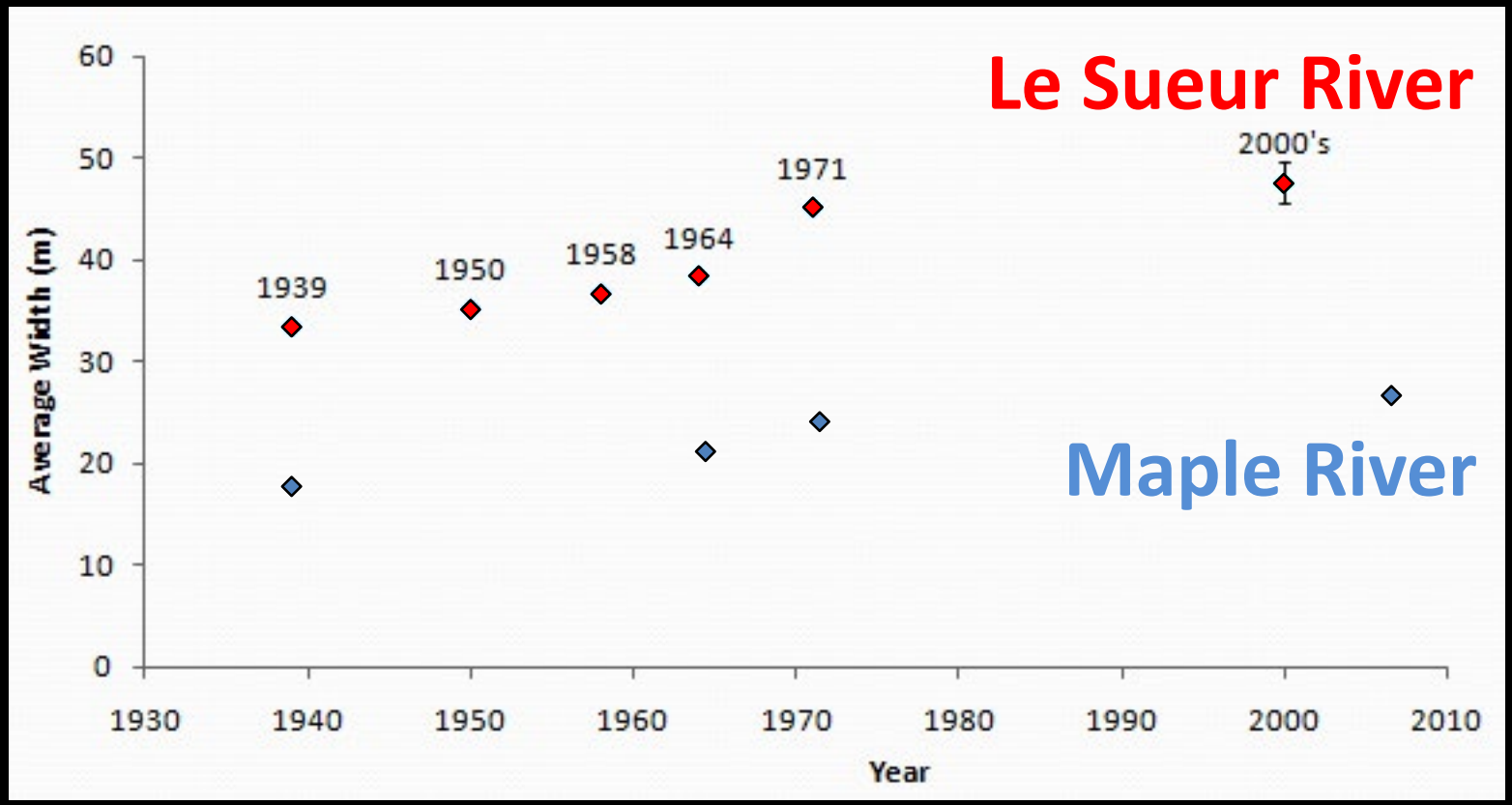
Channel and Floodplains

When are they net sources?

A) When the stream is entrenched

B) When cut bank is higher than depositing bank

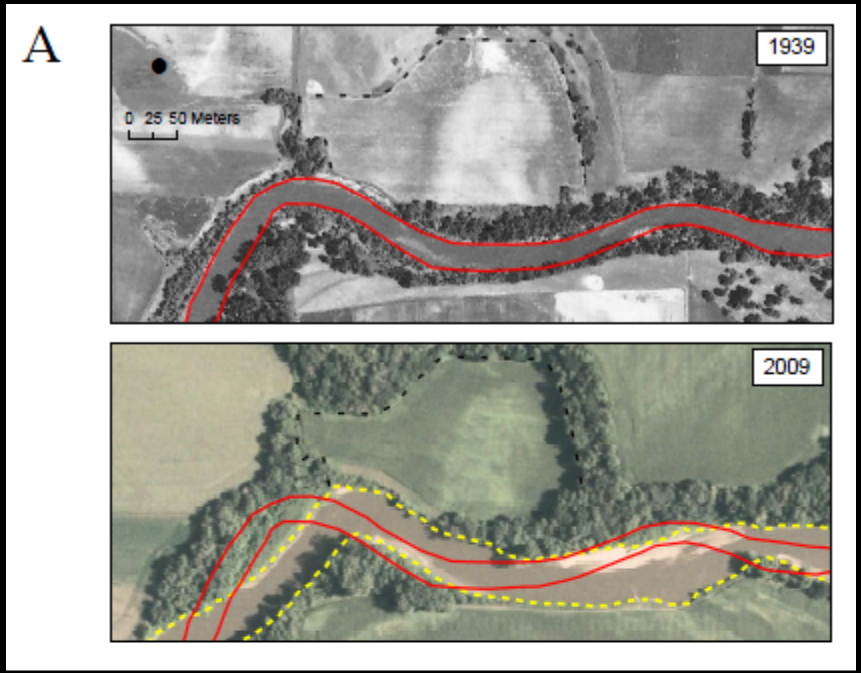
C) Transient periods of channel widening



How to measure channel width/widening?

1. Delineate channel polygon (10+ bends).

2. Divide by channel center length.



Why would a channel widen?

Historic air photo analyses: sources of error

Factors affecting uncertainty in remotely sensed images and measurements of planform changes

Type	Expected influencial factors	Considerations	Reference
Georeferencing uncertainty	Image warping (camera optics)	Periphery of images affected relatively more than centers	Fryer & Brown (1986)
	Georeferenced control points	Hard points reduce error compared to soft points	Mount et al. (2003); Hughes et al. (2006)
	Image resolution/quality	Coarser resolution decreases ability to find GCPs	-
	Anthropogenic changes	Urban development changes availability of GCPs	-
	Georectification transformation	2nd-order polynomial is consistently the best choice	Hughes et al. (2006); Donovan et al. (2015)
Digitization (i.e.,delineation) uncertainty	Vegetation density	Vegetation cover reduces visibility of channel edge	Güneralp et al. (2013, 2014); Winterbottom (2000)
	Shadows along river boundary	Shadows reduce visibility of channel edge	Güneralp et al. (2013, 2014)
	Scale of image during delineation	Increased scale (zooming in) reduces delineation error	Liro et al. (2015)
	Water level	Will impact which vegetated-edge boundaries are visible	Lauer et al. (2017)
	Arbitrary user inconsistency	Users are prone to inconsistency in boundary interpretations	Gurnell et al. (1994); This study
	Topographic data availability	High-resolution DEMs increase delineation accuracy	Mount et al. (2013); Donovan et al. (2015)
Automated delineation/ classification uncertainty	Manual vs. [semi]automated	Automated approaches are generally less accurate and vary by which algorithm or software tool is used	Pavlesky & Smith (2008); Rowland et al. (2016); Schwenk et al. (2017)
	Channel width & complexity	Narrow channels and highly complex bar arrangements can reduce automated classification accuracy	Rowland et al., (2016)
Detecting changes in delineated boundaries	Magnitude of changes	Larger changes more likely to exceed level of detection	This study
	Duration between images	Broader timescales span periods of greater change	
	Reference datum changes	After adjusting images to a common datum, differences may arise due to distinct datum offsets	Anders & Byrnes (1991)
	LoD threshold calculation	Uniform LoD thresholds erroneously reduce number (and quality)* of significant measurements	Lea & Legleiter (2016); *This study

ELSEVIER

Earth-Science Reviews

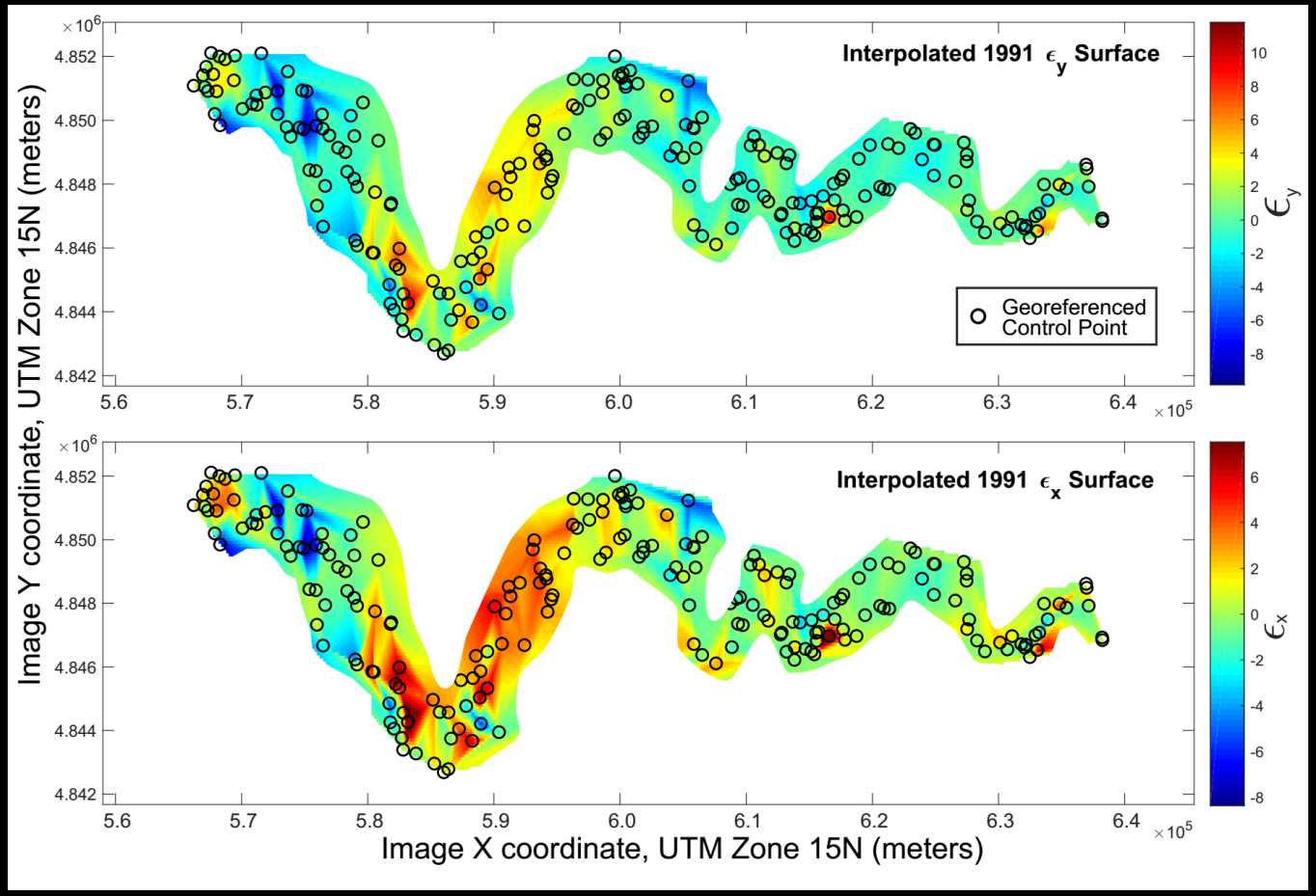
Volume 193, June 2019, Pages 220-236



Accounting for uncertainty in remotely-sensed measurements of river planform change

Mitchell Donovan [a] ✉, Patrick Belmont [a], Bastiaan Notebaert [b], Tyrel Coombs [a], Phillip Larson [c], Michael Souffront [a]

Historic air photo analyses
Spatially variable error



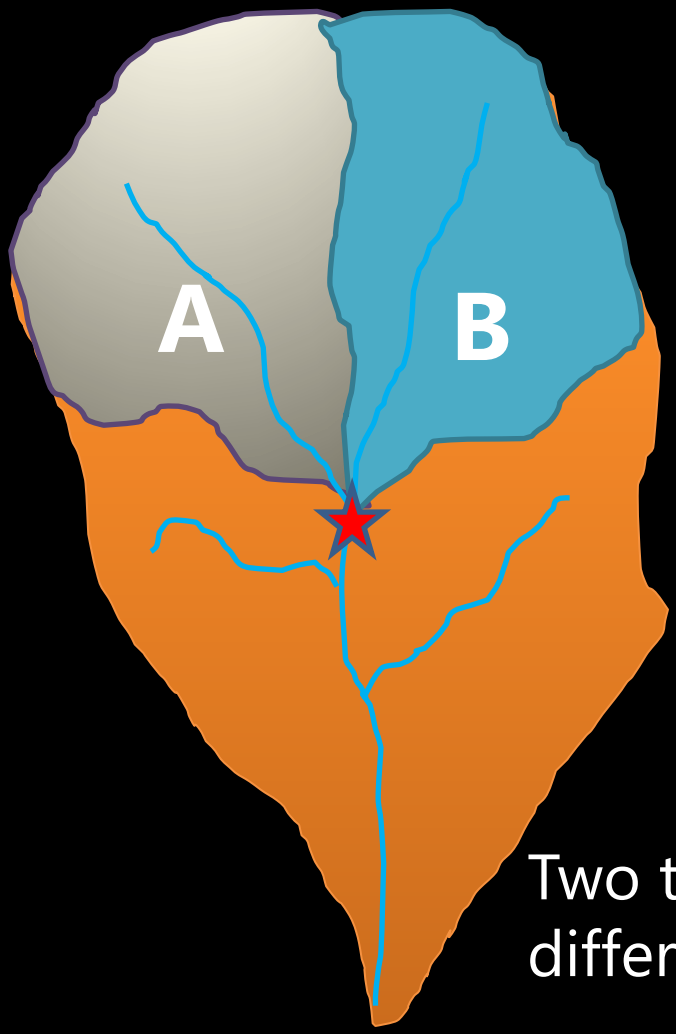
If you assume spatially uniform error, you probably:

discard many reliable measurements of small magnitude

keep some erroneous measurements of large magnitude

Sediment fingerprinting

Gellis and Walling, 2011
Koiter et al., 2013
Belmont et al., 2014





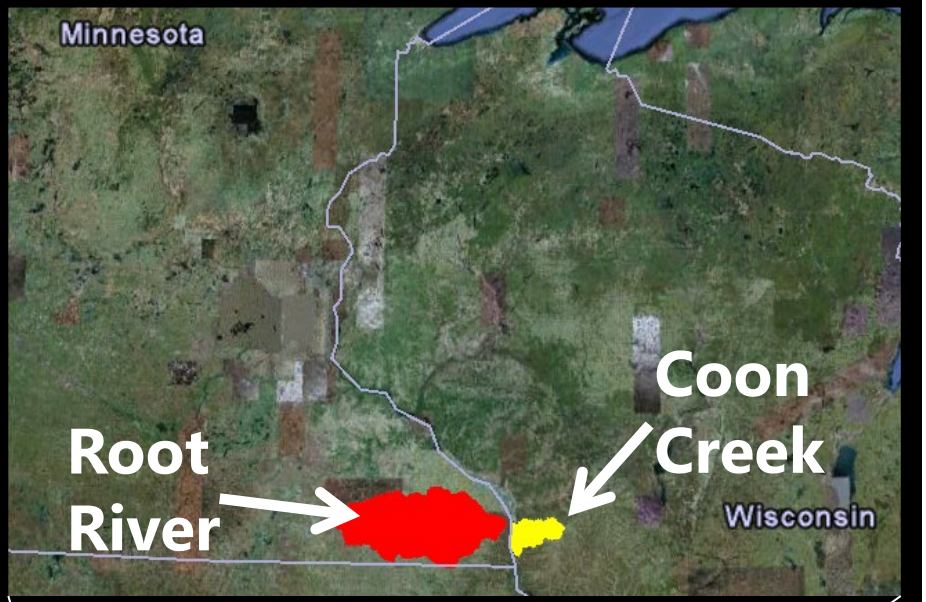


Two types that may provide different information

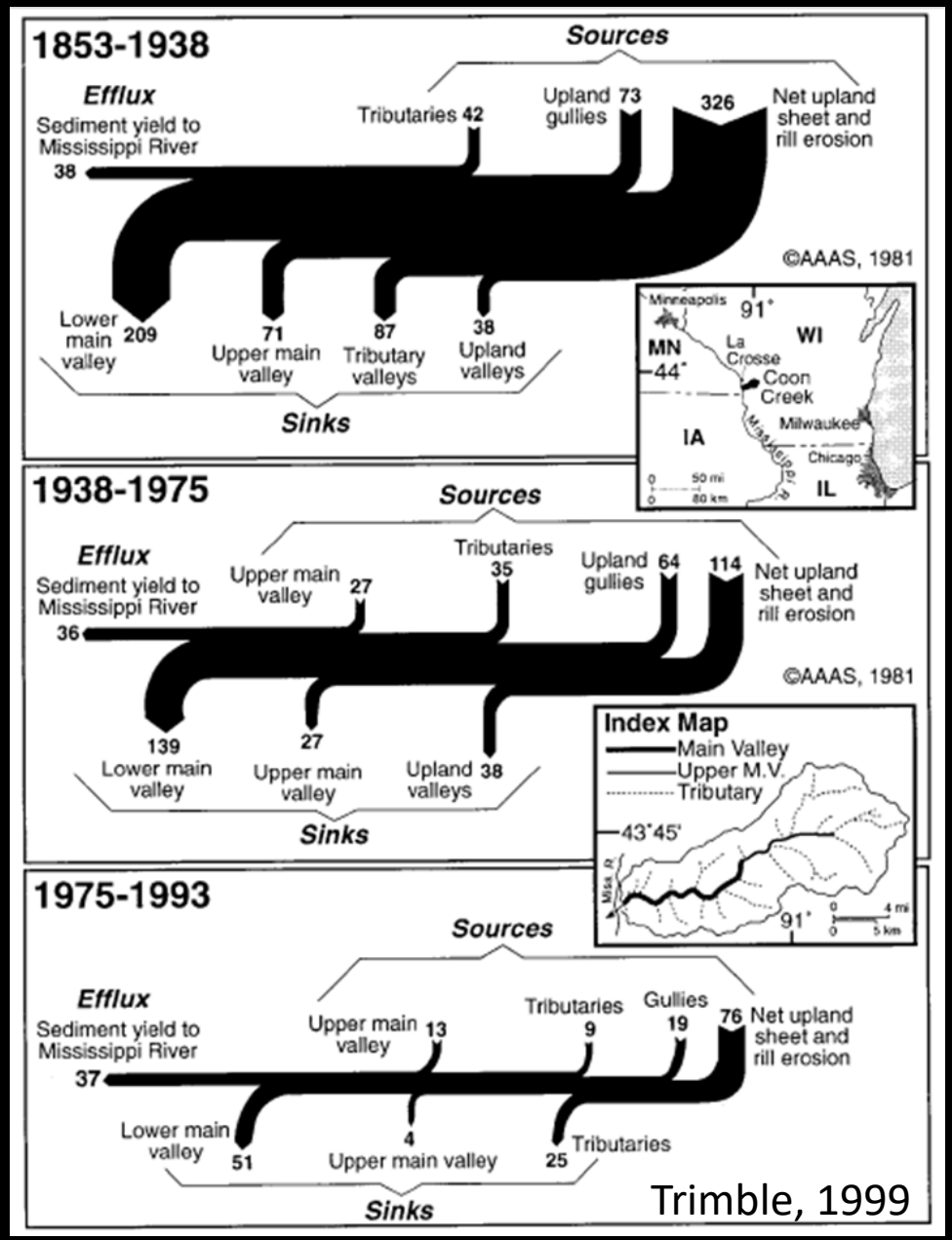
Geographic:
Where in the landscape?

Geomorphic:
Which landforms contributing

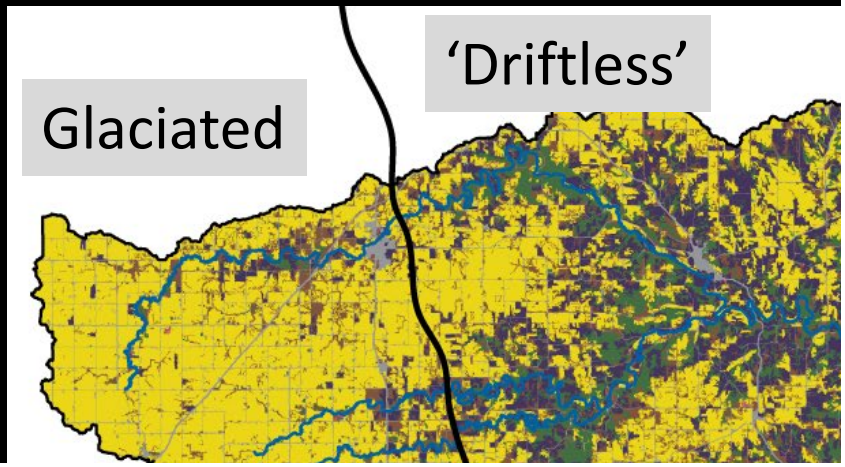
Fingerprinting case study in Root River, SE MN

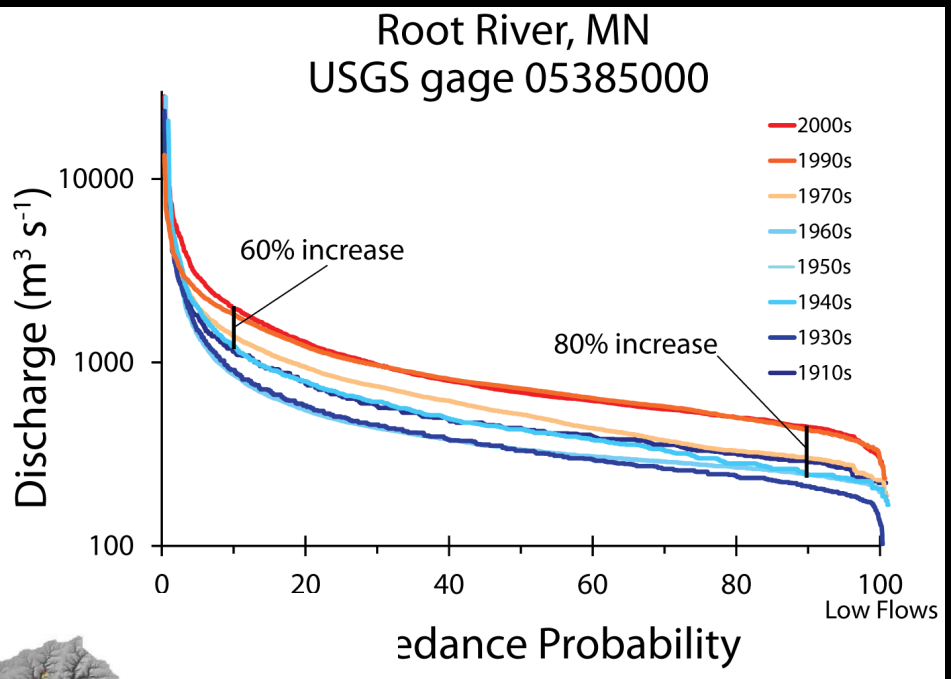




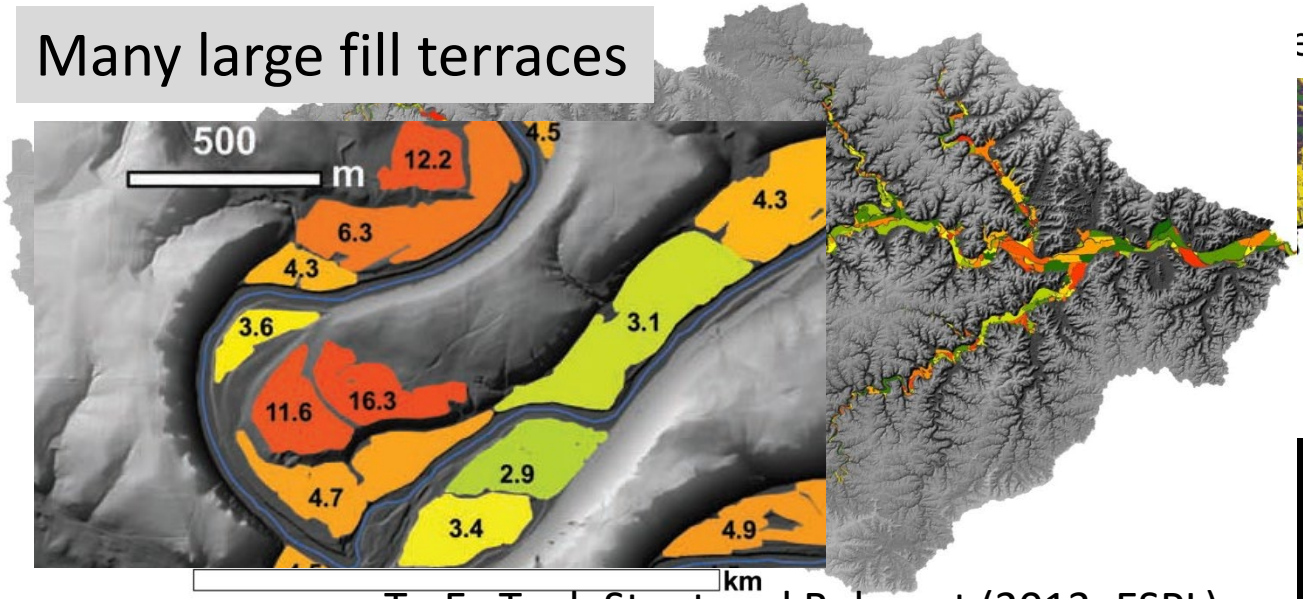


Mostly ag, mostly unglaciated
big increases in flow, big fill terraces



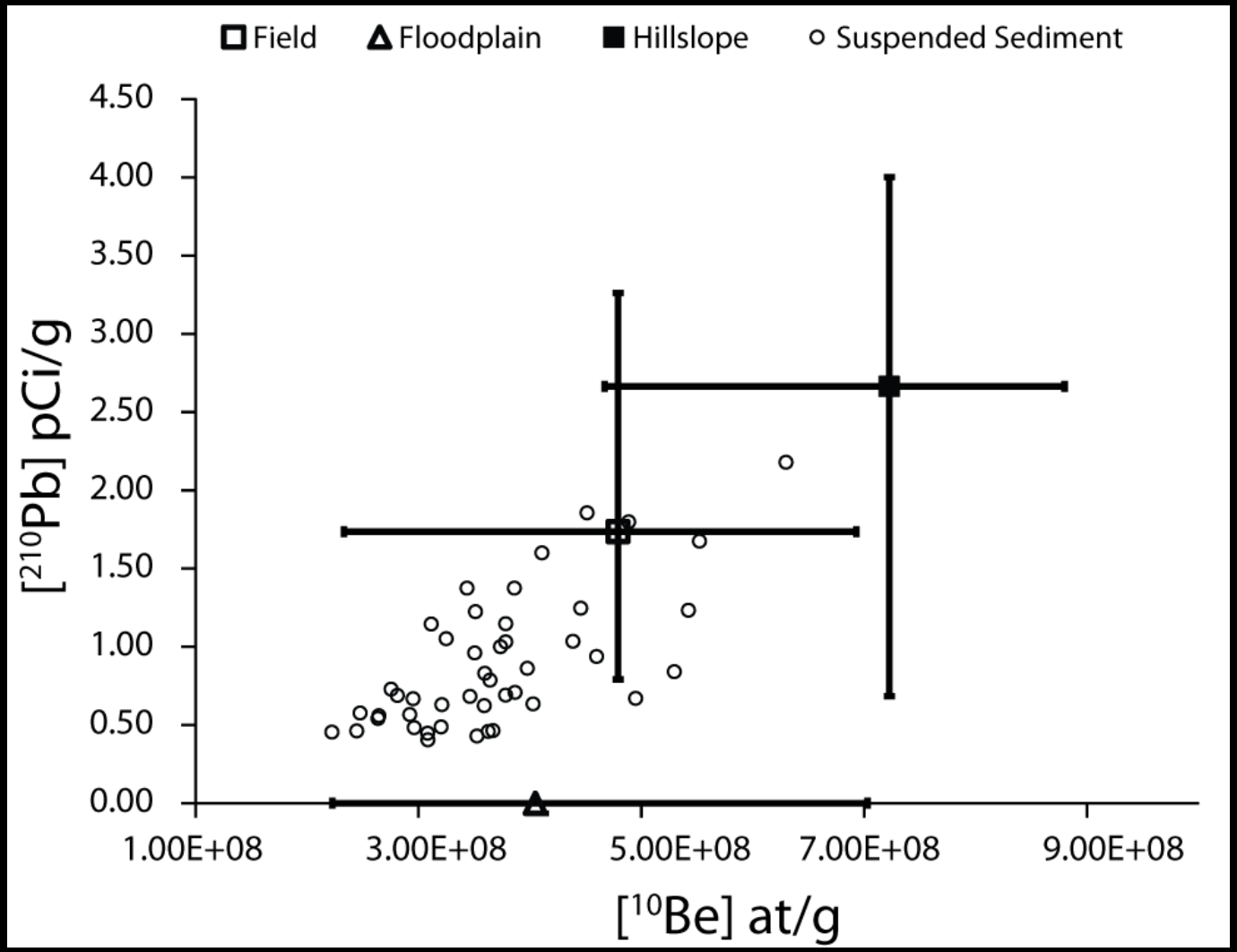


Many large fill terraces



TerEx Tool: Stout and Belmont (2013, ESPL)

^{10}Be and ^{210}Pb results from the entire watershed



Stout et al. (2014)

Much variation in source tracer concentrations

^{10}Be:
Most samples exclusively overlap with ag fields

^{210}Pb:
Majority of samples are 20-50 % field

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/jenvman

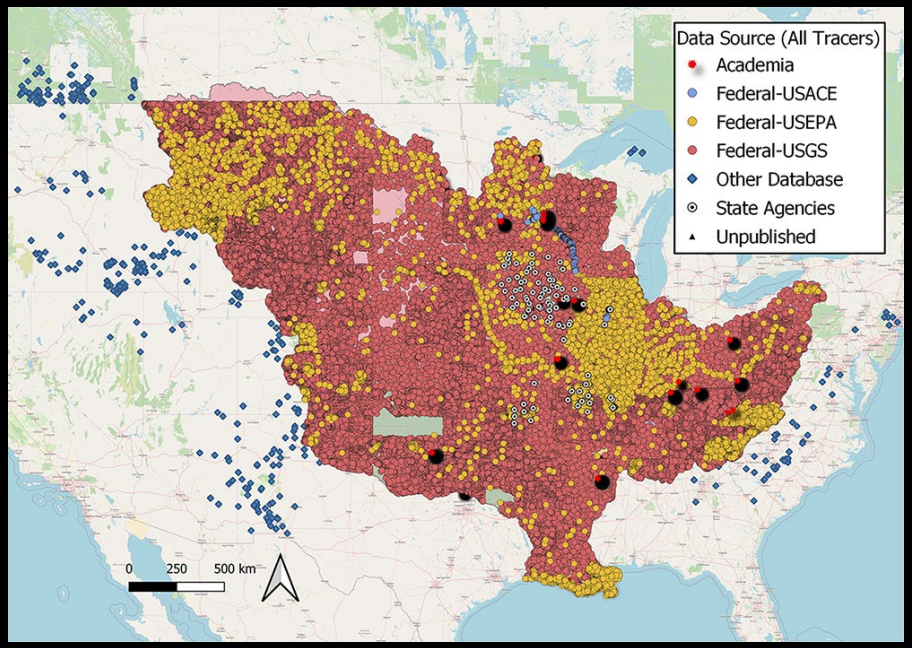
Review

Sediment source fingerprinting as an aid to large-scale landscape conservation and restoration: A review for the Mississippi River Basin

Zhen Xu [a,*], Patrick Belmont [a], Janice Brahney [a], Allen C. Gellis [b]

Most studies found near-channel sources to be dominant.

Lack of standardization in procedural steps makes results difficult to compare.



Roadmap

YESTERDAY

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?

TODAY

Watershed Sediment Budget

Tools and techniques for robust constraints on sources and sinks.

Case studies in sediment supply, transport, and morphodynamics

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.

A bit of hydrology

Targeted modeling and metrics. Stationarity Assumption?

Reservoir and pond sedimentation rates

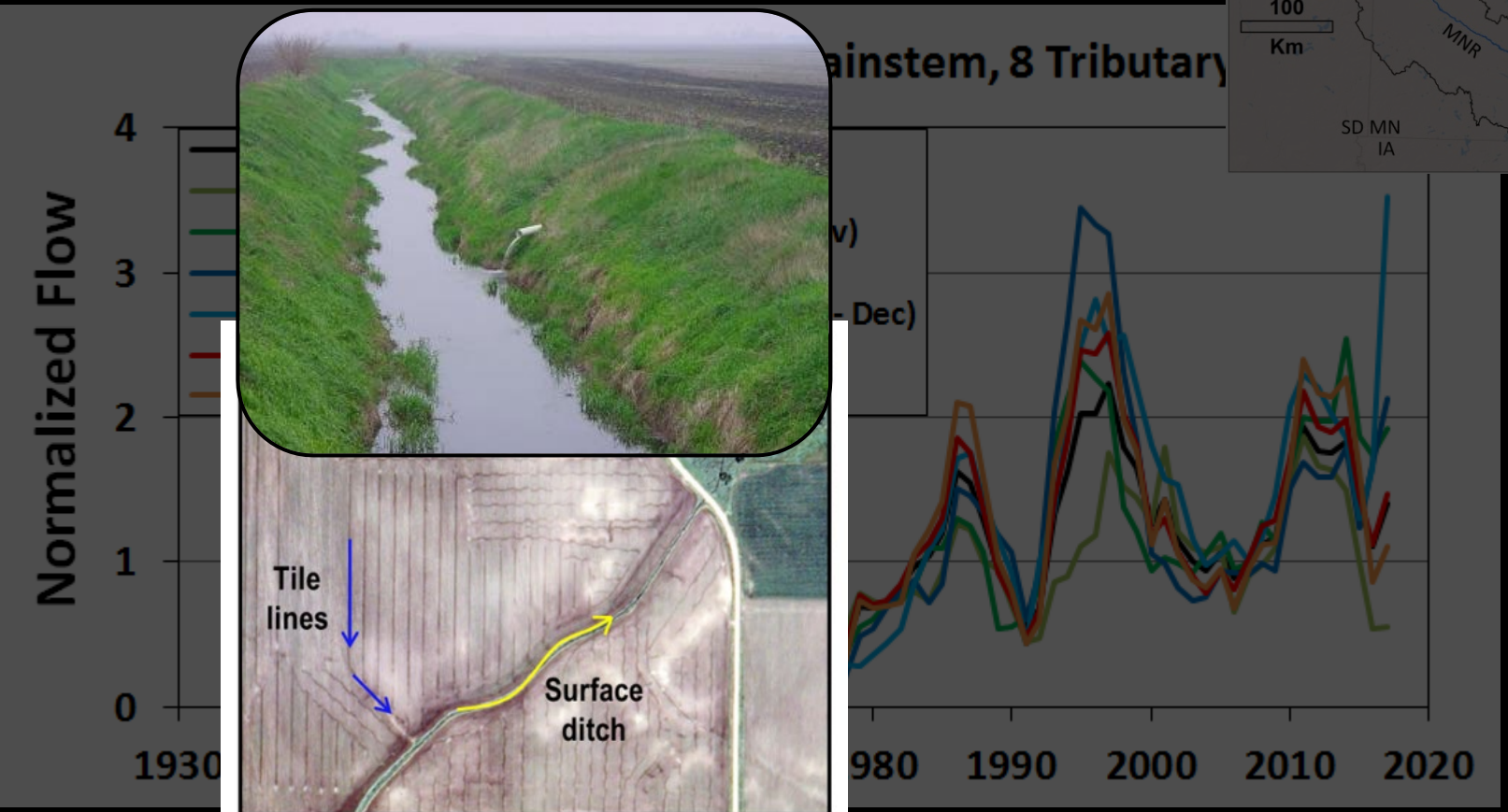
Time- and space-integrated measurements that may be useful.

Rivers change. When, where, and how?

- How do alluvial channels adjust to changes in flow and/or sediment supply?
- What determines the mode & magnitude of the response to perturbations?
- What are the implications for floodplain inundation & evolution?

Minnesota River Basin: Flows have gone waayyy up

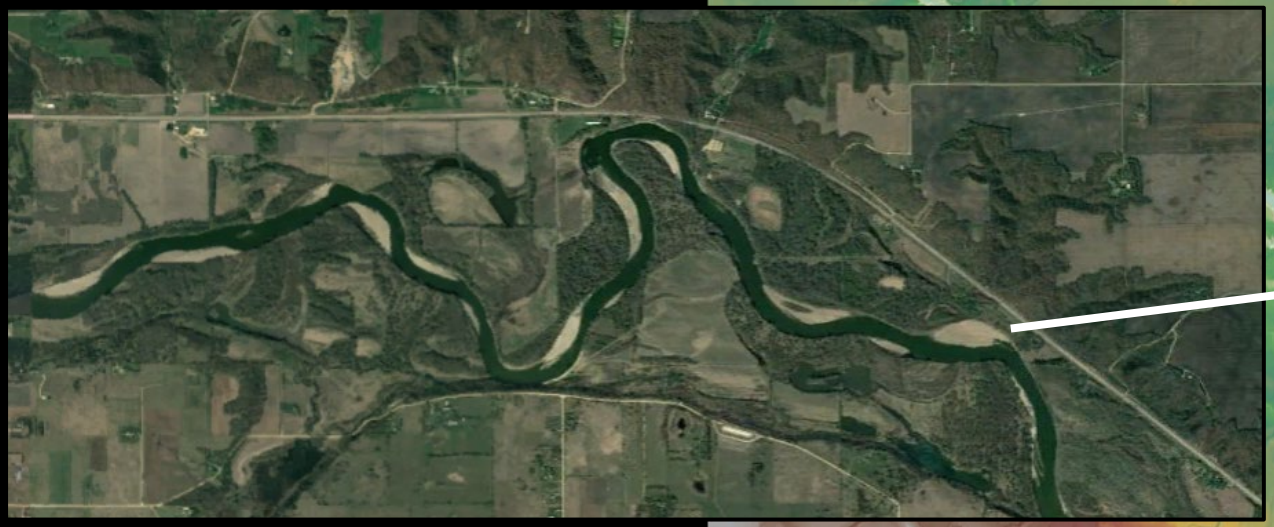


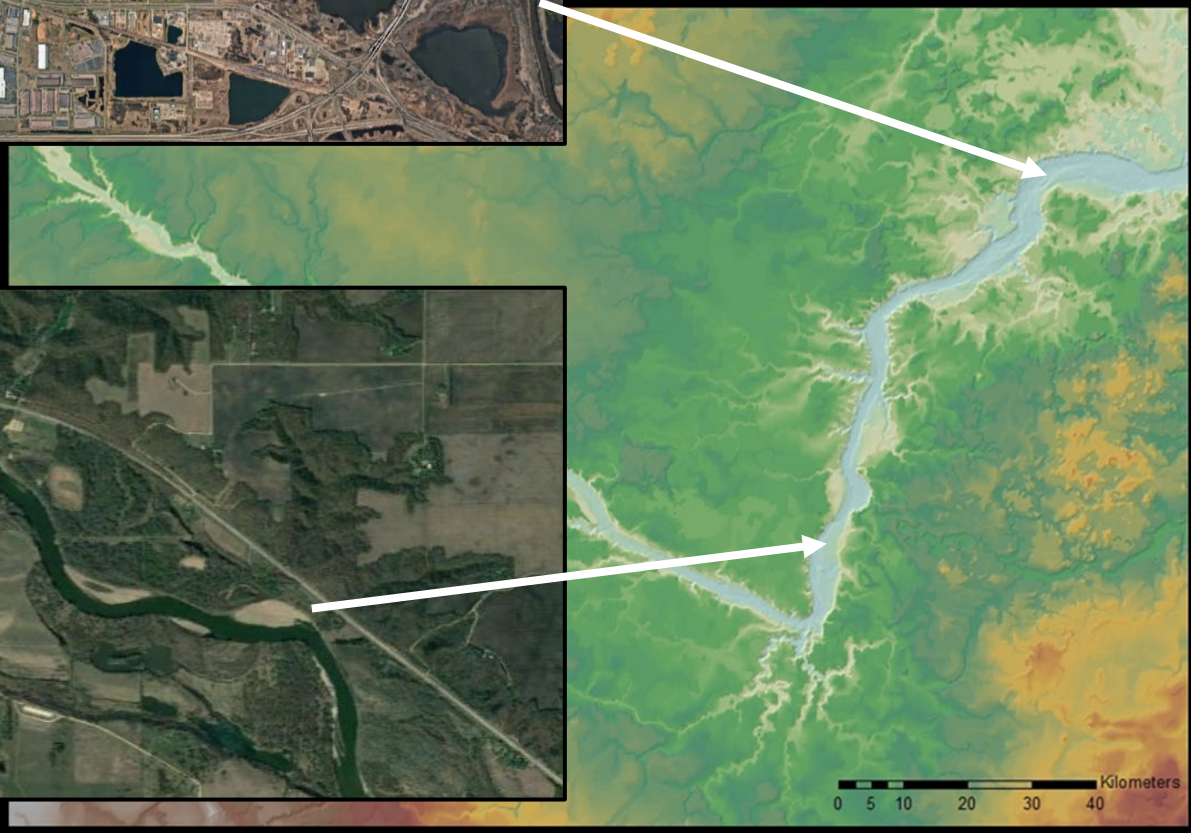


Schottler et al., 2014; Foufoula-Georgiou et al., 2015; Belmont et al., 2016; Kelly et al., 2017

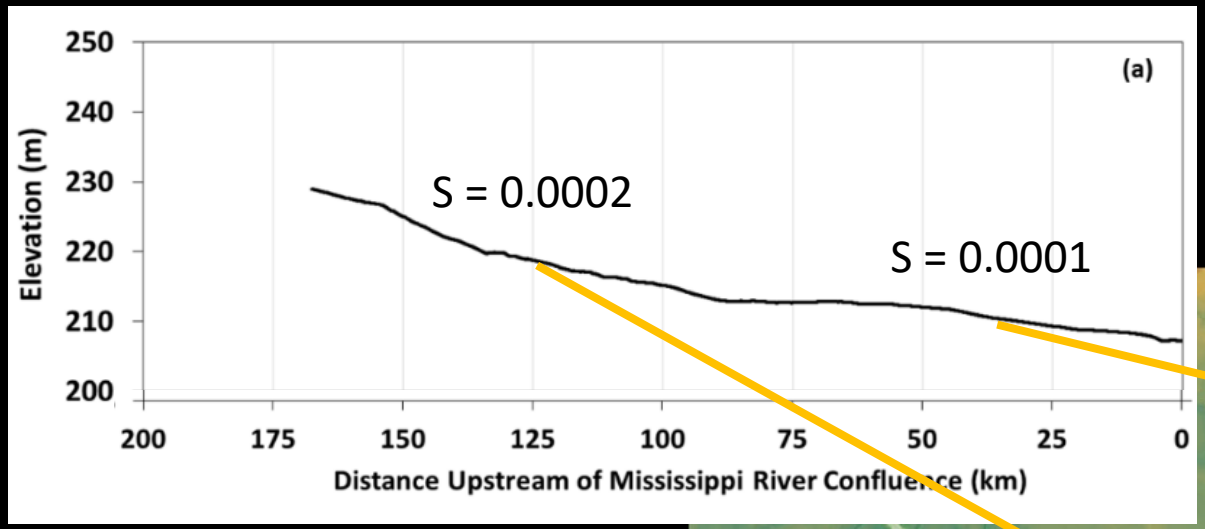
Striking differences in form and behavior along the lower 175 km of the Minnesota River

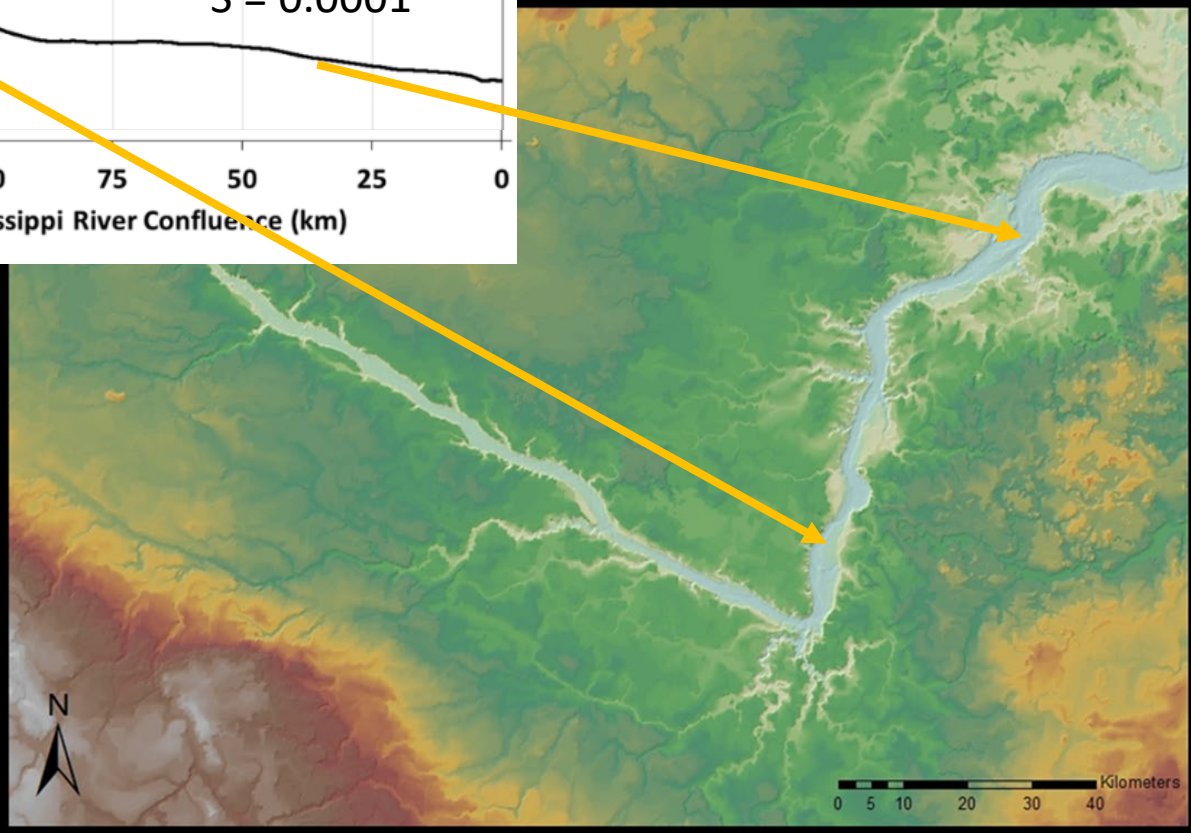




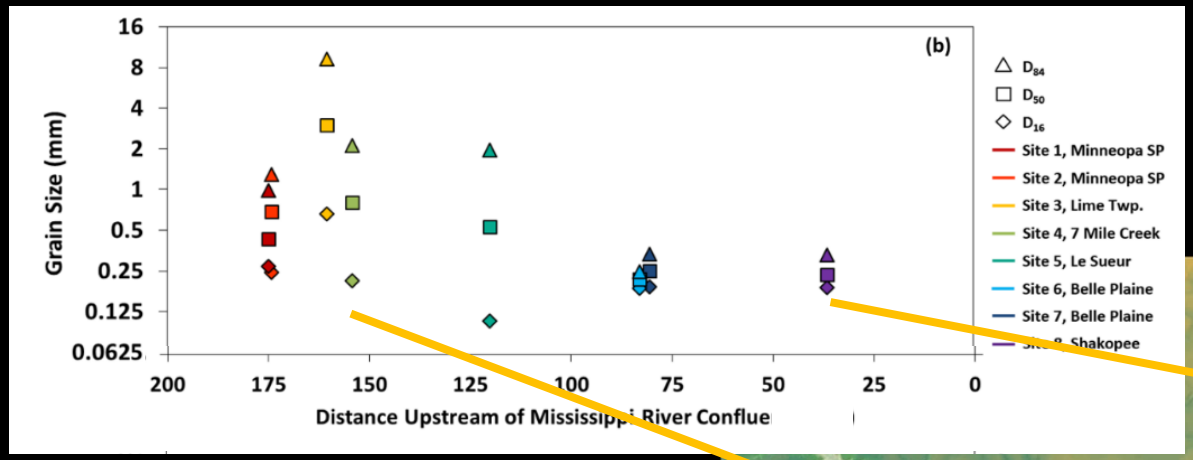


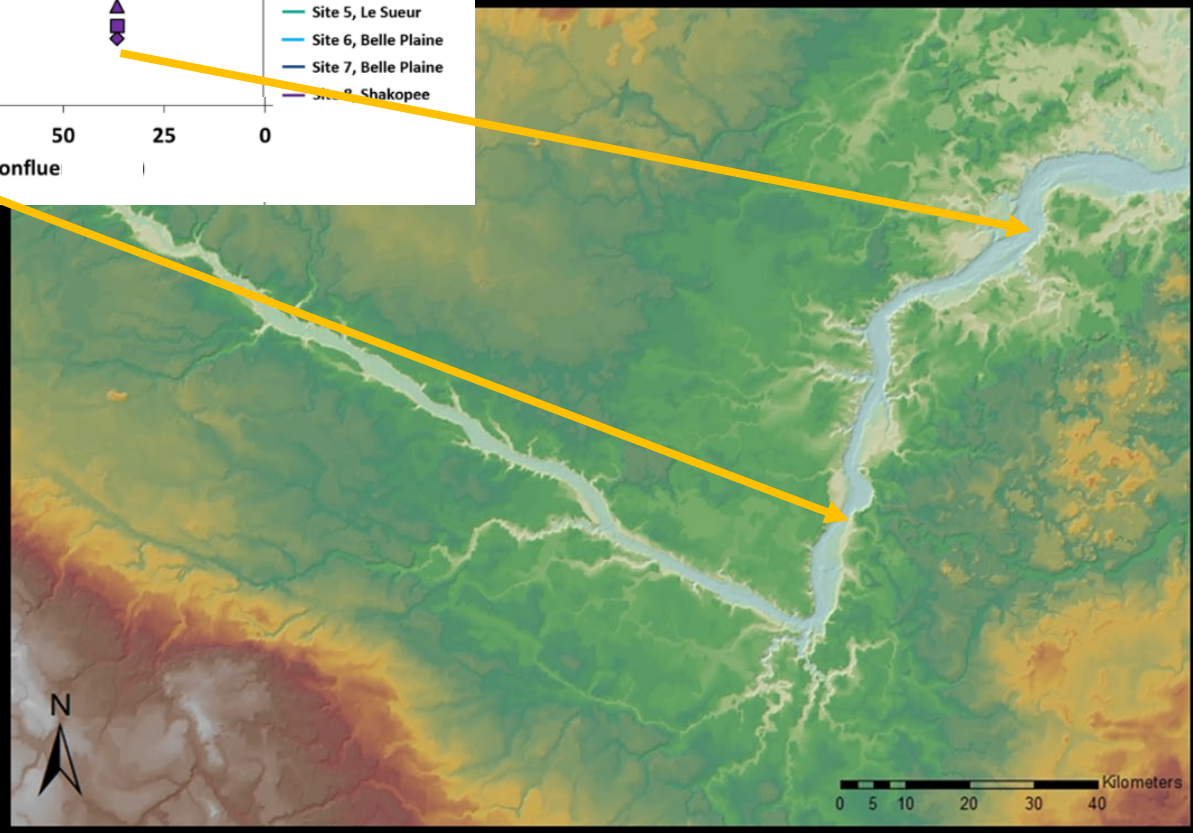
Transition in slope,





Transition in slope, grain size,



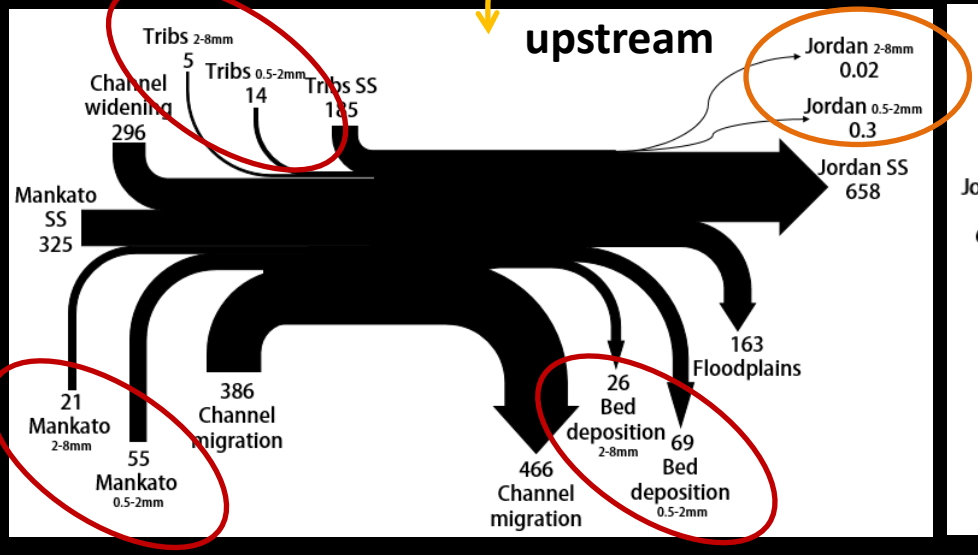


Kelly, 2019

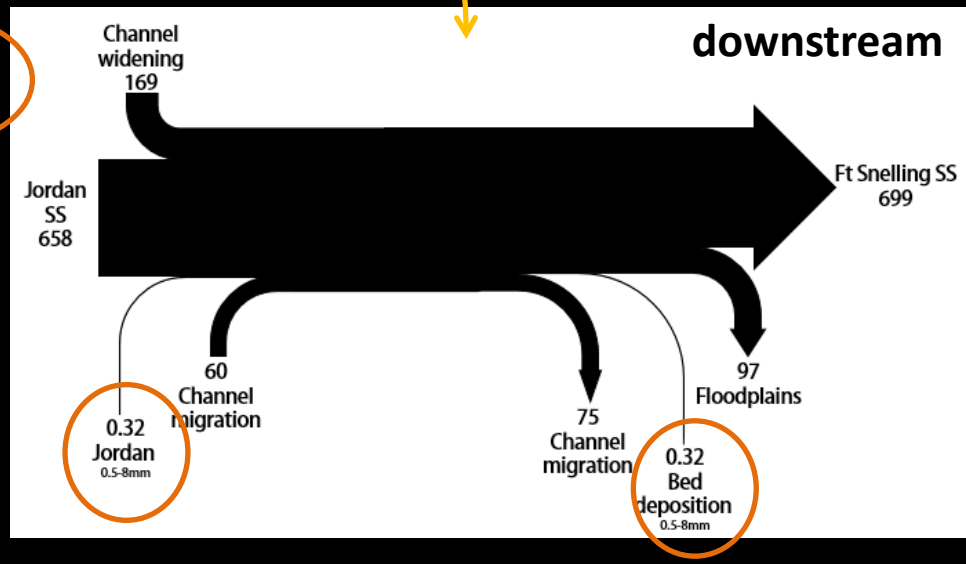
Transition in slope, grain size, bedload transport



Bedload: 19% → 0.5% → 0.00%



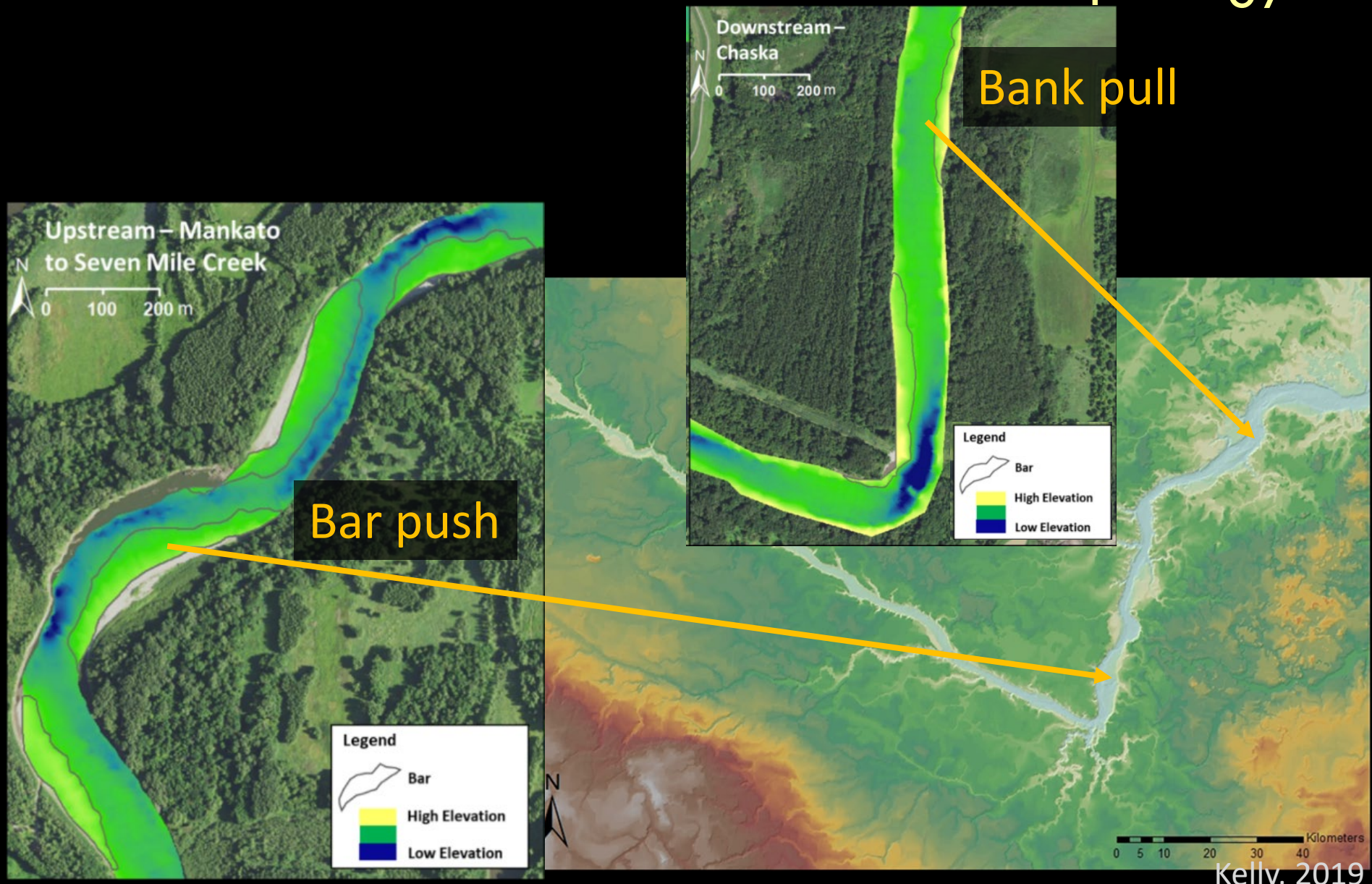
Mixed bedload and suspended load



Suspended load dominated

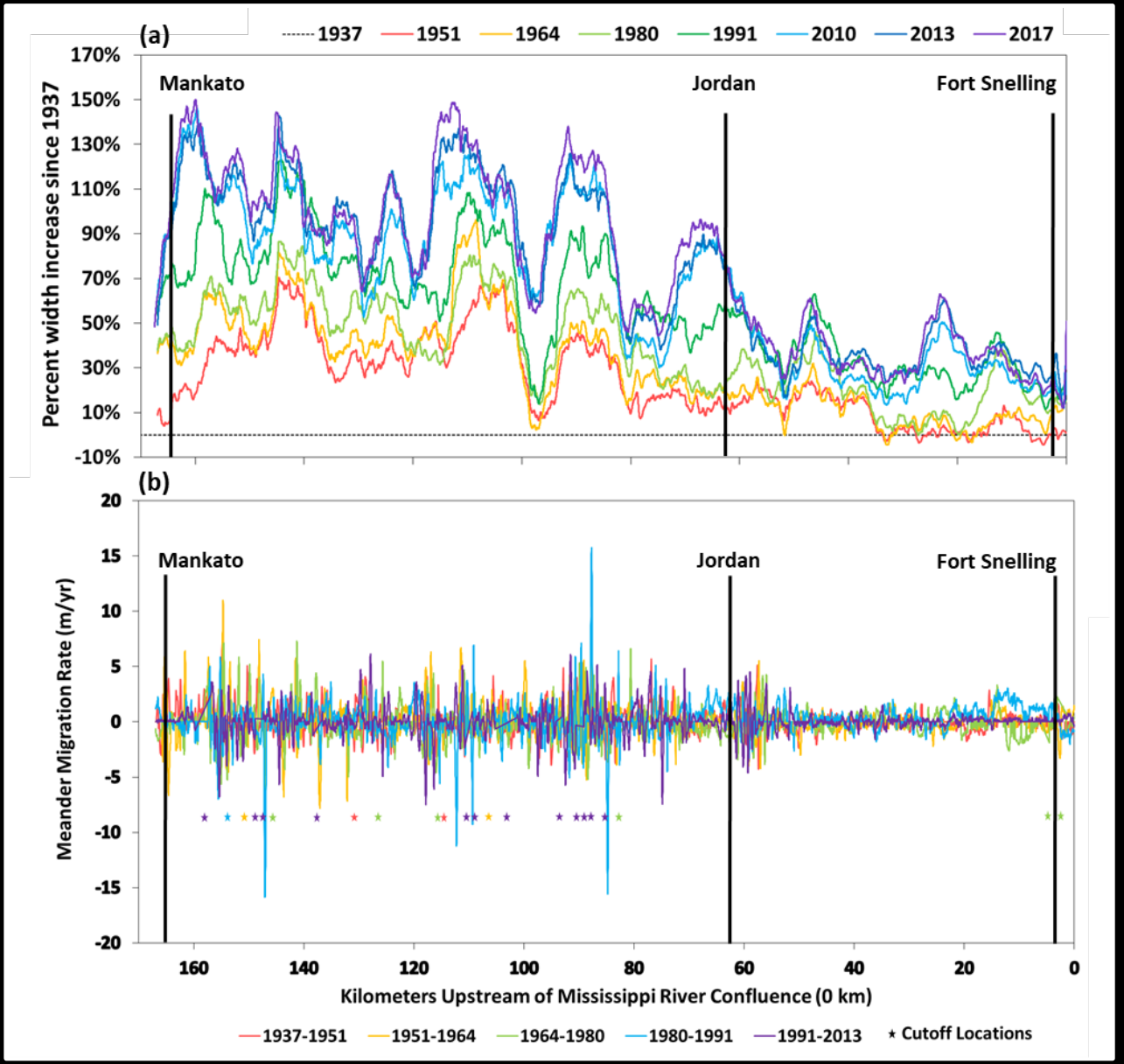
Kelly, 2019

Transition in slope, grain size, bedload transport causes distinct differences in bar morphology…



Kelly, 2019

…and big differences in process rates

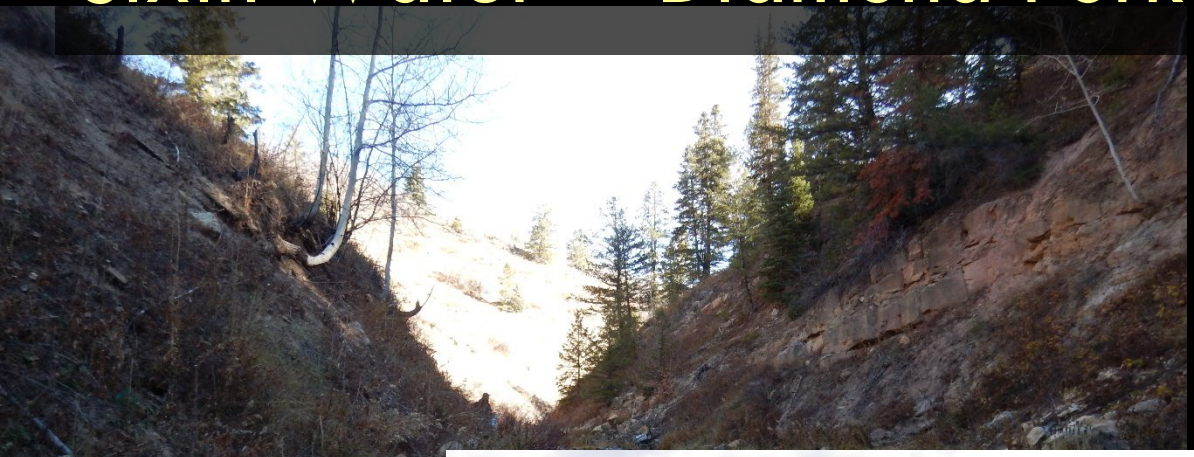


Kelly, 2019

Rivers change. When, where, and how?

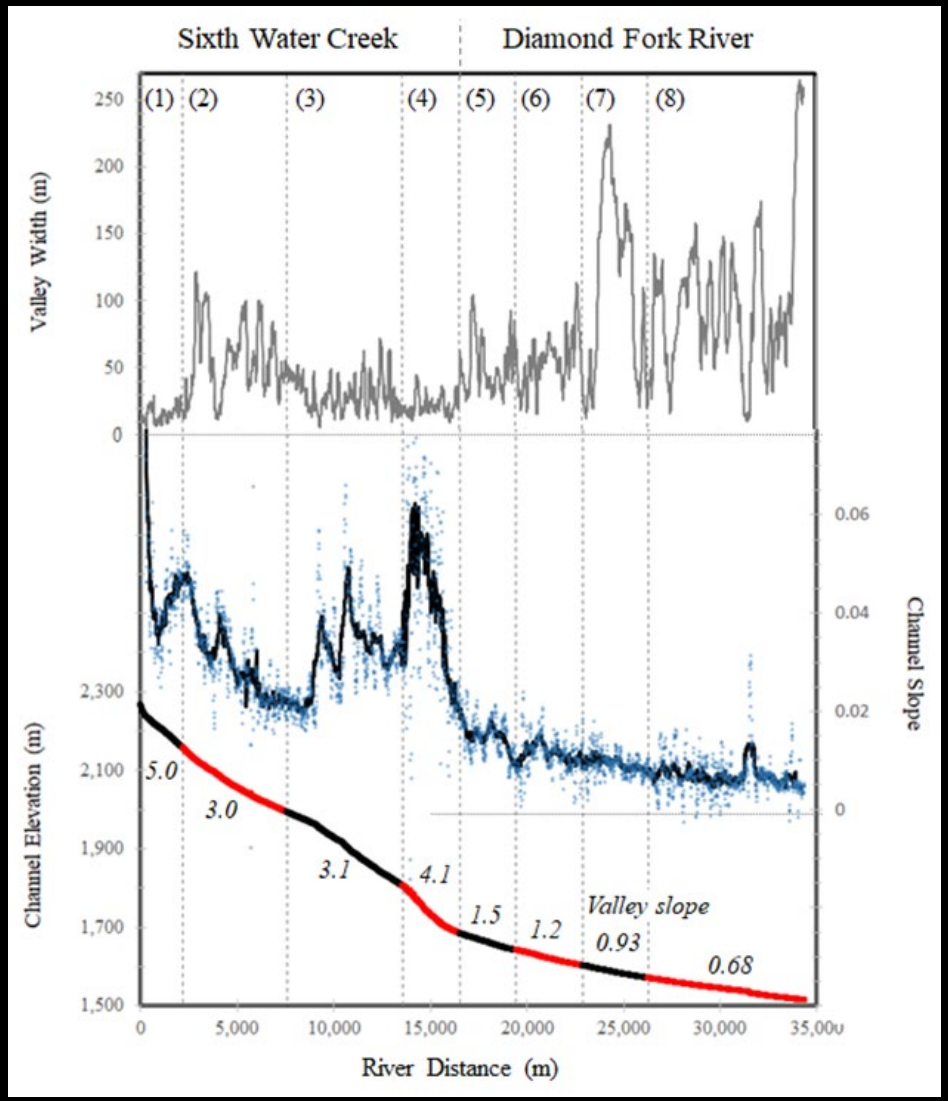
- How do alluvial channels adjust to changes in flow and/or sediment supply?
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Sixth Water ~ Diamond Fork watershed

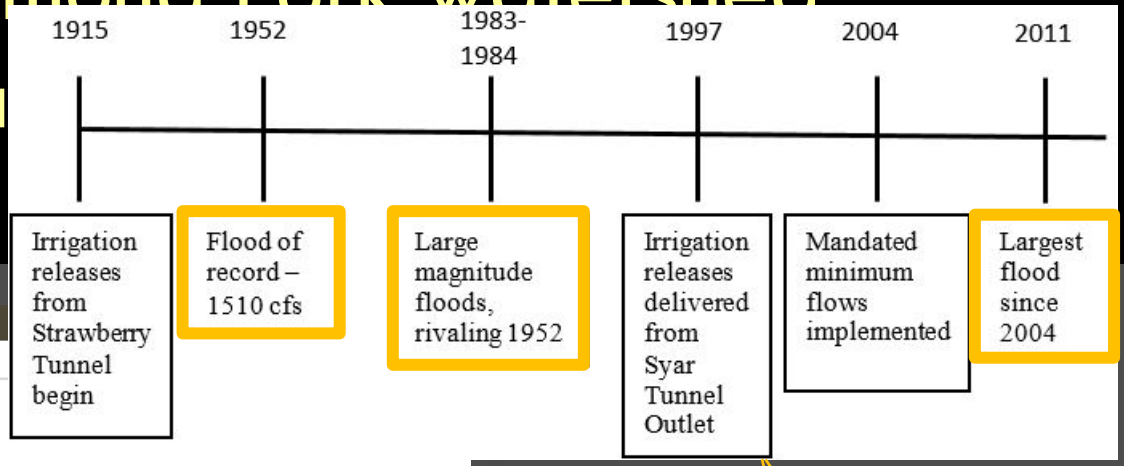


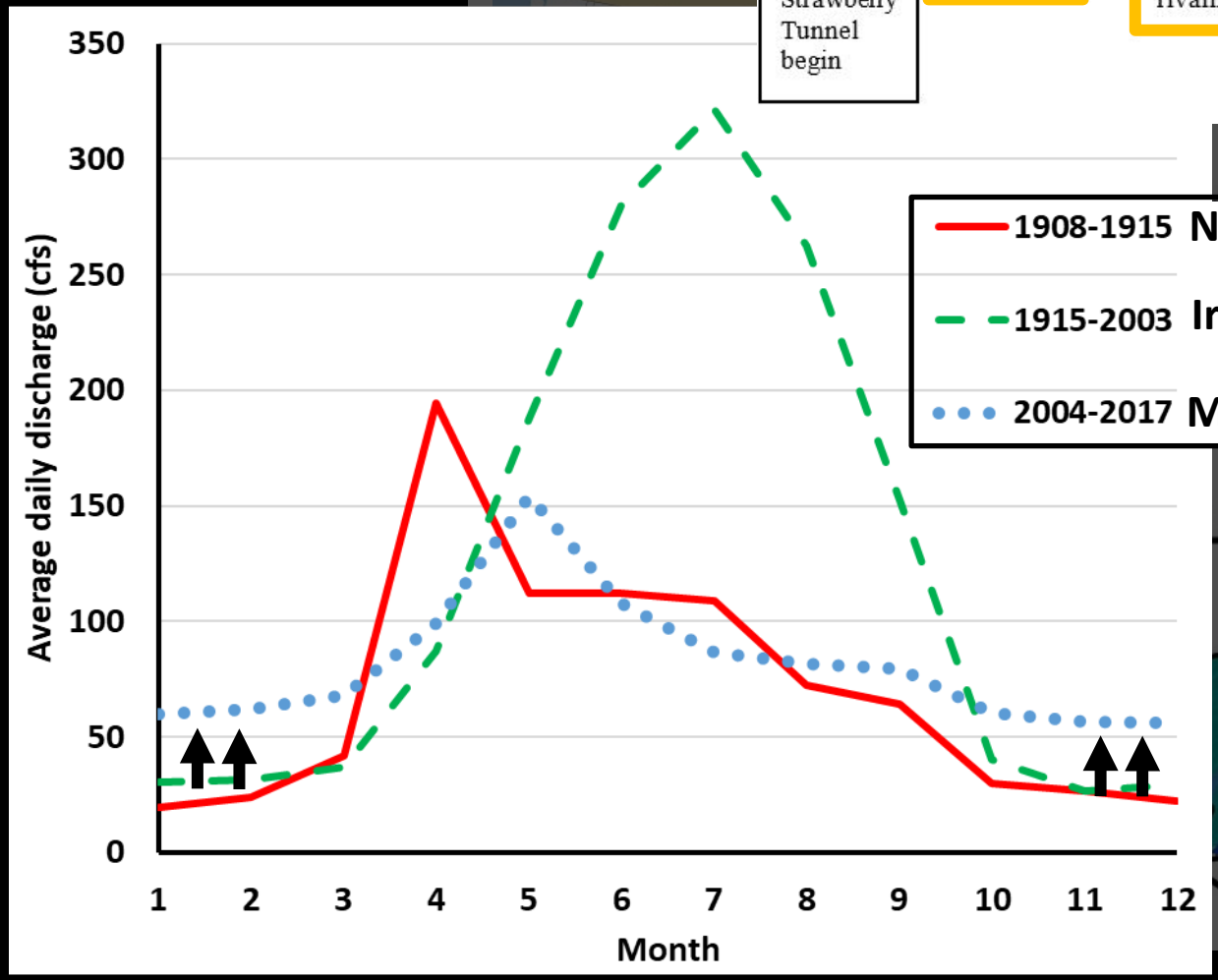


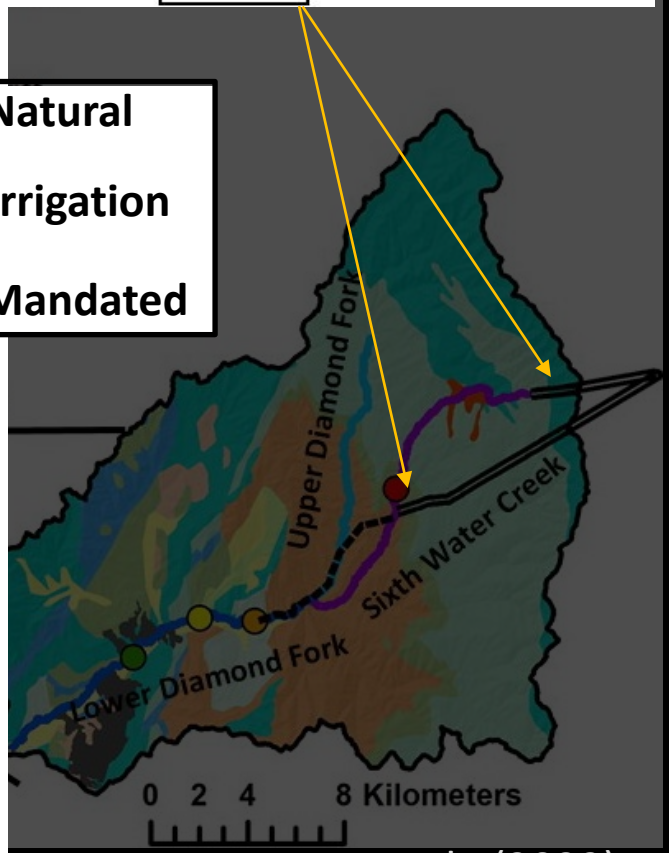
Downstream changes in slope, valleybottom width



Sixth Water ~ Diamond Fork watershed
Big, deliberate cha

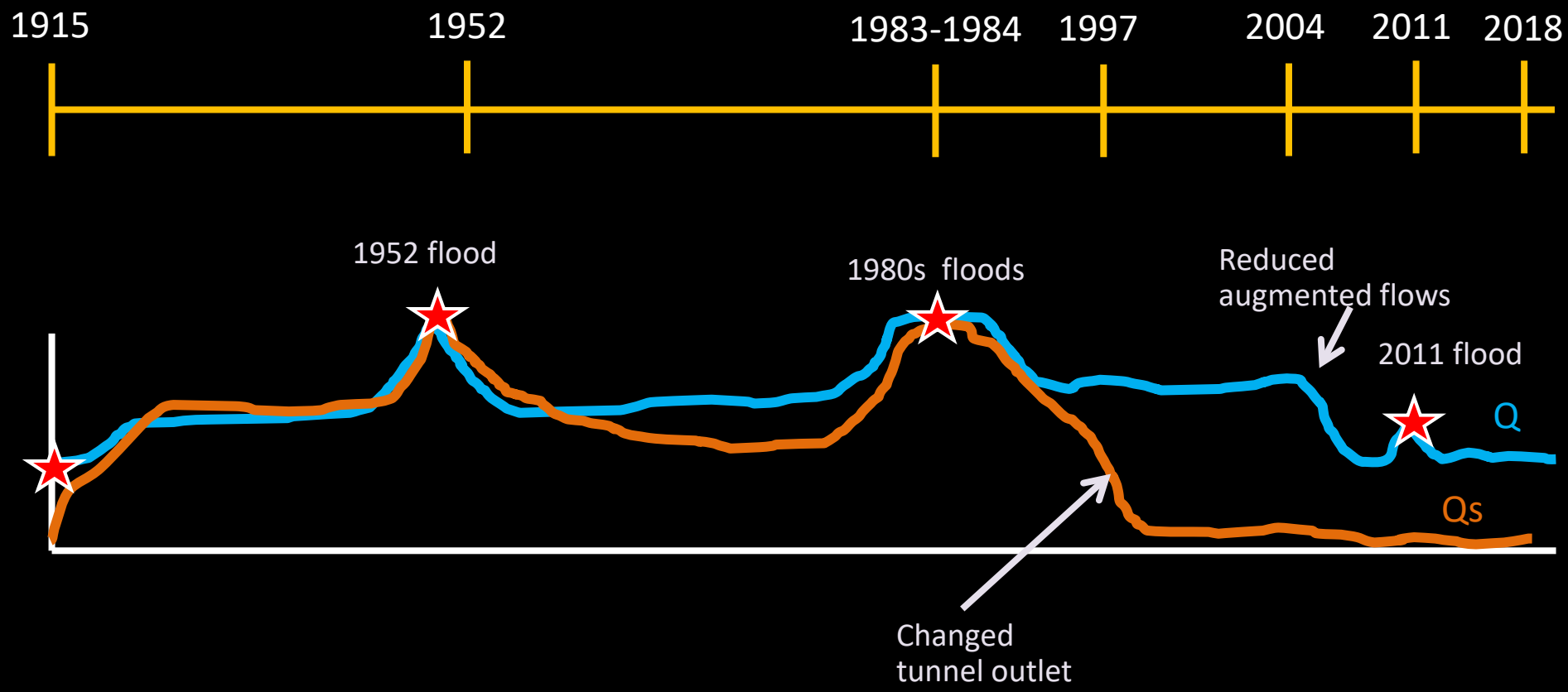






Jones et al., (2023)

A reasonably well-constrained disturbance★ and recovery series



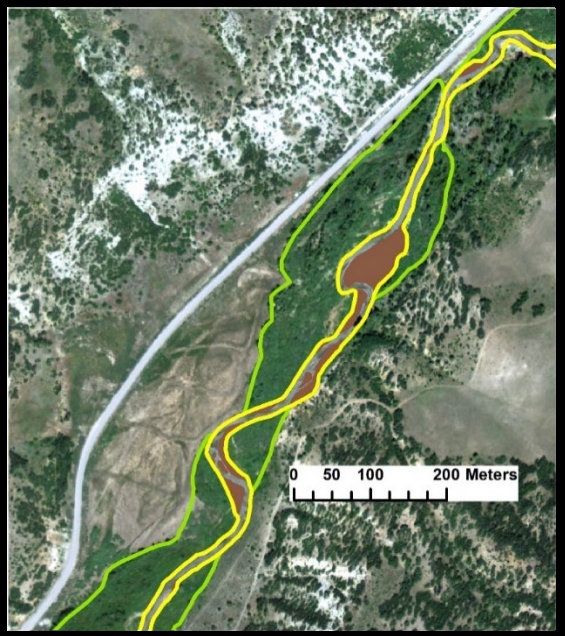
Jones et al., (2023)

Oodles of info from air photos



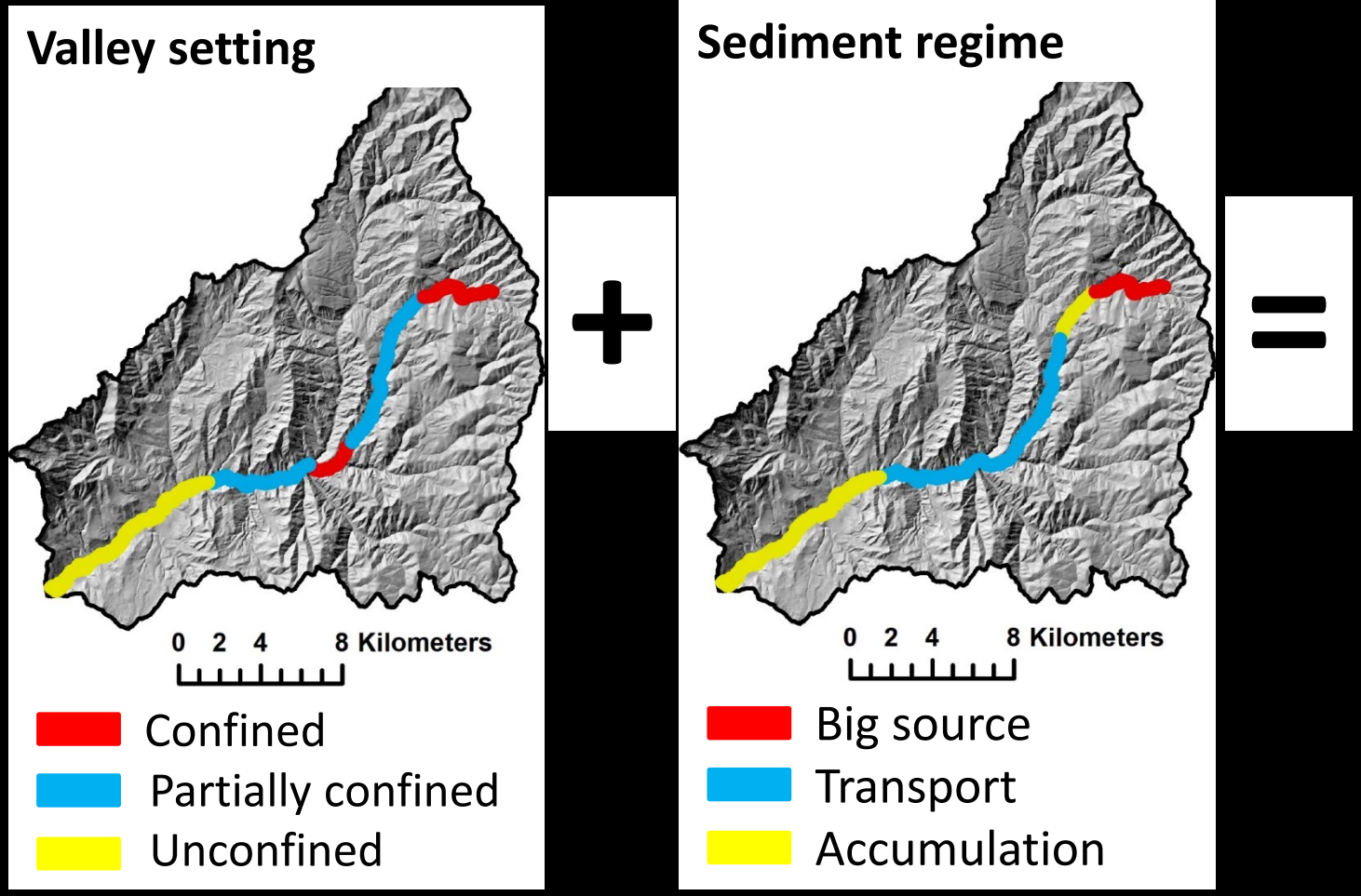
For every photo set, for all 32 km, mapped:

- Active channel and measured width
- In-channel and bank attached bars
- Floodplain vegetation



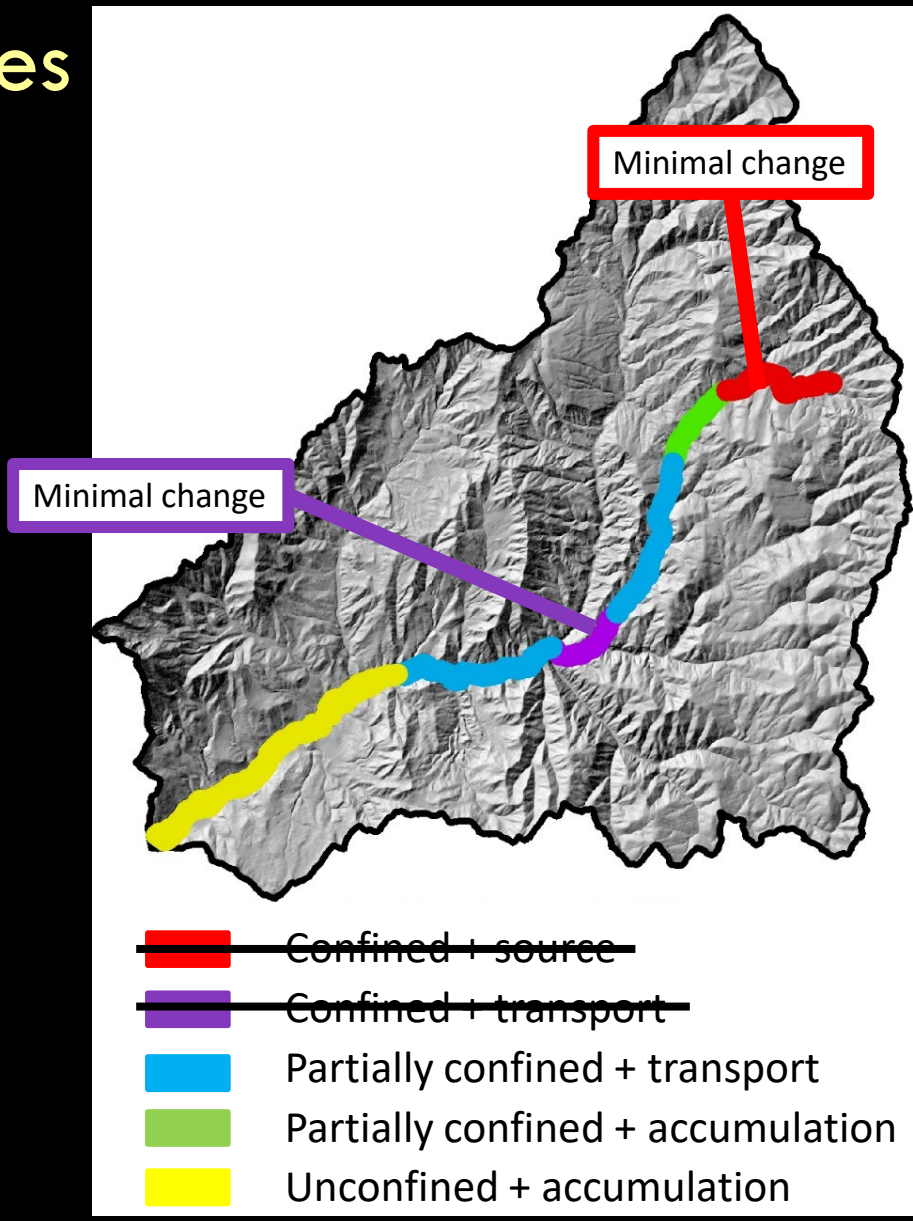
Jones et al., (2023)

Distinct reaches



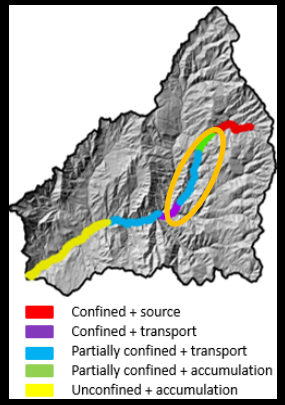
Jones et al., (2023)

Distinct response of reaches

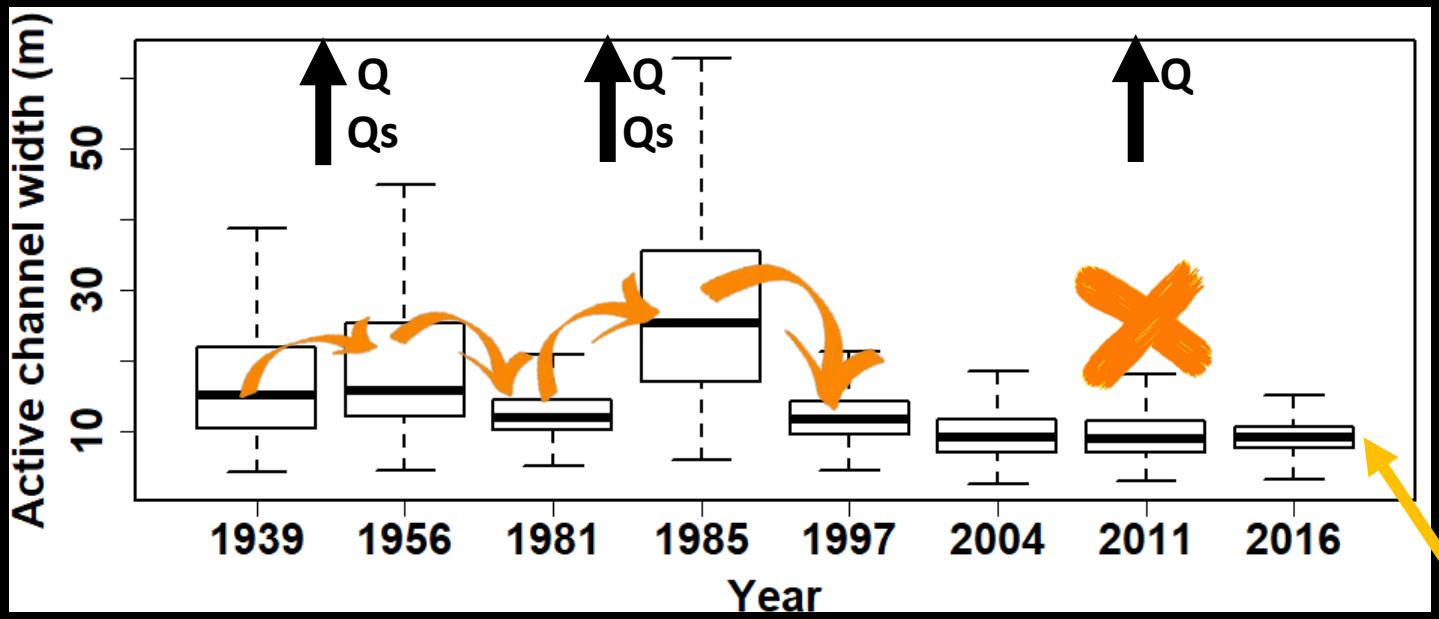


Jones et al., (2023)

Partly confined, transport reach







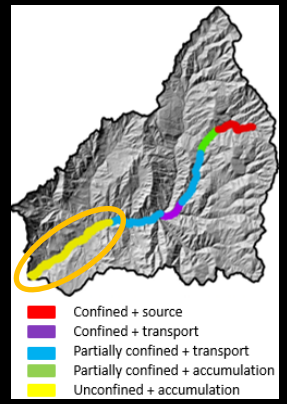
Widen in response to disturbance flows when Q_s is high

Narrow in the absence of Q_s pulse

Stable width of 12 m since 2004

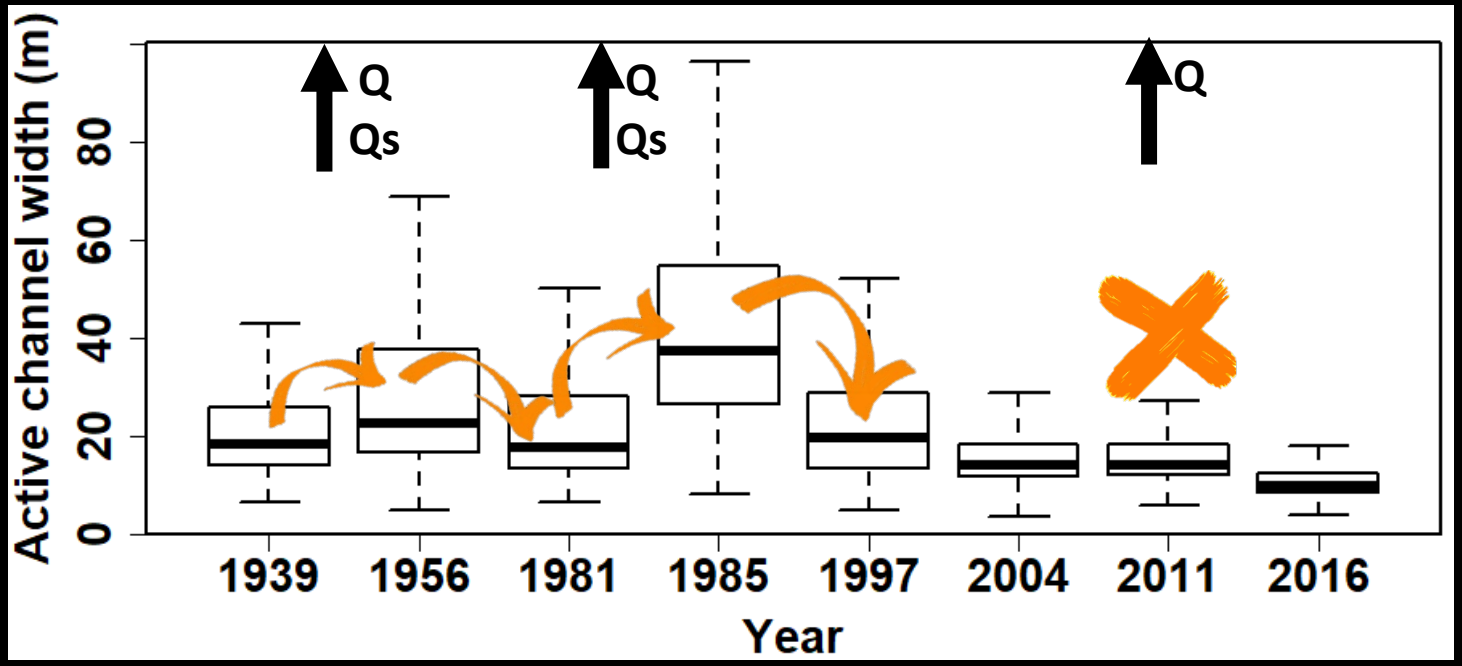
Jones et al., (2023)

Unconfined, accumulation reach



High Q

Low Q



Widen in response to disturbance flows

Narrowing to ~20 m during recovery time

Continued narrowing since 2004

Median width ~12 m

Jones et al., (2023)

Sixth Water ~ Diamond Fork Summary

Valley setting and sediment regime (supply/transport capacity) exert strong control over channel response

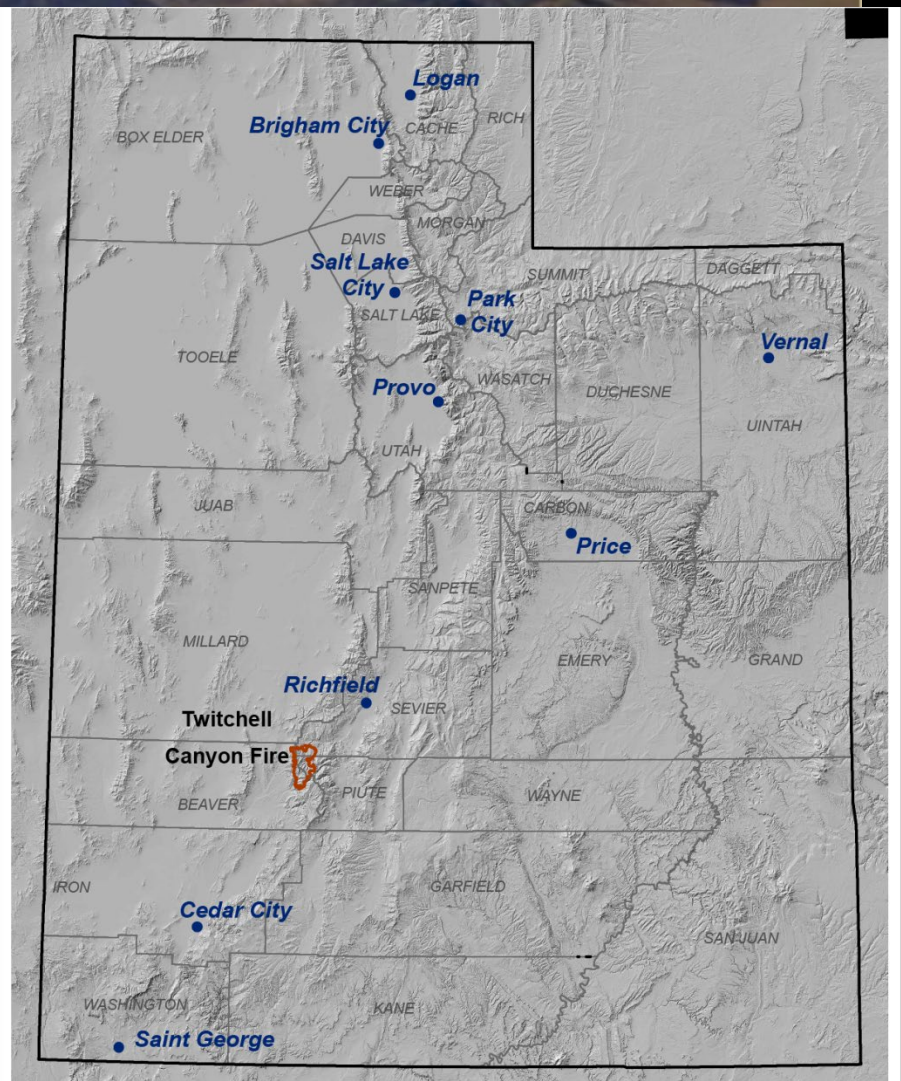
Across watershed, tendency towards a uniform width of ~12 m, appears to be maintained by base flows

Rivers change. When, where, and how?

- How do alluvial channels adjust to changes in flow and/or sediment supply?
- What determines the mode & magnitude of the response to perturbations?
- What are the implications for floodplain inundation & evolution?

Case Study:
Post-wildfire debris flows influence, and are influenced by, connectivity

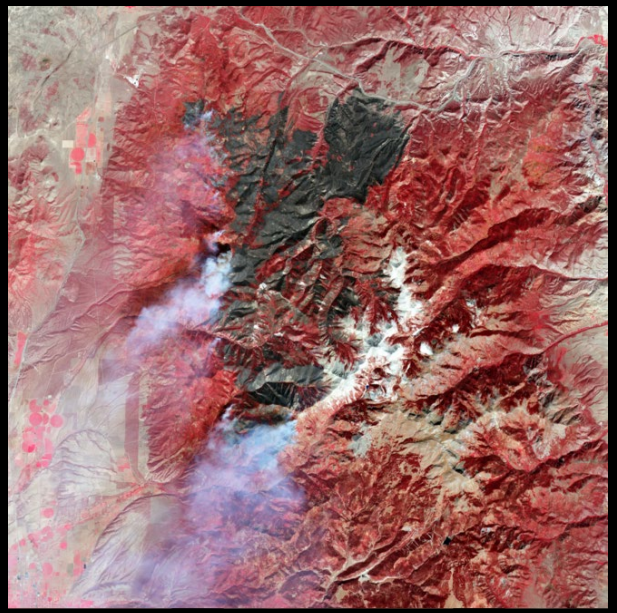


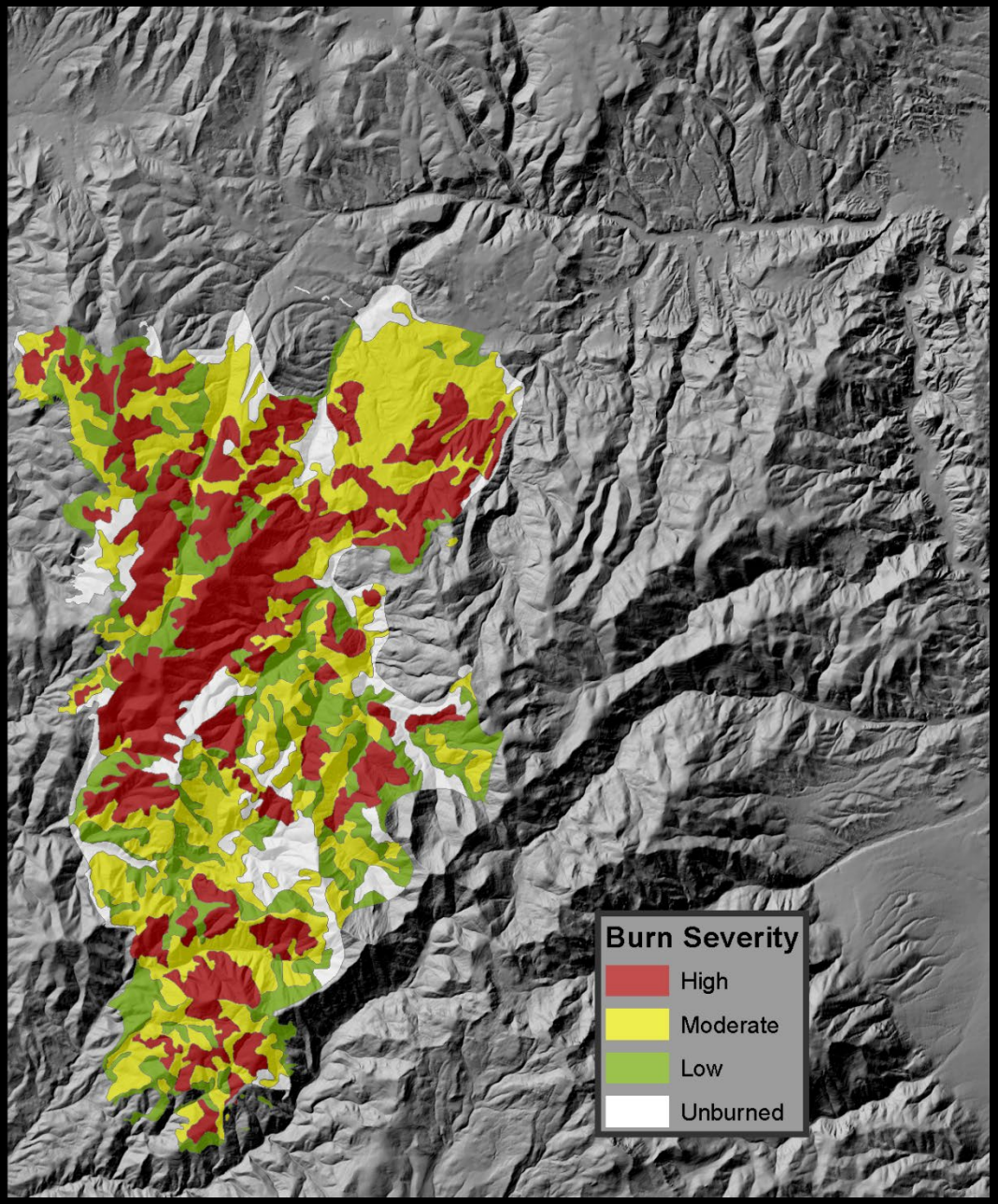


Started by lightning strike

Burned 45,000 acres

1/3 burned at high severity



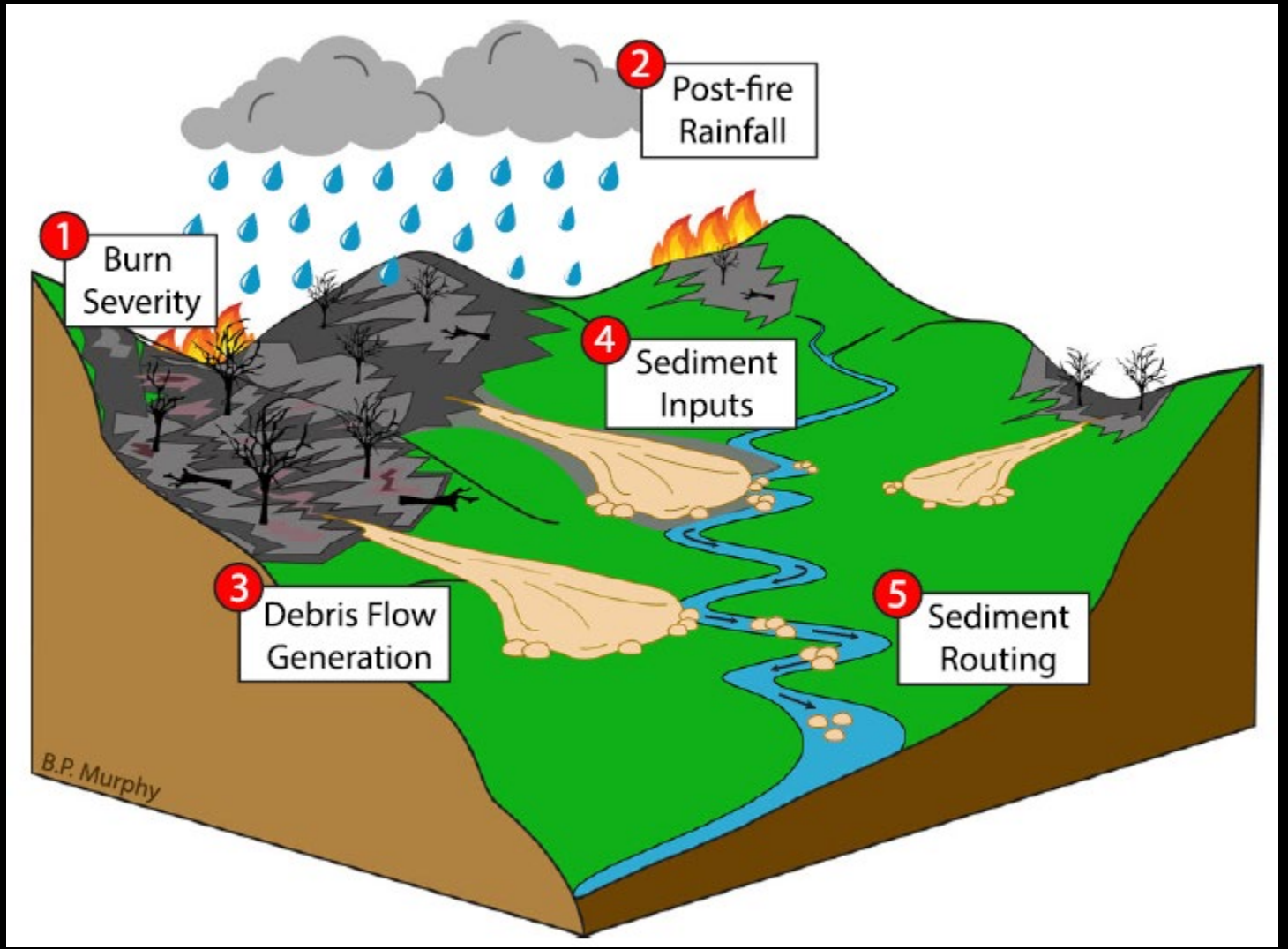






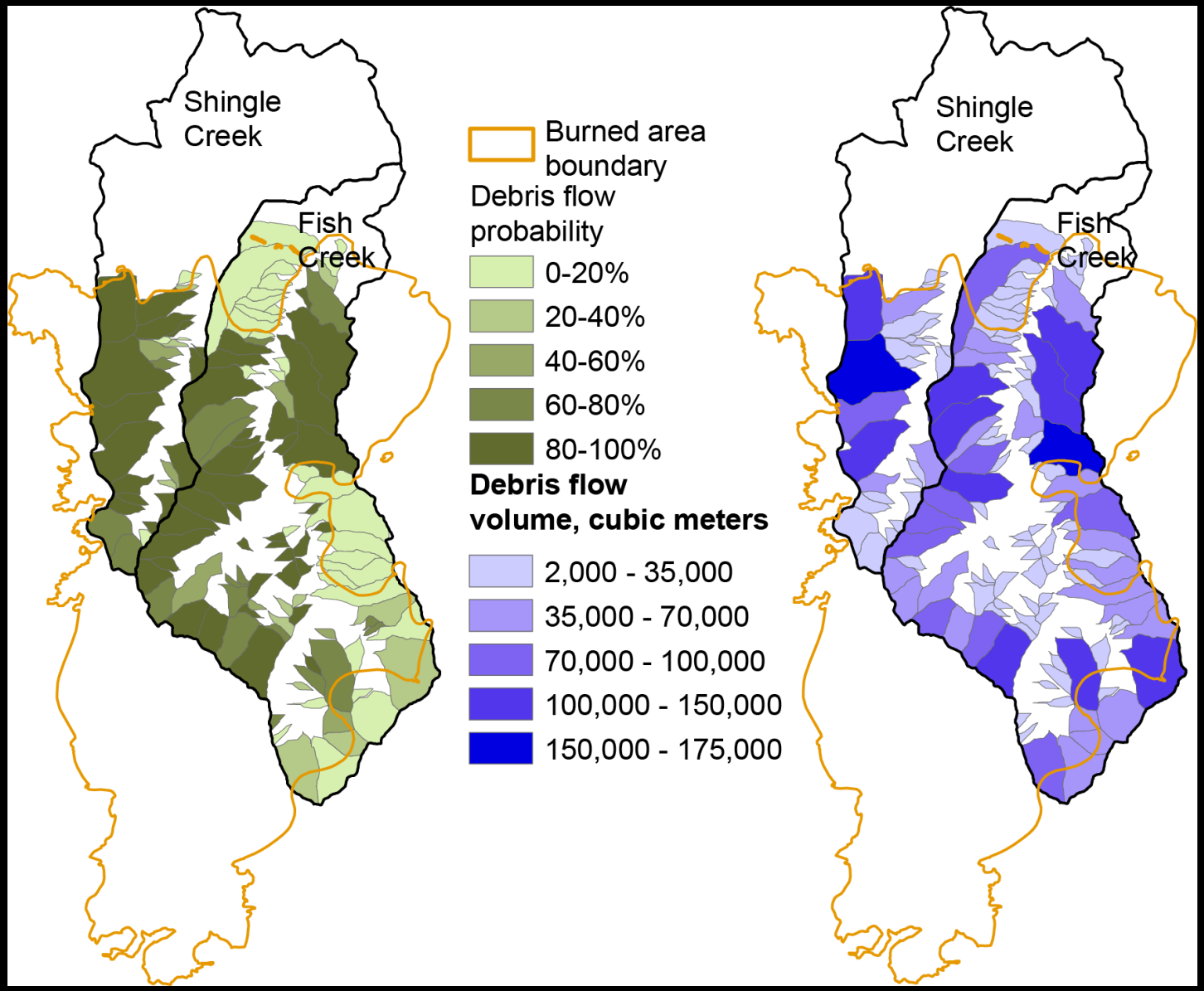

~ 2 m deposition!

What do we need to model this system?



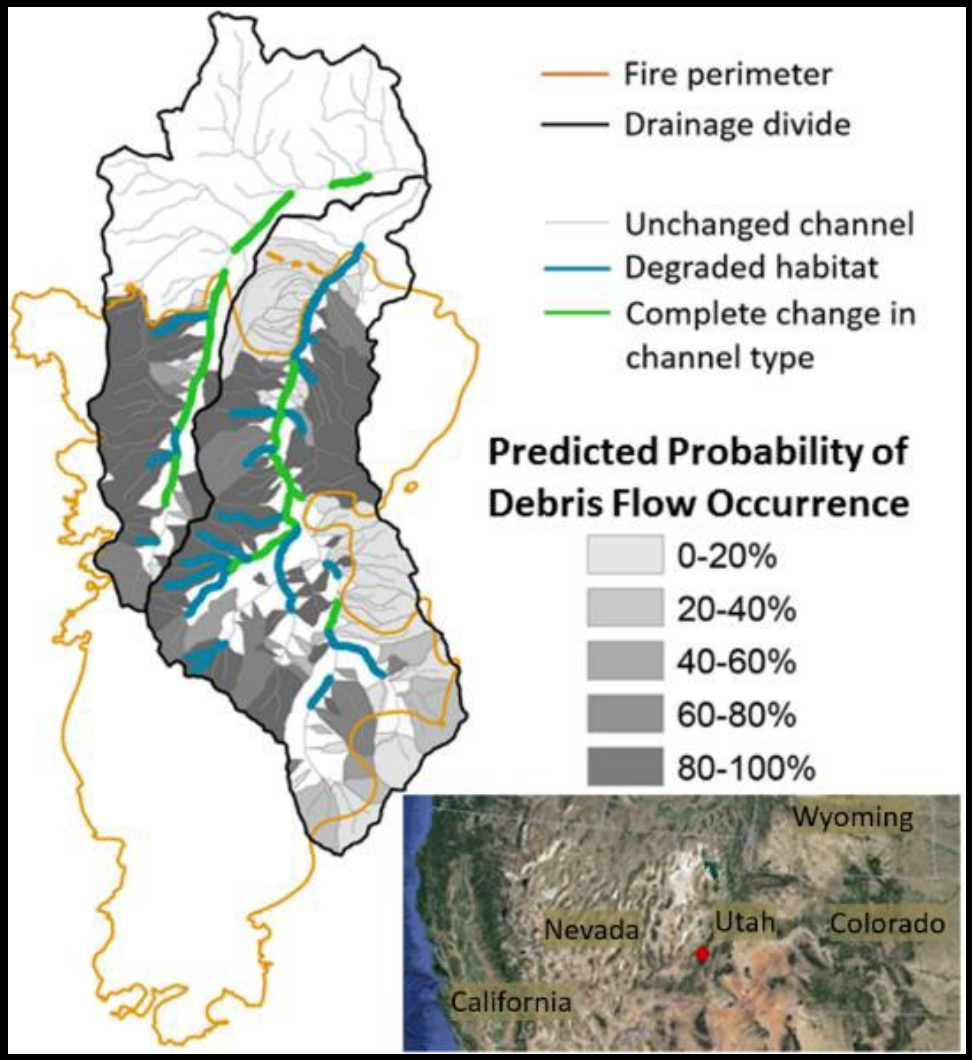
Murphy et al., 2019

Predicting debris flow susceptibility

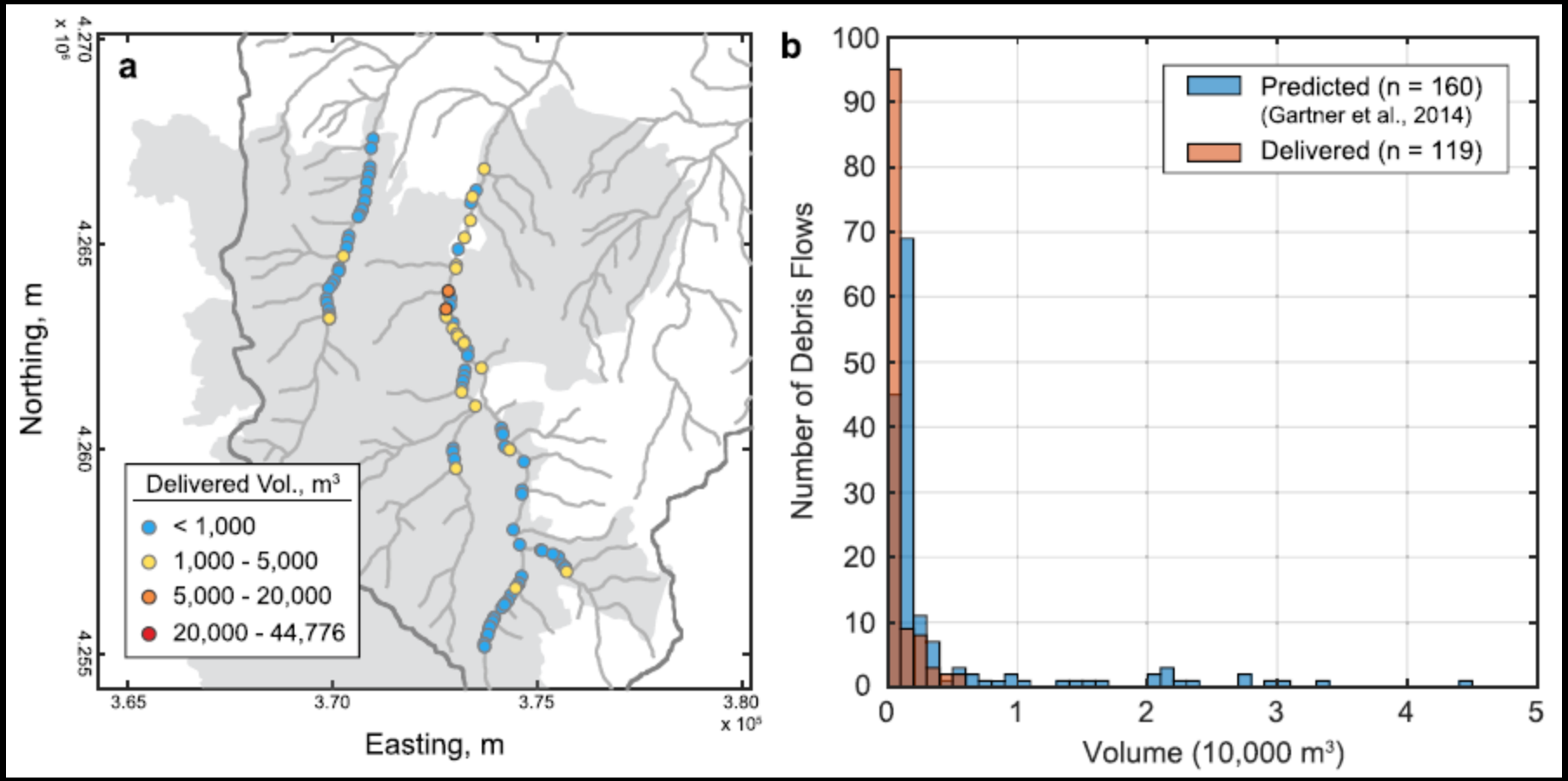


D. Bone and K. Schaffrath applied model of Cannon et al. 2010

Predicted debris flow impacts align with observations of channel change



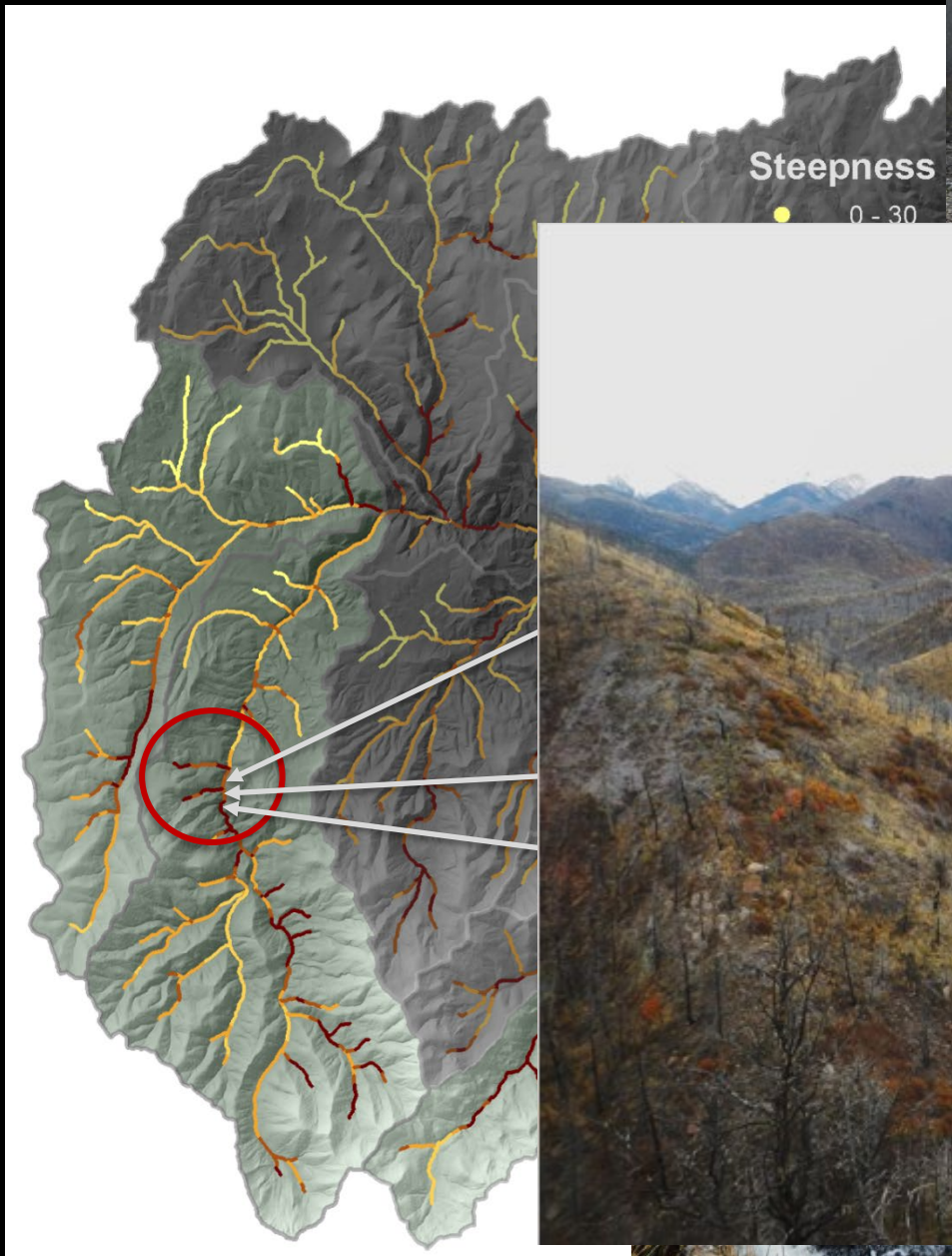
Most debris flow sediment is NOT delivered to the main channel



Murphy et al., 2019

Normalized steepness throu rk

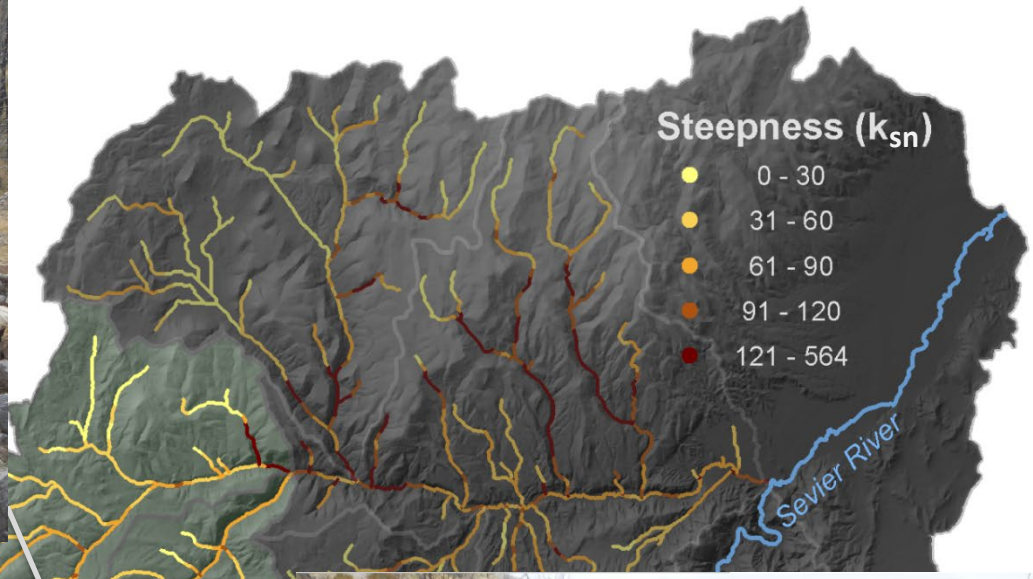






Normalized steepness throughout the channel network







Summary

Minnesota River: Dynamically adjusting to increased flow and sediment supply through channel migration and widening

Spatial difference in channel form can be explained by sediment supply and transport

Sixth Water – Diamond Fork: Valley setting and sediment supply control channel response to flow/sediment disturbance events

Twitchell: Connectivity and valley bottom morphology strongly influence channel response

Photo: Jabari Jones

Roadmap

YESTERDAY

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?

TODAY

Watershed Sediment Budget

Tools and techniques for robust constraints on sources and sinks.

Case studies in sediment supply, transport, and morphodynamics

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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.

A bit of hydrology

Targeted modeling and metrics. Stationarity Assumption?

Reservoir and pond sedimentation rates

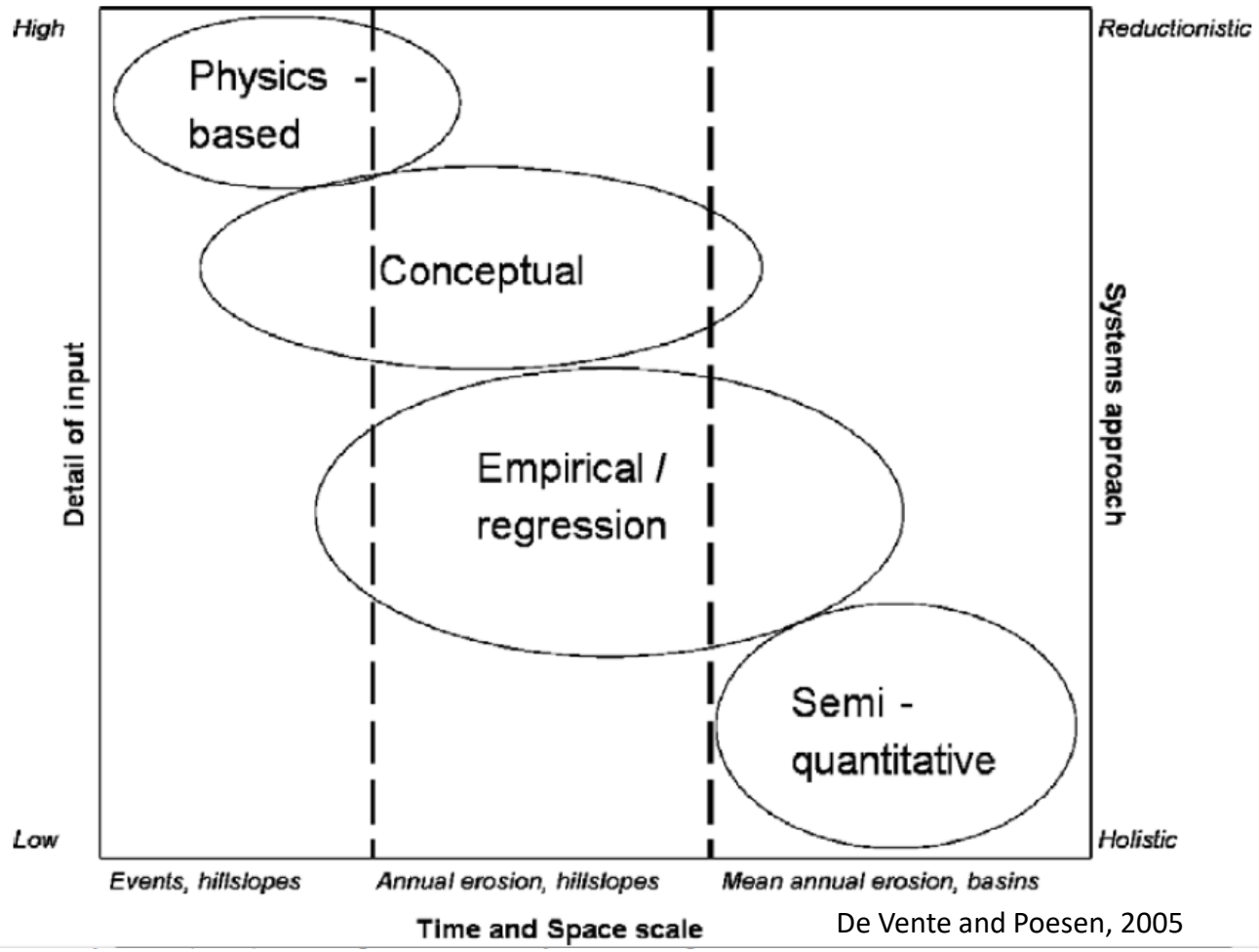
Time- and space-integrated measurements that may be useful.

Oodles of watershed hydro-erosion models

For a relatively comprehensive review: Merritt et al., 2003 Env. Mod. & Soft.

Model	t associated water
	In-stream
AGNPS	yes
ANSWERS	no
CREAMS	no
EMSS	no
GUEST	no
HSPF	yes
IHACRES-WQ	yes
IQQM	no
LASCAM	yes
LISEM	no
MIKE-11	yes
PERFECT	no
SEDNET	yes
SWRRB	yes
TOPOG	no
USLE	no
WEPP	no

G, sediment generation;
[a] Requires a sediment
[b] Uses prescribed loads for a land use type.



De Vente and Poesen, 2005

See also Aksoy and Kavvas, 2005
For a useful, if uncritical, review

Semi-quantitative models

Pacific Southwest Inter-Agency Committee (PSIAC)

See review by: De Vente and Poesen, 2005

Factor	Score	Main characteristics
Surface geology	0	(a) massive hard formations
	5	(a) rocks of medium hardness, (b) moderately weathered, (c) moderately fractured
	10	(a) marine shales and related mudstones and siltstone
Soils	0	(a) high percentage rock fragments, (b) aggregated clays, (c) high in organic matter
	5	(a) medium texture, (b) occasional rock fragments, (c) caliche layers
	10	(a) fine texture, easily dispersed, saline–alkaline, high shrink–swell characteristics, (b) single grain silts and fine sands
Climate	0	(a) humid climate with rainfall of low intensity, (b) precipitation in form of snow, (c) arid climate with low-intensity storms, (d) arid climate with rare convective storms
	5	(a) storms of moderate duration and intensity, (b) infrequent convective storms
	10	(a) storms of several days duration with short periods of intense rainfall, (b) frequent intense convective storms, (c) freeze–thaw occurrence
Runoff	0	(a) low peak flows, (b) low volume of runoff per unit area, (c) rare runoff events
	5	(a) moderate peak flows, (b) moderate volume of flow per unit area
	10	(a) high peak flows, (b) large volume of flow per unit area
Topography	0	(a) gentle upland slopes (<5%), (b) extensive alluvial planes
	10	(a) moderate upland slopes (<20%) (b) moderate floodplain development
	20	(a) steep upland slopes (>30%), high relief, little or no floodplain development
Ground cover	−10	(a) completely protected by vegetation, rock fragments, litter; little opportunity for rainfall to reach erodible material
	0	(a) cover <40%; noticeable litter, (b) if trees present understory not well developed
	10	(a) ground cover <20%, vegetation sparse, little or no litter, (b) no rock in surface soil
Land use	−10	(a) no cultivation, (b) no recent logging, (c) low-intensity grazing
	0	(a) <25% cultivated, (b) 50% or less recently logged, (c) <50% intensively grazed, (d) ordinary road and other construction
	10	(a) >50% cultivated, (b) almost all of the area intensively grazed, (c) all of area recently burned
Upland erosion	0	(a) no apparent signs of erosion
	10	(a) about 25% of the area characterised by rill and gully or landslide erosion, (b) wind erosion with deposition in stream channels
	25	(a) >50% of the area characterised by rill and gully or landslide erosion
Channel erosion and sediment transport	0	(a) wide shallow channels with flat gradients, short flow duration (b) channels in massive rock, large boulders or well vegetated, (c) artificially controlled channels
	10	(a) moderate flow depths medium flow duration with occasionally eroding banks or bed
	25	(a) eroding banks continuously or at frequent intervals with large depths and long flow duration, (b) active headcuts and degradation in tributary channels
After summation of the individual scores, the total index class can be determined and translated into an estimated sediment yield	Index class	Estimated sediment yield ranges (t/km^2/year) (For the Pacific Southwest USA)
	>100	>1830
	75–100	610–1830
	50–75	300–610
	25–50	120–300
	0–25	<120

Semi-quantitative models

Factorial Scoring Model (FSM)

Verstraeten et al., 2003

$$SSY = 4139*A^{-0.44} + 7.77*\text{FSMIndex} - 310.99$$

Must be calibrated to a particular landscape

Common critique: these evaluations may be more likely to *reinforce pre-conceptions* than provide new, objective insight

Factor	Score	Description
Topography	1	very gentle slopes near reservoir and main rivers; elevation difference <200 m within 5 km
	2	moderate slopes near reservoir and main rivers; elevation difference 200–500 m within 5 km
	3	steep slopes near reservoir and main rivers; elevation difference >500 m within 5 km
Vegetation cover	1	good contact cover of the soil (>75% surface protected)
	2	moderate contact cover (25–75% protected surface)
	3	poor contact cover (<25% protected)
Gullies	1	bank and ephemeral gullies are very rare
	2	few bank and/or ephemeral gullies can be observed
	3	many bank and/or ephemeral gullies can be observed
Lithology	1	dominant limestone, sandstone or conglomerate (low weathering degree)
	2	dominant Neogene sedimentary deposits (gravels, etc.)
	3	strongly weathered (loose) material and/or marls
Catchment shape	1	elongated catchment shape with one main river channel draining to the reservoir; no significant direct runoff from slopes into the reservoir
	2	between elongated and (semi-) circular catchment shape
	3	(semi-) circular catchment shape with many rivers draining into the reservoir and/or much direct runoff from hill slopes to the reservoir

Push-button Geomorphology
USLE: Universal Soil Loss Equation

Predicts long-term average erosion (of fine sediment) from sheet or rill erosion
NOTE: does not account for gully, wind, or tillage erosion

Developed in 1940s – 60s for Corn Belt using empirical data

Typically applied to agricultural and construction sites

Calibrated with 10,000 plot-years of runoff and erosion measurements
from 49 locations

USLE: Universal Soil Loss Equation

$$A = R \times K \times LS \times C \times P$$

A = long-term soil loss (t/ac)

R = rainfall and runoff factor (geographic location)

curve number, greater intensity, duration → higher R

K = standardized soil erodibility factor (t/ac)

= f (texture, structure, permeability, OM)

LS = slope length factor

steeper, longer slopes more prone to erosion

C = crop/vegetation and management factor

compares field to standard, fallow, untilled field

P = support management practices

attempts to quantify effect of BMPs

RUSLE: Revised USLE

$$A = R \times K \times LS \times C \times P$$

A = long-term soil loss (t/ac)

R = rainfall and runoff factor (geographic location)

K = standardized soil erodibility factor (t/ac)

new maps, time varying-erodibility

LS = slope length factor

new approach to computing sensitivity to gradient and length

C = crop/vegetation and management factor

new approach for evaluating sensitivity

P = support management practices

new conservation practices incorporated

RUSLE2: Revised USLE (again)

$$A = R \times K \times LS \times C \times P$$

new Graphical User Interface (GUI)

several updates to equations and maps

attempts to account for deposition and sediment delivery ratio implicitly
- using concavity/convexity of landscape

doesn't allow for dynamic vegetation, but differentiates between
- canopy and ground cover
- distribution of live and dead roots
- soil moisture

MUSLE: Modified USLE

$$A = 11.8(Q_{surf} \times q_{peak} \times area_{hru})^{0.56} \times K \times LS \times C \times P \times CFRG$$

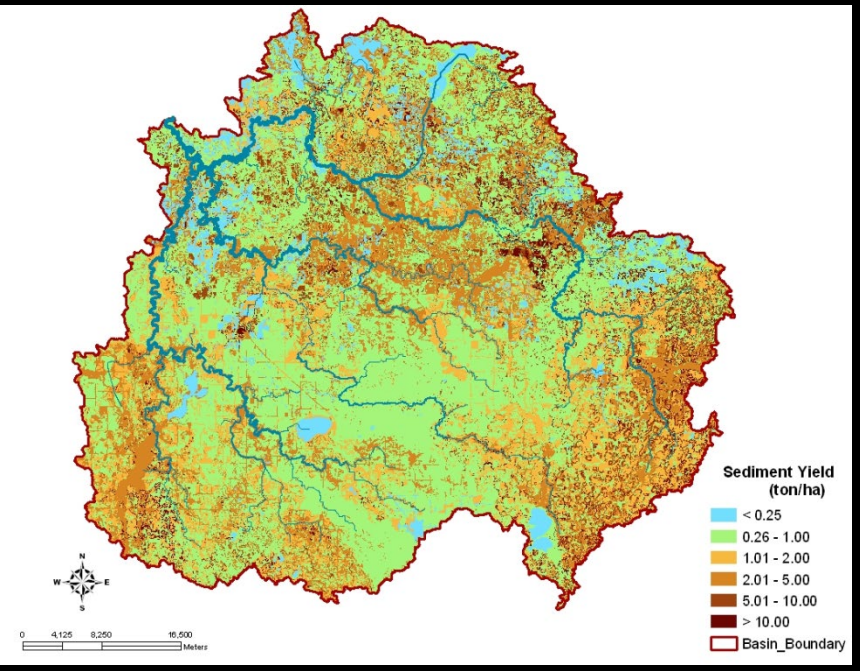
An empirical attempt to account for detachment and transport

Q_{surf} = runoff volume (mm/d)
q_{peak} = peak runoff rate (m^3/s)
$area_{hru}$ = area of hydro response unit

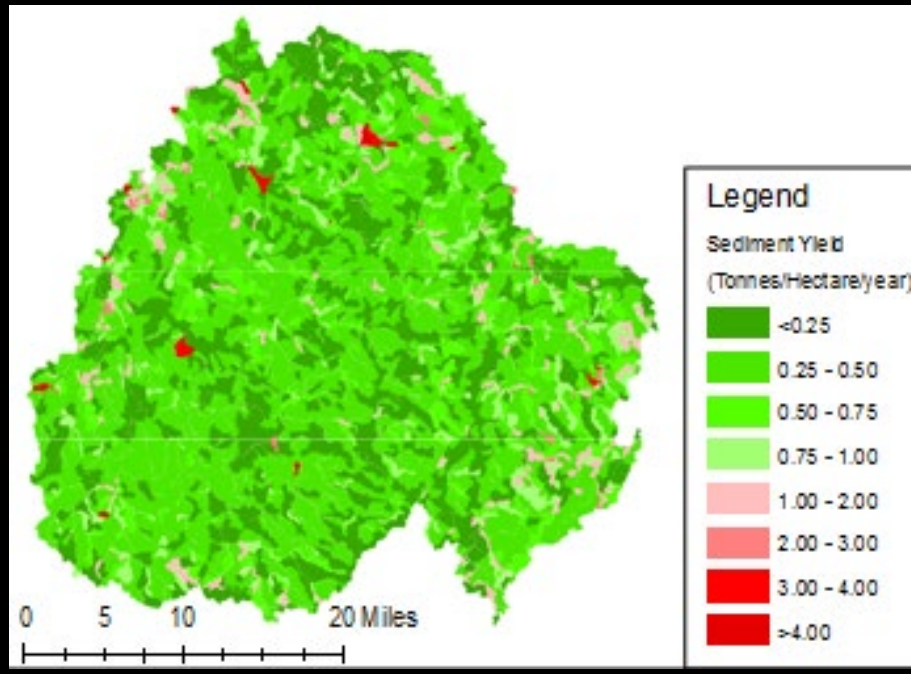
Coarse fragment factor
$=e^{(-0.053r)}$
r is % rock in first soil layer

Push-button Geomorphology

* SWAT



WEPP



Useful at small scale to obtain relative sensitivity of terrestrial sediment sources

Common Limitations:

No basis to distinguish terrestrial vs channel sources: problem for calibration

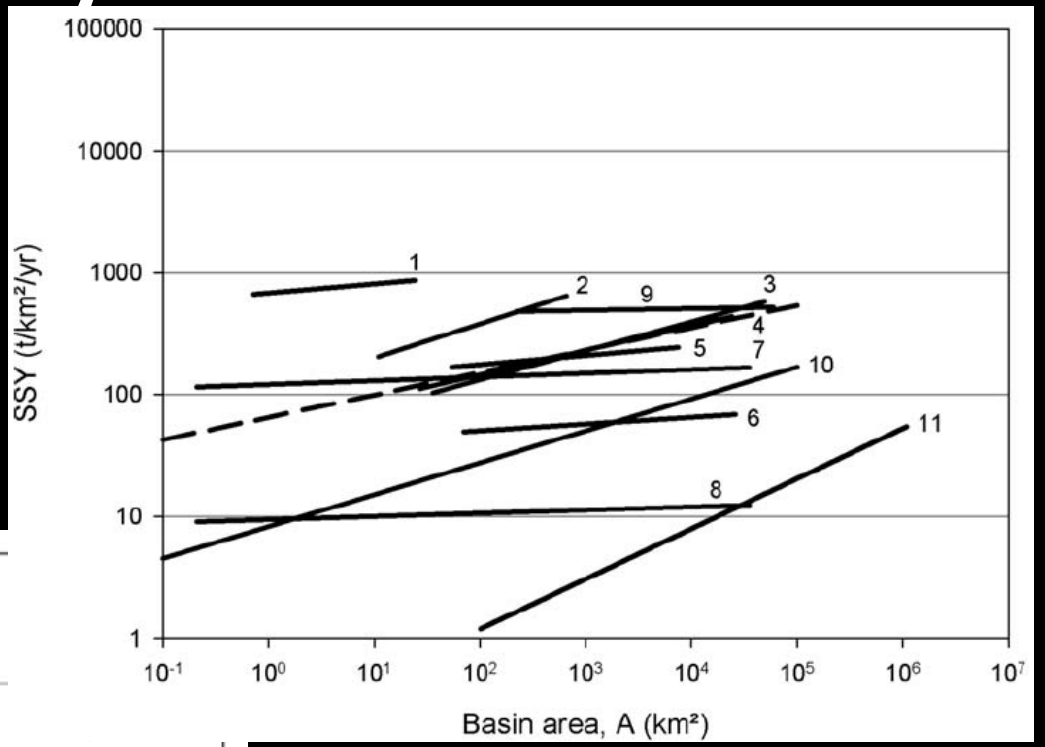
Flow and sediment routing mechanisms are primitive

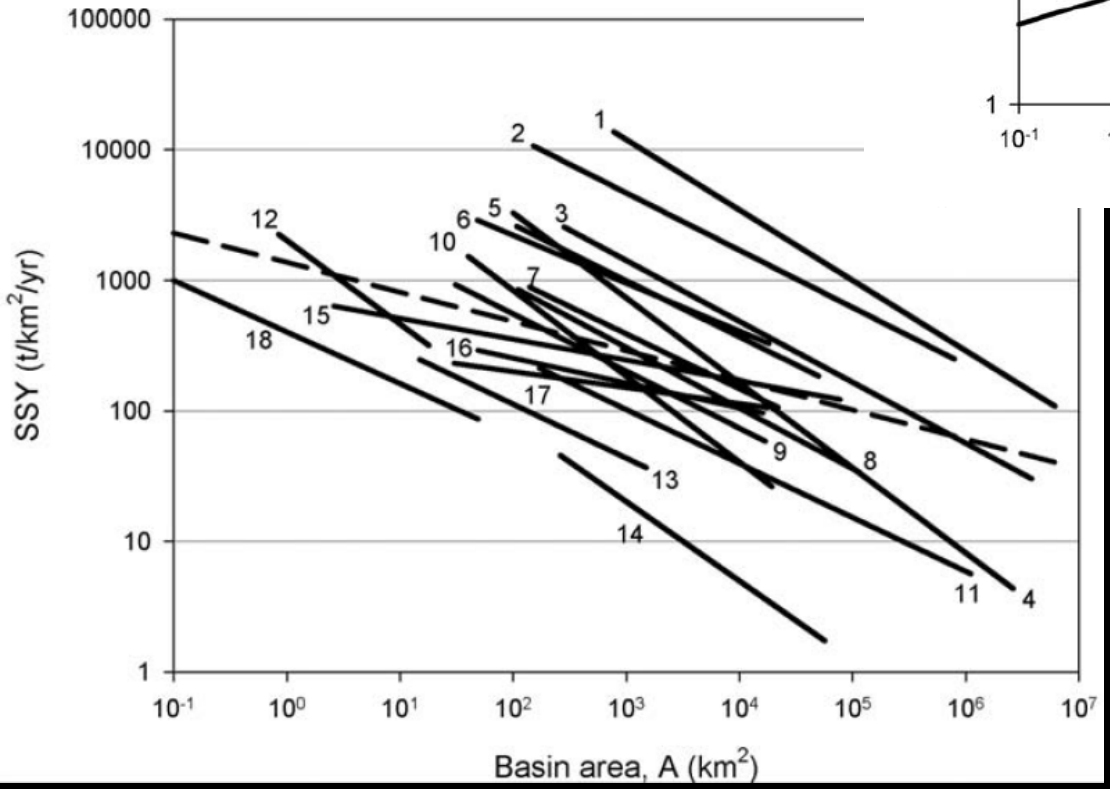
Hydrology run with curve number or Green-Ampt Infiltration Equation

Lots of knobs to turn, users limited in ability to identify problematic variables

The Sediment Delivery Problem

* Walling, 1983





de Vente et al., 2007

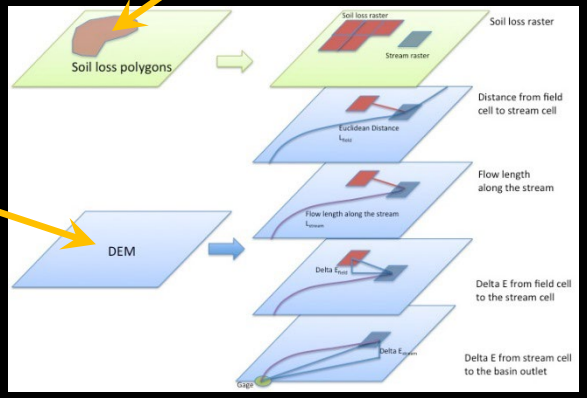
TopoFilter: Where does sediment come from?

Se Jong Cho, Peter Wilcock

Goal: use USLE to predict local soil erosion rates and a DEM to account for the topographic effect on sediment storage, to map the primary sources of eroded sediment that reaches the watershed outlet

USLE Annual Erosion Rate (***S***) for each soil map unit

Elevation (***E***), distance to stream (L_f) and downstream distance to outlet (L_s)



A (very simple) topographic relation for Sediment Delivery Ratio

TopoFilter: Where does sediment come from?

Se Jong Cho, Peter Wilcock

1. A simple topographic relation

$$SDR_{fi} = f\left(L_{fi}, \frac{dE_{fi}}{L_{fi}}\right) = \exp\left[a_1\left(\frac{dE_{fi}}{L_{fi}}\right)^{b_1} L_{fi}\right]$$

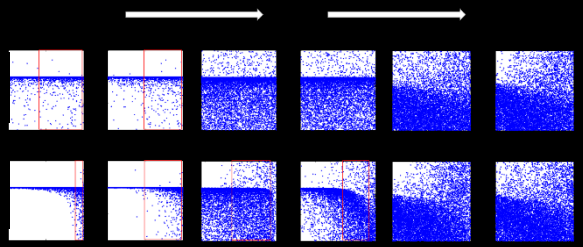
$$SDR_{si} = f\left(L_{si}, B_{fpi}, \frac{dE_{si}}{L_{si}}\right) = \exp\left[a_2\left(\frac{dE_{si}}{L_{si}}\right)^{b_2} L_{si} * B_{fpi}\right]$$

by logic and definition:

$a_1 = [-0.001,\ 0], b_1 = [-1,\ 0]$;

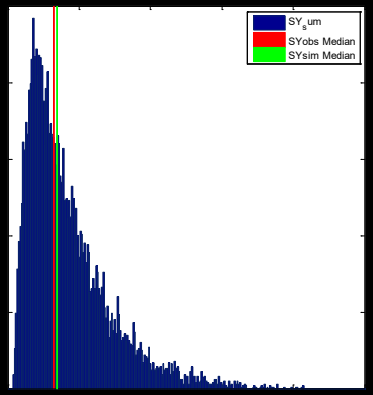
$a_2 = [-0.001,\ 0], b_2 = [-1,\ 0]$

2. Run 10,000 simulations using values of a_1, a_2, b_1, b_2 drawn randomly from a uniform distribution



3. Narrow the range for each parameter a_1, a_2, b_1, b_2 by eliminating portions that never produce an adequate fit to the observed total sediment delivery. This is called 'conditioning'.

4. Sediment Delivery *SD* from 10,000 simulations. The median (3,445 Mg) is close to the observed (3,252 Mg)



5. Do we believe that any of these 10,000 simulations (combinations of a_1, a_2, b_1, b_2) are correct? **No way!**

But we note that some locations just about always contribute the most sediment

Map shows locations that contribute to 90% of the sediment delivery in 95% (red), 75% (red + green) and 50% (red + green + blue) of the simulations.

area = 335 sq.km

Geomorphology 309 (2018) 1–19

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Topographic filtering simulation model for sediment source apportionment

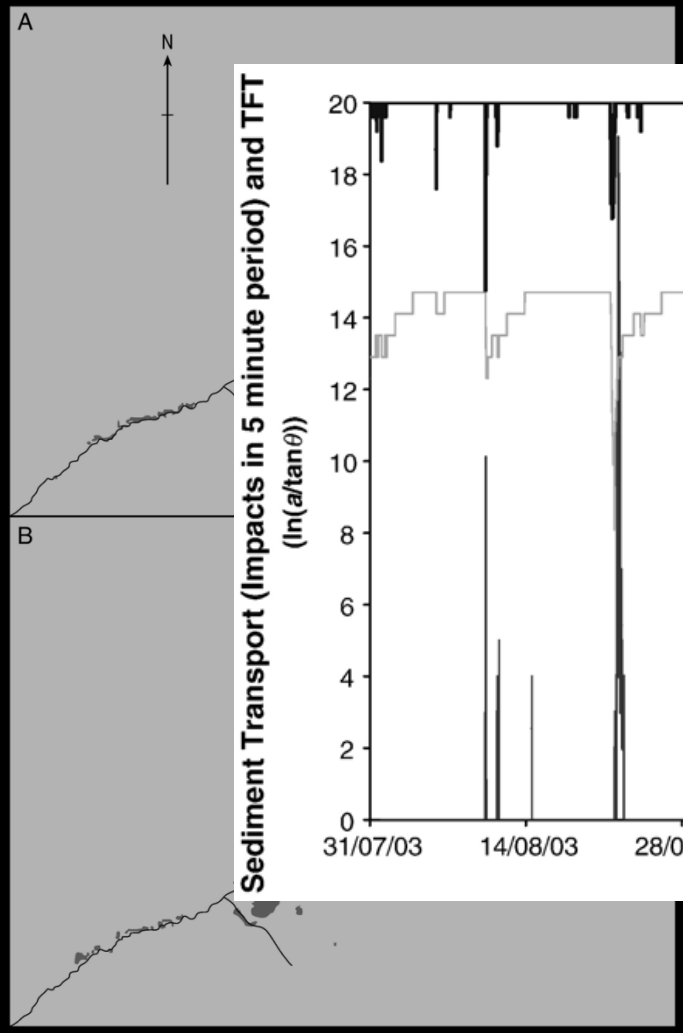
Se Jong Cho *, Peter Wilcock, Benjamin Hobbs

Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, MD, USA

Push-button Geomorphology

SedMAP: Effects of hydrologic connectivity on delivery of coarse material

Reid et al., 2007



See also: sednet.org

Roadmap

YESTERDAY

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

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

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

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Case studies in sediment supply, transport, and morphodynamics

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Millennial-scale landscape rates of erosion.

A bit of hydrology

Targeted modeling and metrics. Stationarity Assumption?

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

Long-term, basin-average erosion rates from cosmogenic nuclides

Establish ‘background’ erosion rate for a watershed

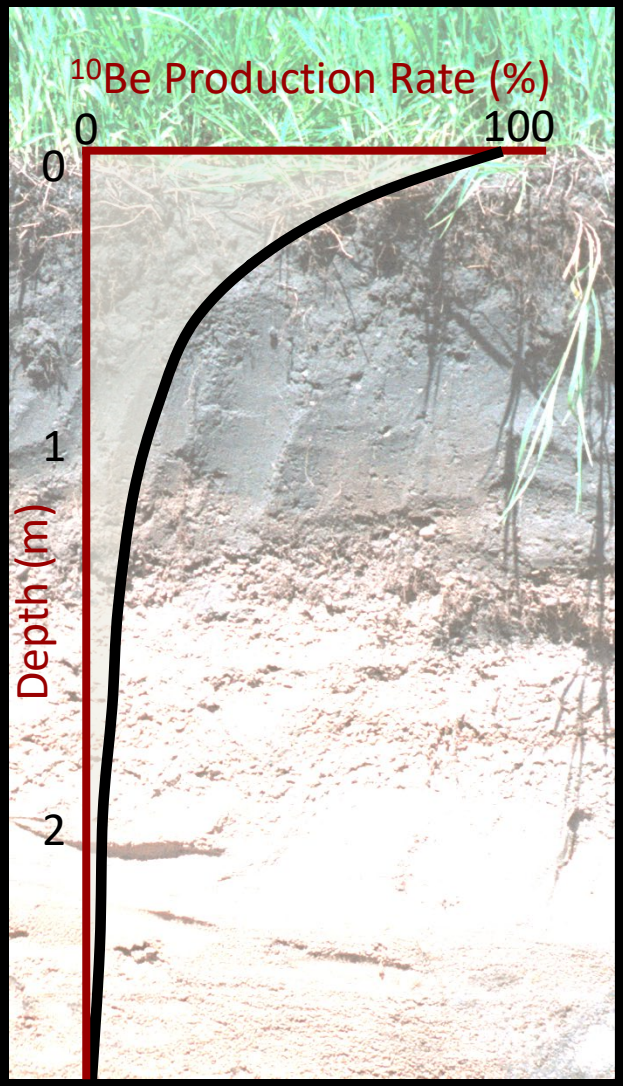
Quantify sediment supply
(10^2 - 10^5 year time scale)

Quantify human-induced changes in erosion (decadal time scale)



Recent reviews:
Granger et al., 2013
von Blanckenburg and Willenbring, 2014
Dunai and Lifton, 2014

Measuring basin-average erosion rates



In a steady-state erosional environment…

TCN concentration in eroding material records the rate at which the sediment moved through the exposure window

By ‘erosion rate’, we really mean DENUDATION RATE

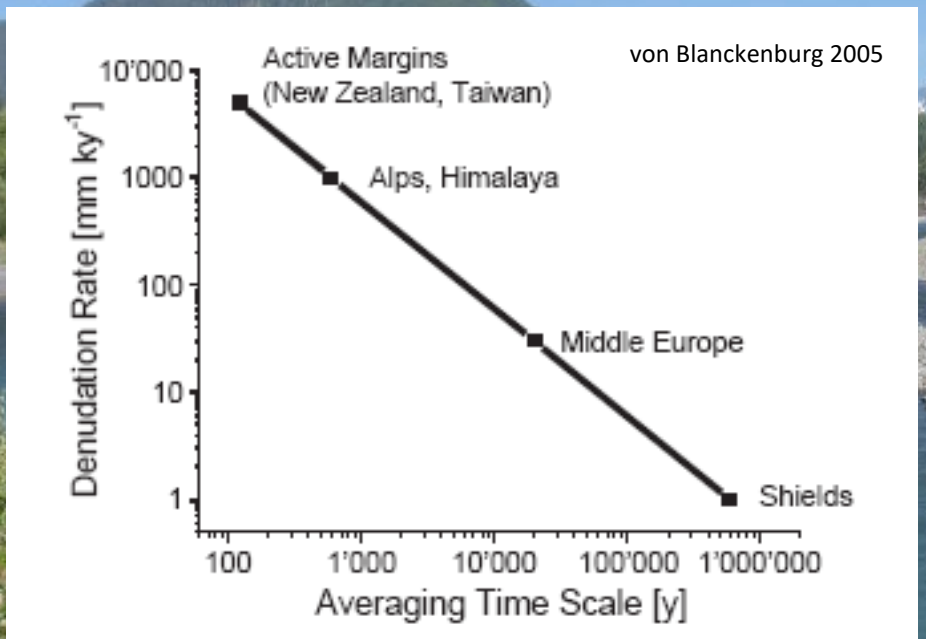
D = E + W

Using ^{10}Be to estimate basin-average erosion rates

Brown et al. 1995, Granger et al. 1996, Bierman & Steig 1996, von Blanckenburg 2006; Dunai, 2010

Let nature do the averaging…

$$\varepsilon_{(t)} = \frac{P\Lambda}{N}$$



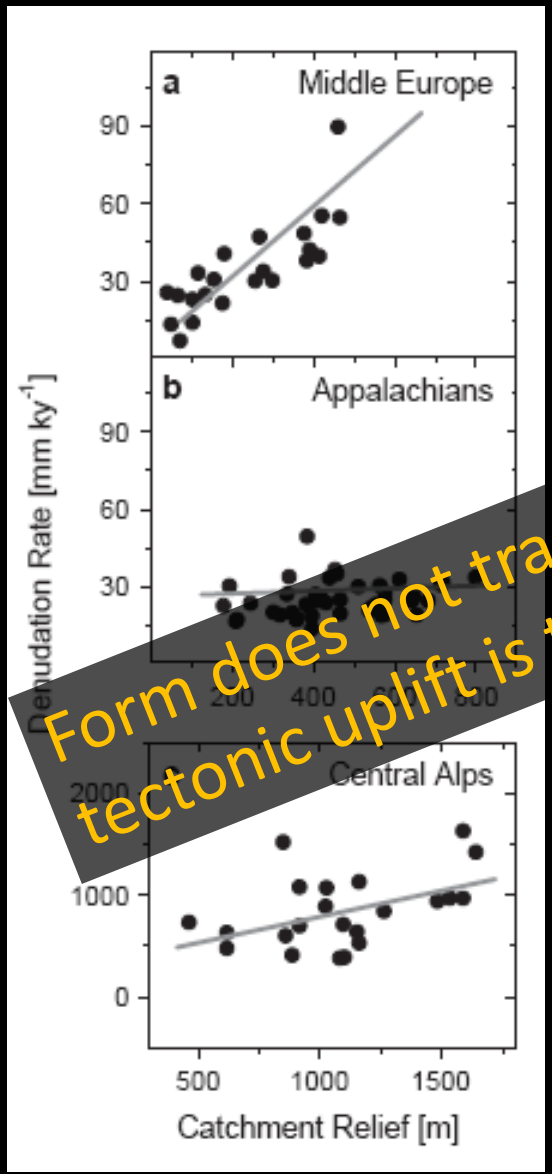
von Blanckenburg 2005

P – altitude, latitude

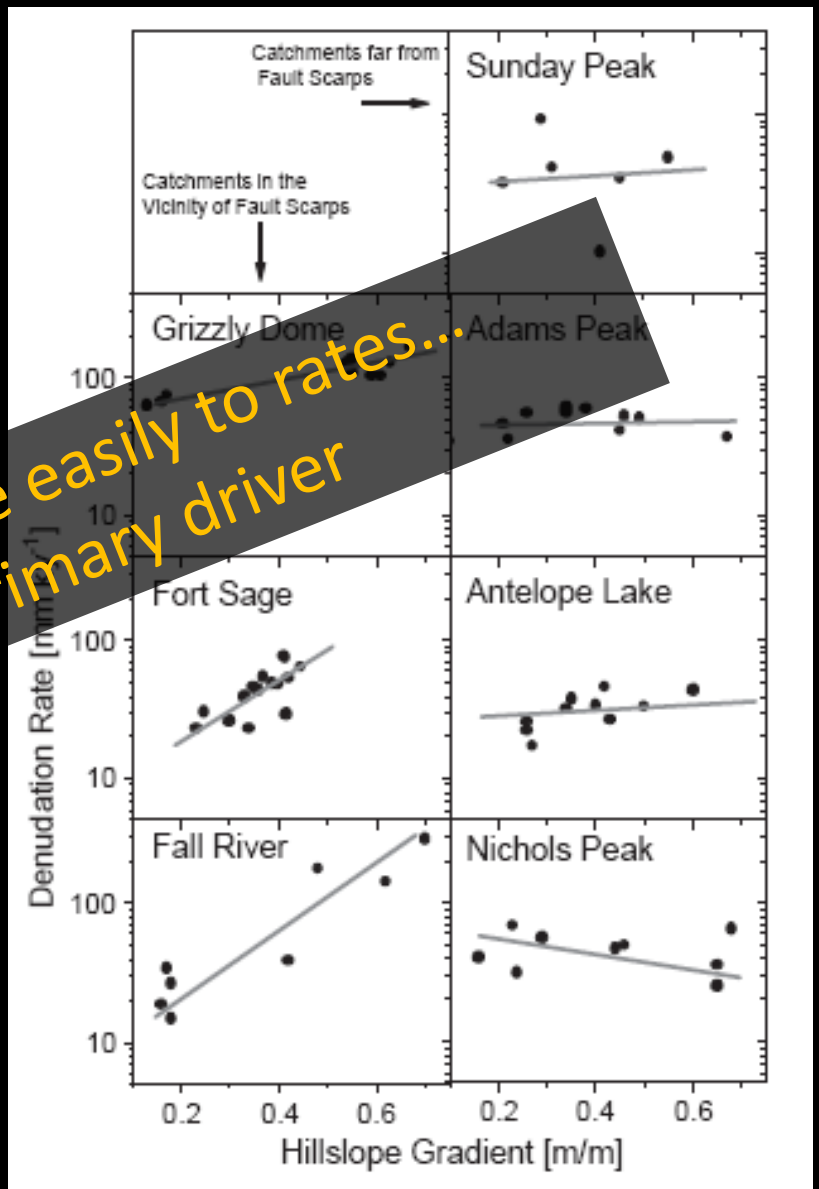
Λ – rock/soil density

$$t \approx \frac{\Lambda}{\varepsilon}$$

Some profound observations about watershed-average erosion rates

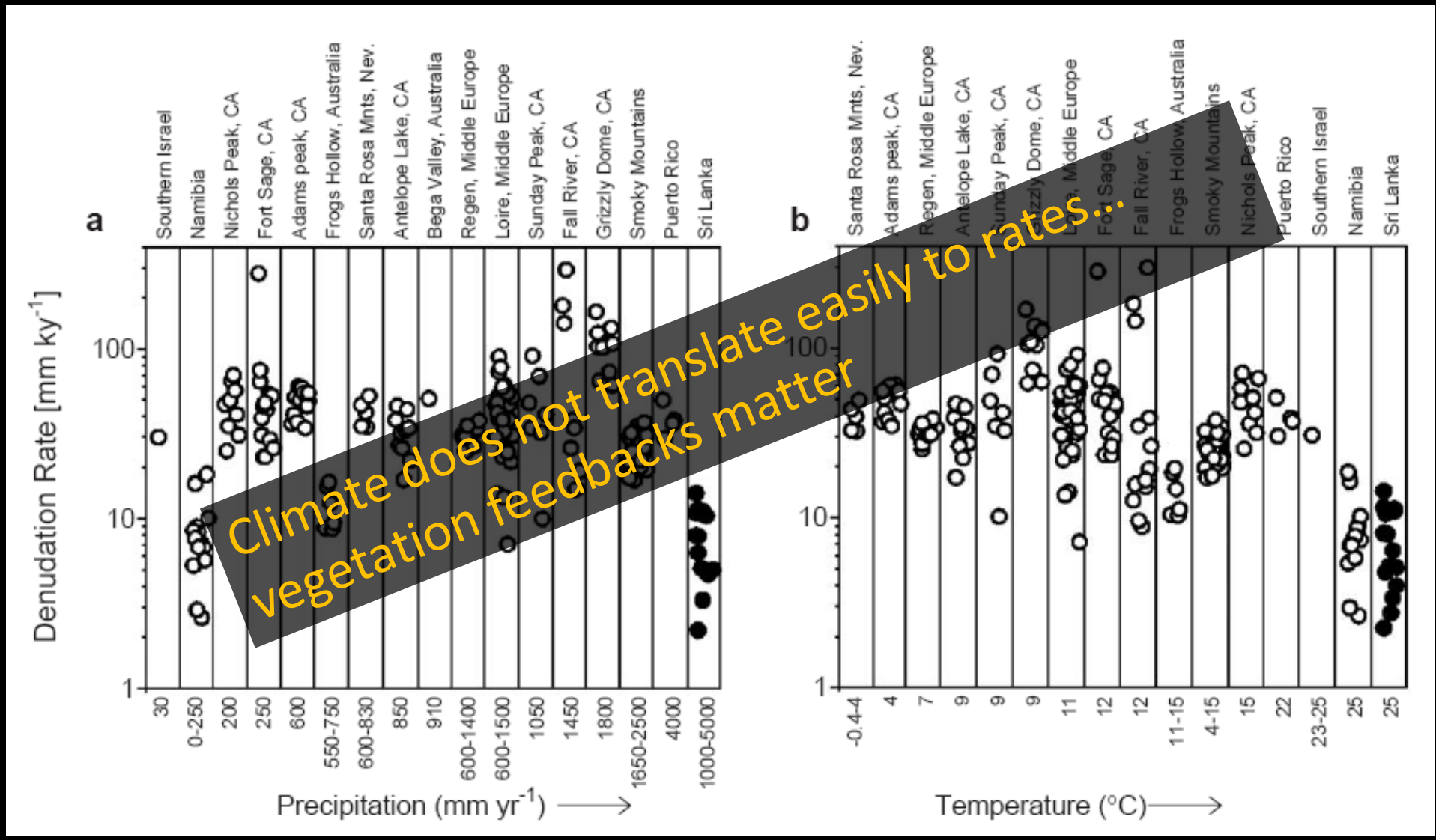


Riebe et al., 2000, von Blanckenburg, 2006



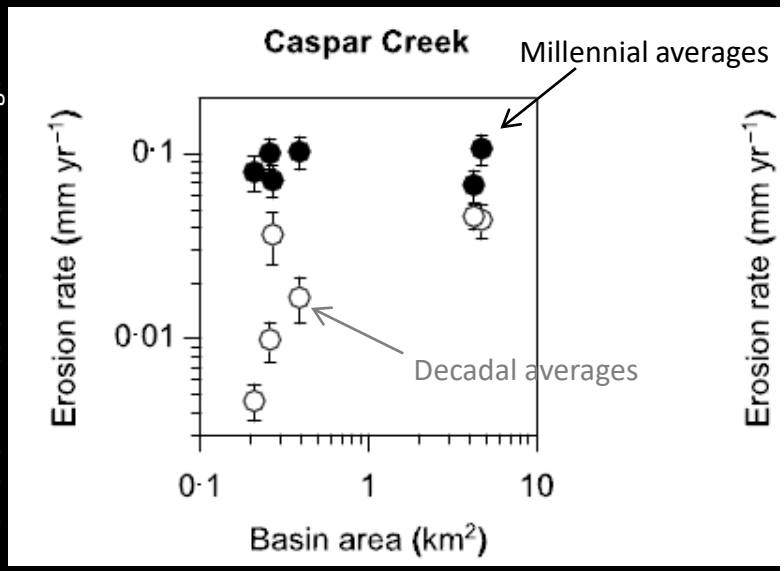
Form does not translate easily to rates...
tectonic uplift is the primary driver

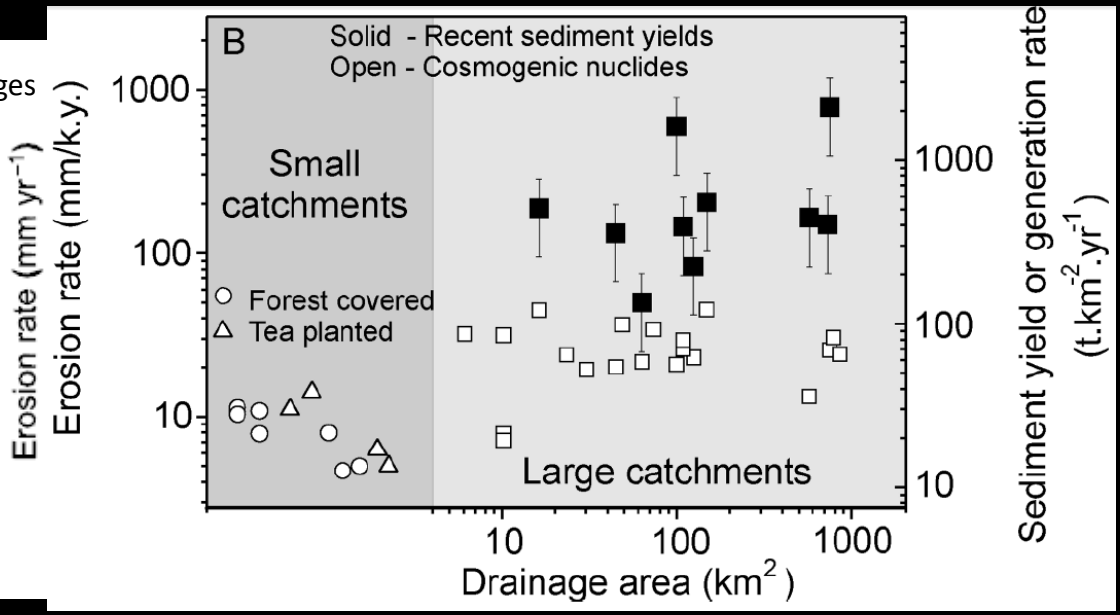
Some profound observations about watershed-average erosion rates



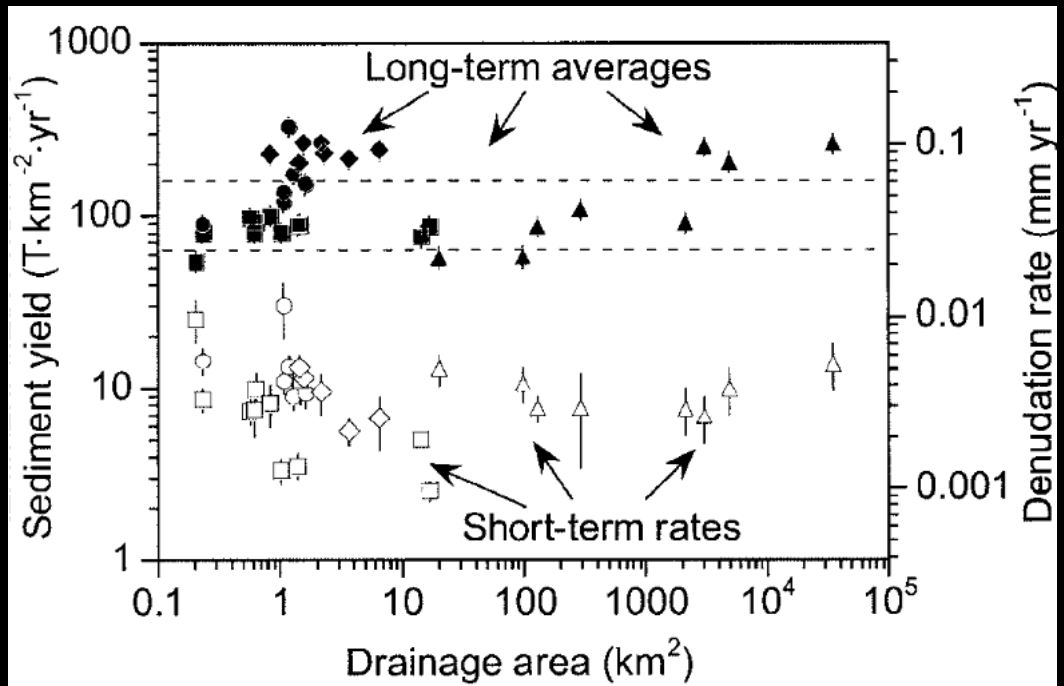
Long term and short term rates not always equal

Ferrier et al. 2009 California Coast Range





Kirchner et al. 2001 Idaho batholith



Many sites where short-term rates faster than long-term.

Either or both timescales might be relevant depending on your needs.

Cosmo erosion rate database
https://earth.uow.edu.au/

Roadmap

YESTERDAY

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?

TODAY

Watershed Sediment Budget

Tools and techniques for robust constraints on sources and sinks.

Case studies in sediment supply, transport, and morphodynamics

Basin-average erosion rates: The cosmo method

Millennial-scale landscape rates of erosion.

Push-button Geomorphology

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

A bit of hydrology

Targeted modeling and metrics. Stationarity Assumption?

Reservoir and pond sedimentation rates

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

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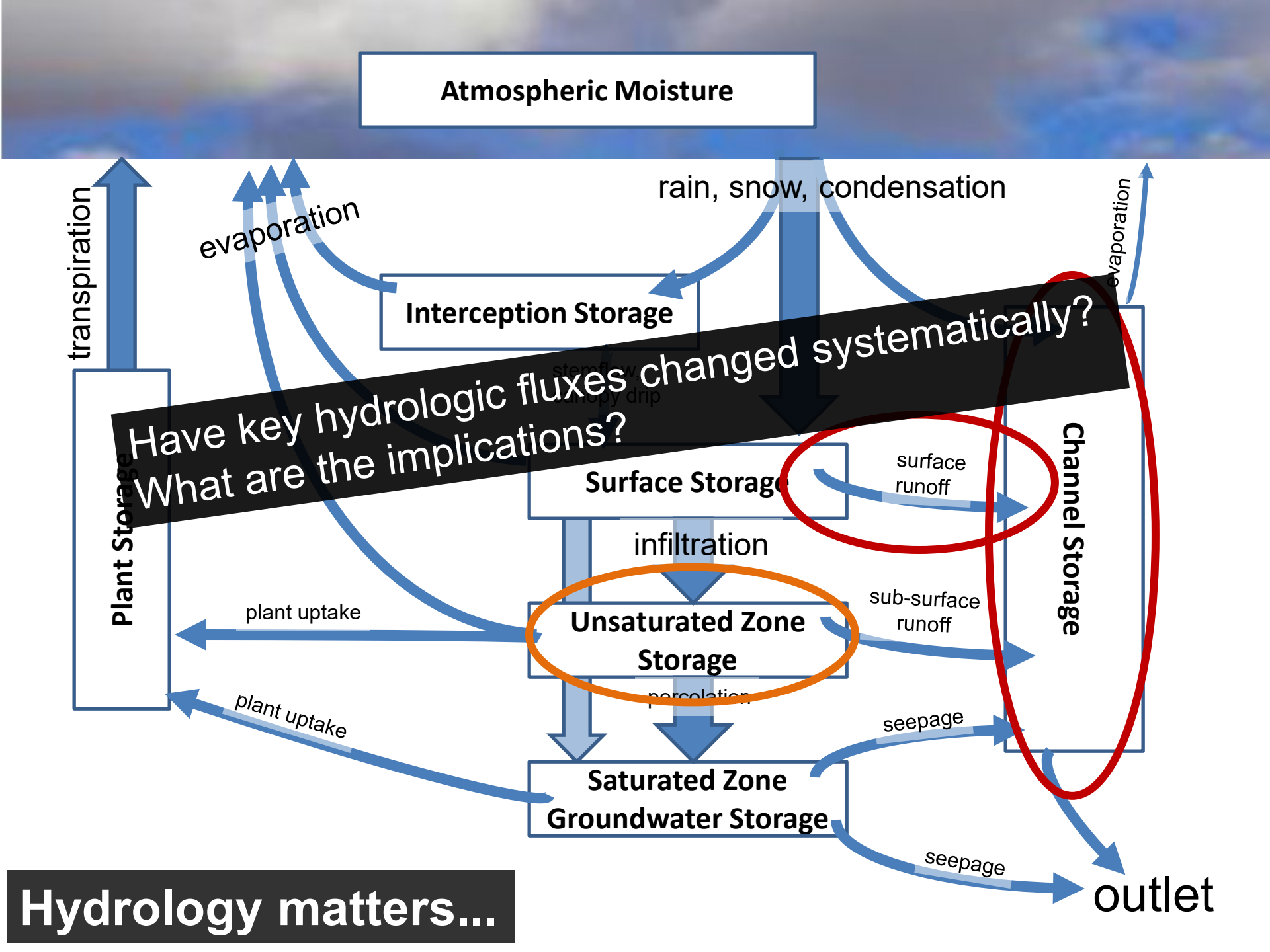
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Atmospheric Moisture
transpiration
evaporation
rain, snow, condensation
evaporation
Interception Storage
stemflow
canopy drip
Have key hydrologic fluxes changed systematically?
What are the implications?
Plant Storage
Surface Storage
surface runoff
Channel Storage
infiltration
plant uptake
Unsaturated Zone Storage
sub-surface runoff
percolation
plant uptake
seepage
Saturated Zone Groundwater Storage
seepage
outlet
Hydrology matters...

Hydrologic modeling

VIC

WEAP
Water Evaluation And Planning
SEI

Soil & Water Assessment Tool | SWAT

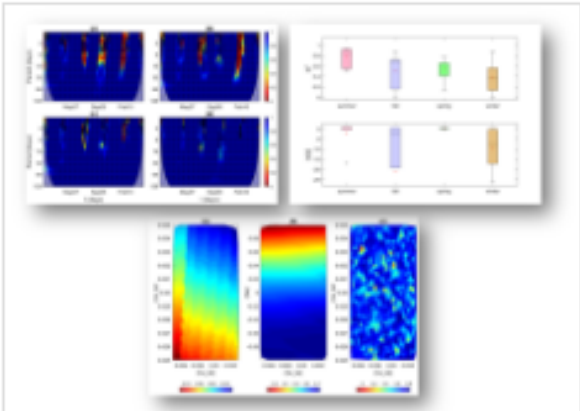
MIKE by DHI

Water E

TOPMODEL

PIHM

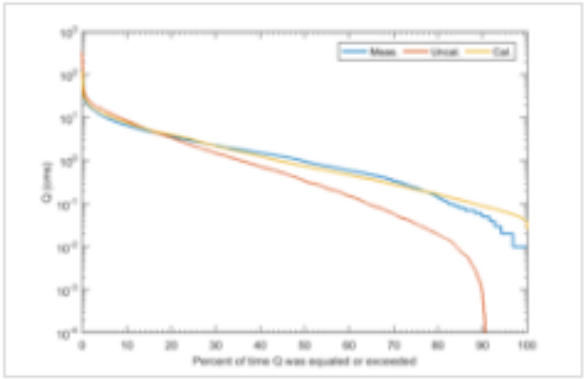
HydroME Toolbox:



The HydroME Toolbox contains several tools to aid with the calibration of a hydrologic model in the time and frequency domains. HydroME generates box plots to illustrate the full distribution of common model performance metrics, such as NSE or R^2, Euclidian distance and empirical Quantile-Quantile (Q-Q) plots, and flow duration curves, as well as magnitude squared Fourier coherence and wavelet coherence plots to localize frequency mismatches in time. The accompanying MS Excel files contain example data in the format needed for the toolbox to generate the plots. Update with your data to generate the plots.

Download HydroME Toolbox.

FDC Toolbox :



The FDC toolbox is a subset of the HydroME Toolbox for generating Flow Duration Curve plots that can be used to compare measured and simulated flows. Use the accompanying MS Excel file as example data.

Download FDC Toolbox.

Excellent perspective on t

Clark et al. (2015) A unified
1. Modeling concept. *Wate*

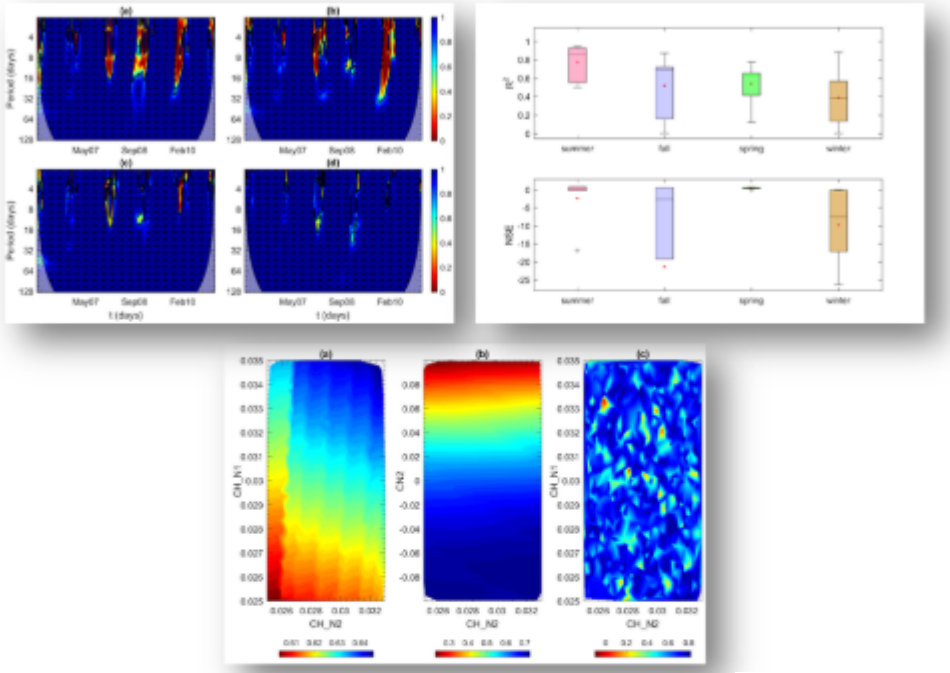
Hrachowitz, et al. (2013). A
a review. *Hydrological scie*

Farmer, W. H., & Vogel, R.
of hydrologic models. *Wate*

Kumarasamy, K., & Belmont, P. (2018). Calibration Parameter Selection and Watershed Hydrology Model Evaluation in Time and Frequency Domains. Water, 10(6), 1.

Hydro-erosion models: if you're going to use them, make sure they are calibrated for the relevant flows

HydroME Toolbox:



The HydroME Toolbox contains several tools to aid w
of a hydrologic model in the time and frequency dom
generates box plots to illustrate the full distribution of
performance metrics, such as NSE or R^2, Euclidian c
empirical Quantile-Quantile (Q-Q) plots, and flow dur
well as magnitude squared Fourier coherence and w
plots to localize frequency mismatches in time. The a
Excel files contain example data in the format neede

water

MDPI

Article

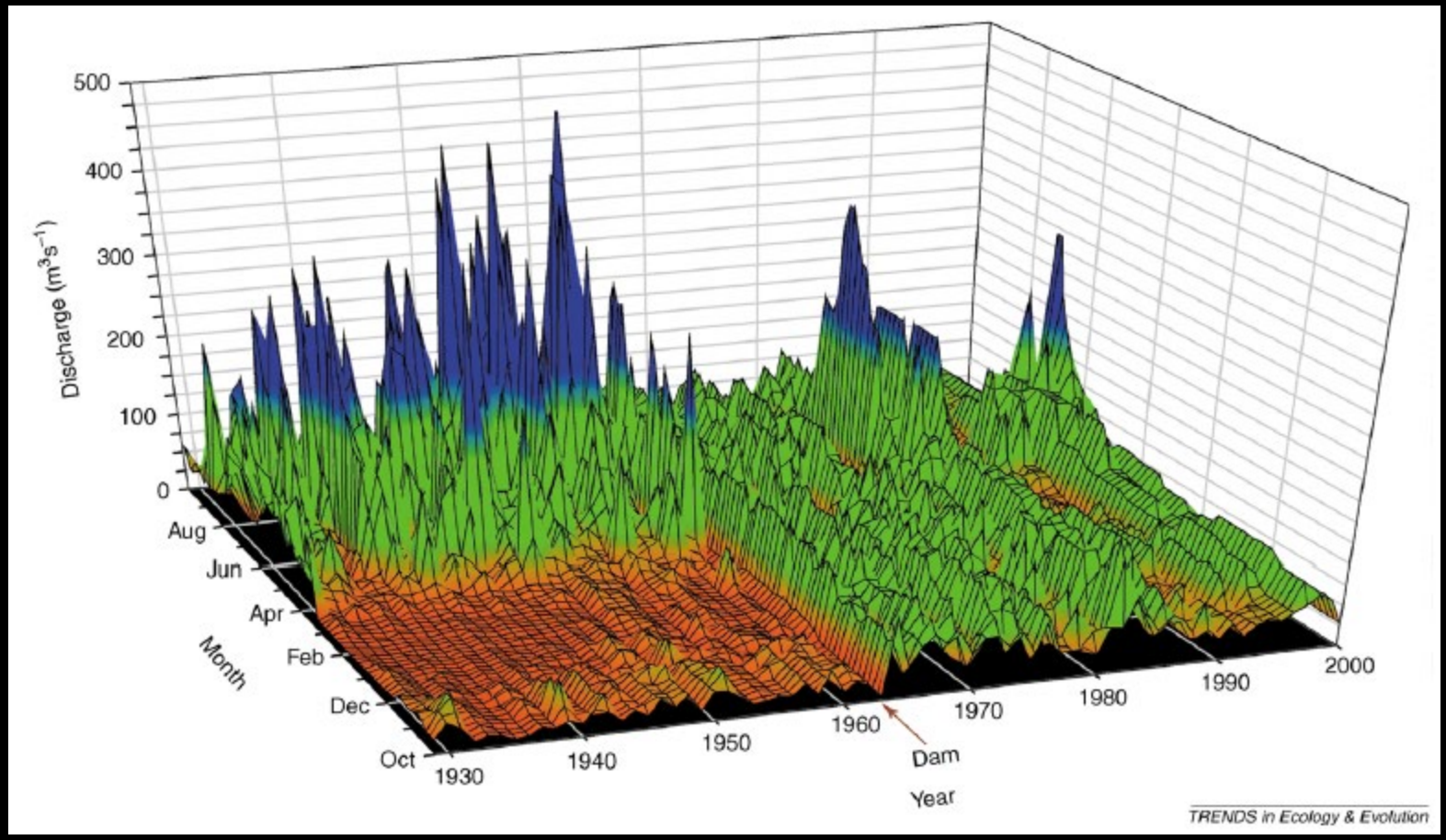
Calibration Parameter Selection and Watershed Hydrology Model Evaluation in Time and Frequency Domains

Karthik Kumarasamy * and Patrick Belmont

Department of Watershed Sciences, Utah State University, Logan, UT 84322-5210, USA; patrick.belmont@usu.edu

* Correspondence: karthik.k@aggiemail.usu.edu

Have flows changed?



Lytle and Poff, 2004

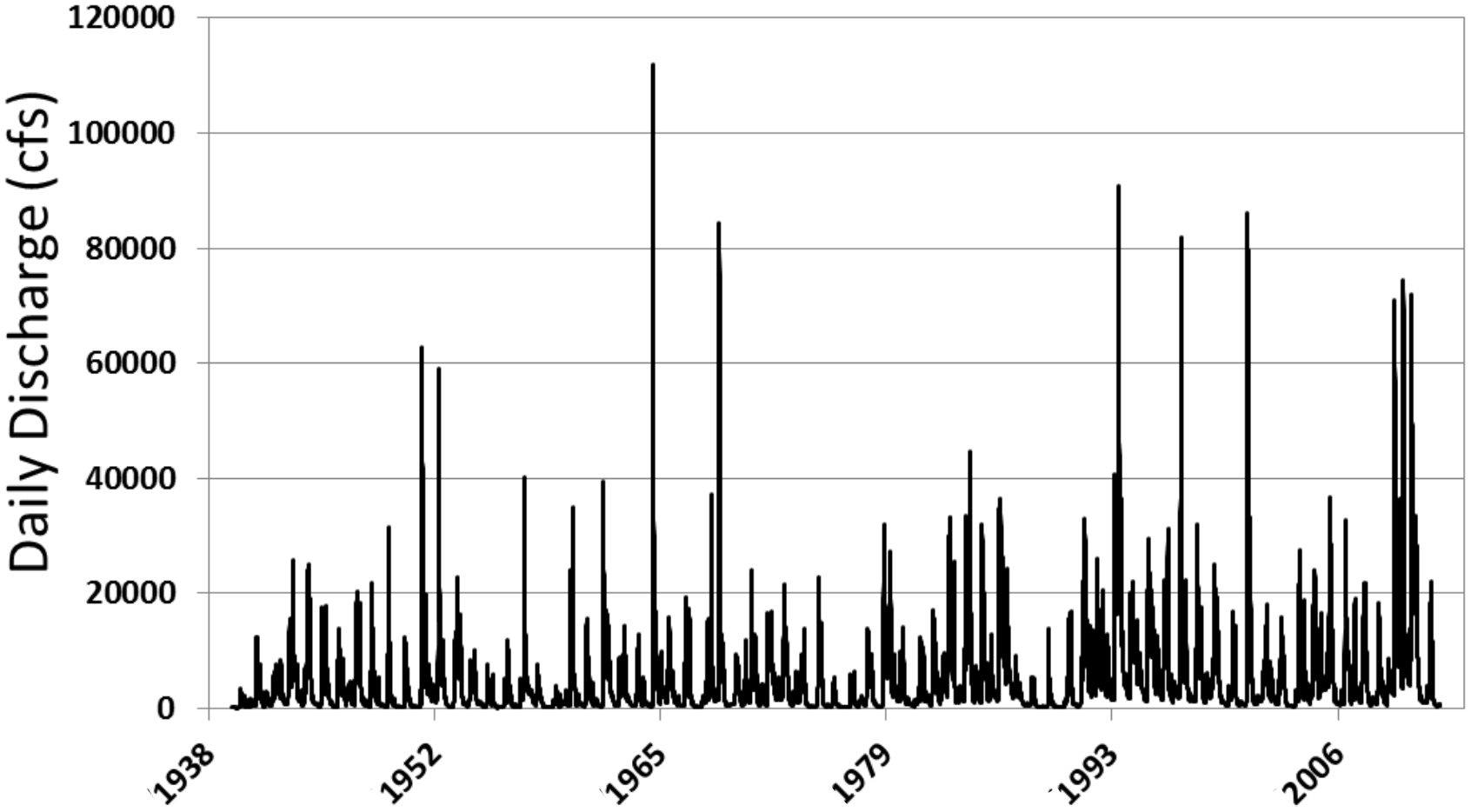
A basic lexicon of flow regime characteristics

- Magnitude: the amount of water moving past a fixed location per unit time. The larger (or smaller) the magnitude of a flood (or drought), the greater the expected physical impact.
- Frequency: the number of events of a given magnitude per time interval (e.g. per year). For a given river or stream, frequency is typically related inversely to magnitude.
- Duration: the period of time associated with a particular flow event. Expressed in terms of number of days a flood or drought lasts.
- Timing: the date during the year that flood or drought occurs, often derived from long-term flow records.
- Predictability: the degree to which flood or drought events are autocorrelated temporally, typically on an annual cycle. Predictable events might also be correlated with other environmental signals (e.g. rainfall events, seasonal thermal extremes, sudden increases or decreases in flow).

Lytle and Poff, 2004

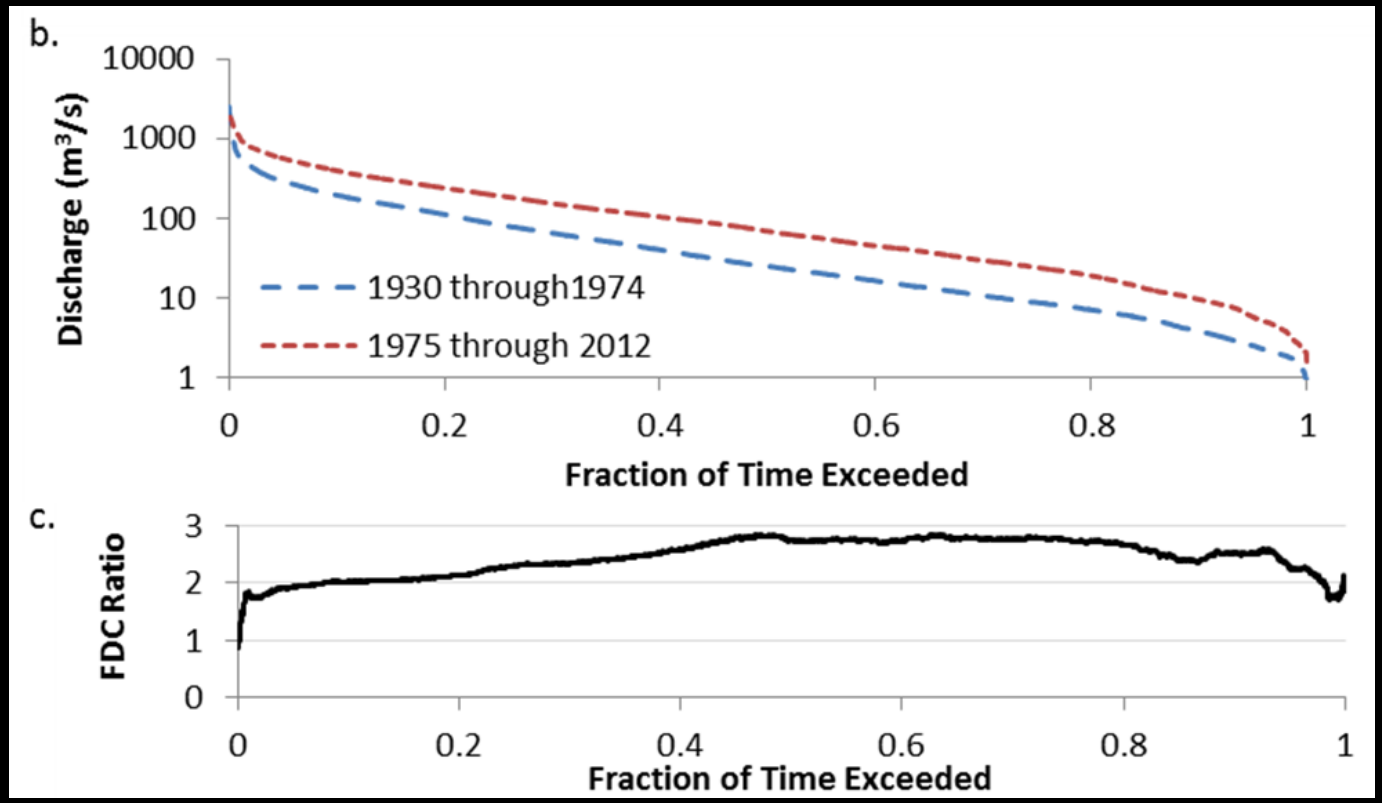
Flow Duration Curves?

Organizing ‘chaos’…Flow Duration Curves



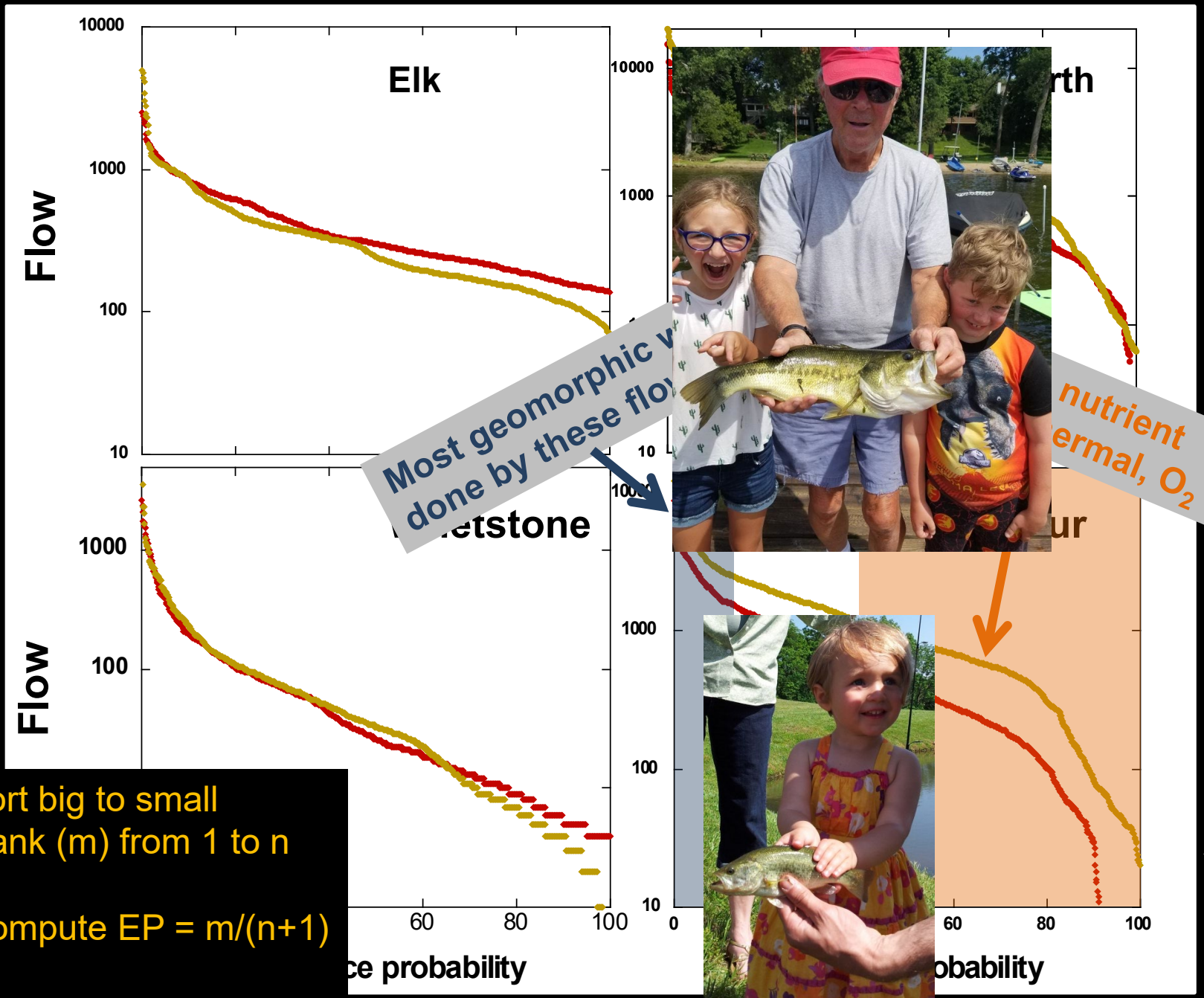
Minnesota River: daily averaged flows

Illustrating shifts in FDCs



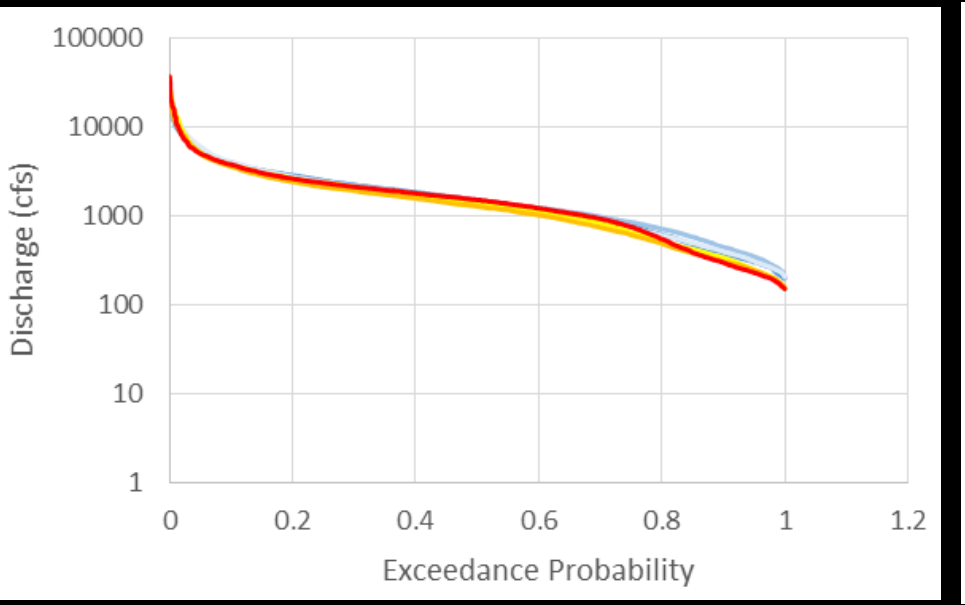
Lauer et al., 2017

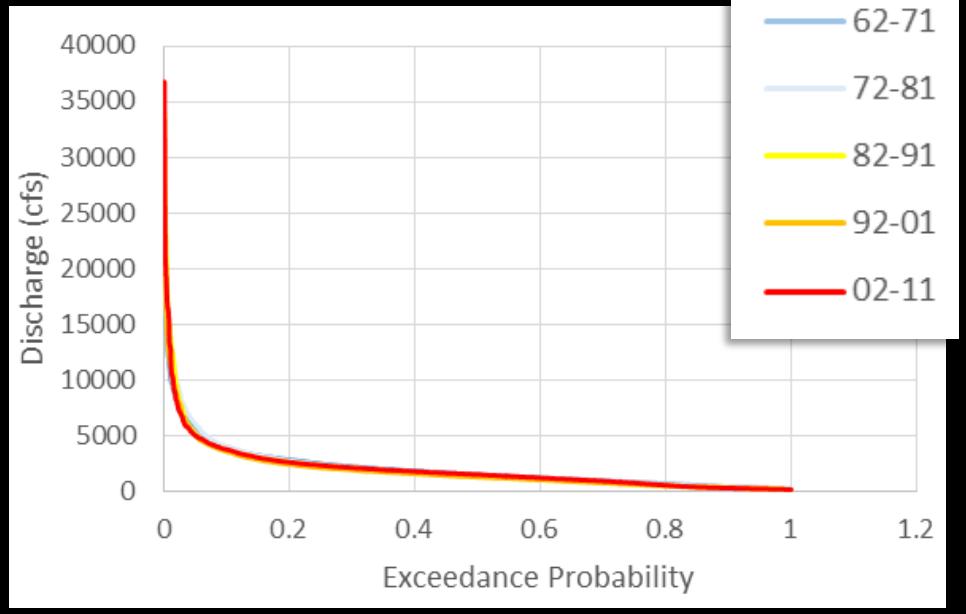
Changes (or not) in Flow Duration Curves

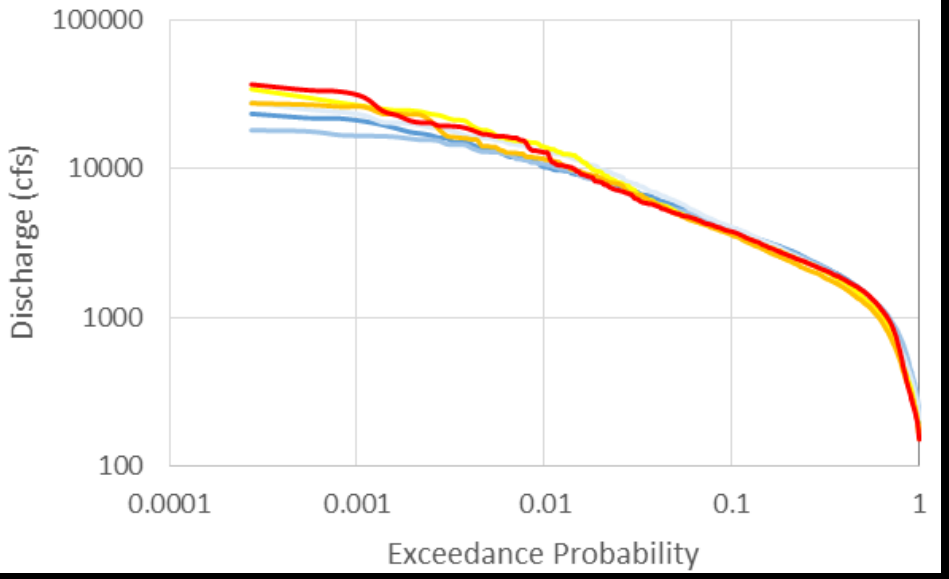


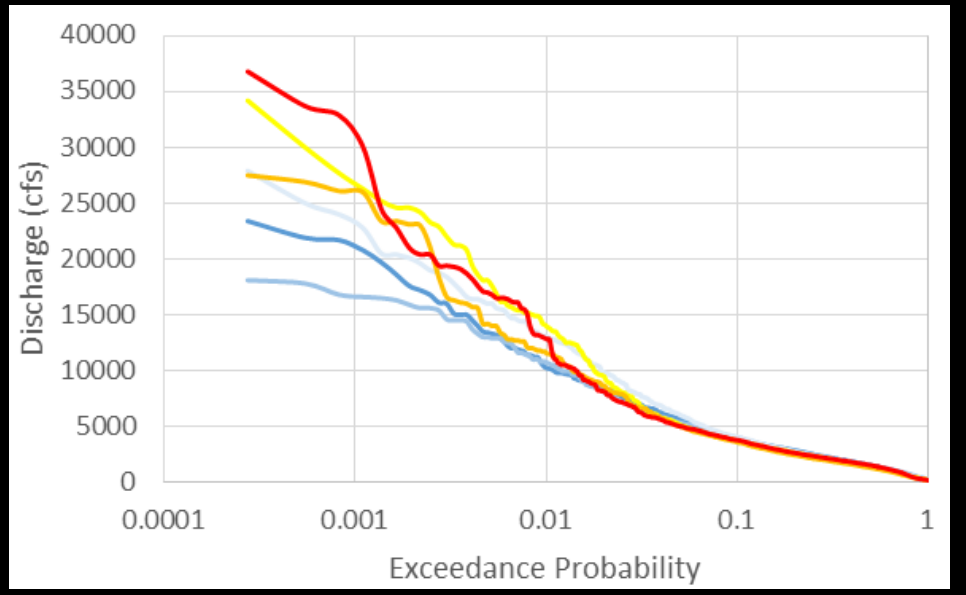
Slide modified from Schottler, 2011 WRC Co

FDCs: Choose your axes carefully









R package for

automated download of USGS flow data
basic streamflow metric analysis & plots

Hydrol. Earth Syst. Sci., 23, 2939–2963, 2019
https://doi.org/10.5194/hess-23-2939-2019
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the Creative Commons Attribution 4.0 License.

Hydrology and Earth System Sciences
Open Access
EGU

Using R in hydrology: a review of recent developments and future directions

Louise J. Slater[1], Guillaume Thirel[2], Shaun Harrigan[3], Olivier Delaigue[2], Alexander Hurley[4], Abdou Khouakhi[5], Ilaria Prosdocimi[6], Claudia Vitolo[3], and Katie Smith[7]

CRAN
Mirrors
What's new?
Task Views
Search

About R
R Homepage
The R Journal

Software
R Sources
R Binaries
Packages
Other

Precompiled binary distributions of the base system and contributed packages, **Windows and Mac** users most likely want one of these versions of R:

- Download R for Linux
- Download R for (Mac) OS X
- Download R for Windows

R is part of many Linux distributions, you should check with your Linux package management system in addition to the link above.

Source Code for all Platforms

Windows and Mac users most likely want to download the precompiled binaries listed in the upper box, not the source code. The sources have to be compiled before you can use them. If you do not know what this means, you probably do not want to do it!

- The latest release (Thursday 2016-03-10, Very Secure Dishes) R-3.2.4.tar.gz, read what's new in the latest version.
- Sources of R alpha and beta releases (daily snapshots, created only in time periods before a planned release).

http://cran.r-project.org/web/packages/waterData/waterData.pdf
http://cran.r-project.org/web/packages/waterData/vignettes/vignette.pdf
http://cran.r-project.org/web/packages/waterData/index.html

Flood frequency analysis?

Flood frequency analysis

$$P = \frac{1}{T}$$

T = Return Period or Recurrence Interval

P = Probability of Exceedance

$$\log Q_T = \mu_{\log Q} + K_T \sigma_{\log Q}$$

Q_T = Discharge you are computing

μ_{logQ} = Mean of the log transformed annual peak flow series

σ_{logQ} = Standard deviation of the log transformed annual peak flow series

K_T = Frequency factor (from table, = f (skew and return period)

$$Q_T = 10^{logQ_T}$$

See flood frequency document distributed with electronic course materials for a detailed explanation of probability and statistics that go into flood frequency analysis

FDC and FF spreadsheet

Alternative flood frequency tools

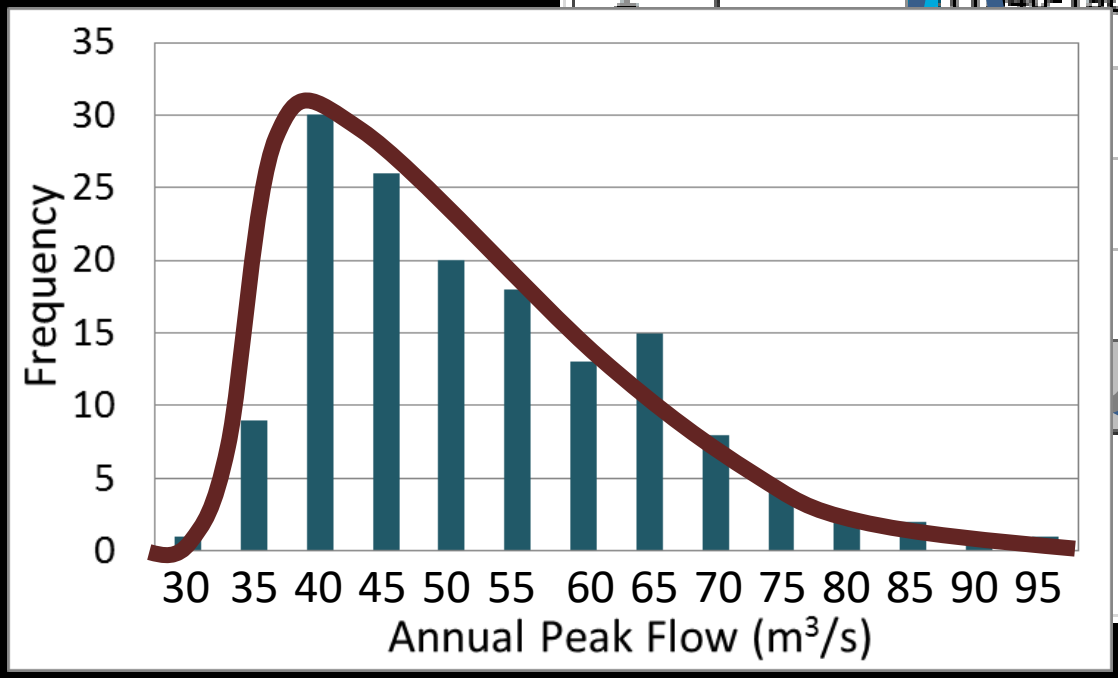
USGS Peak FQ Program
http://water.usgs.gov/software/PeakFQ/

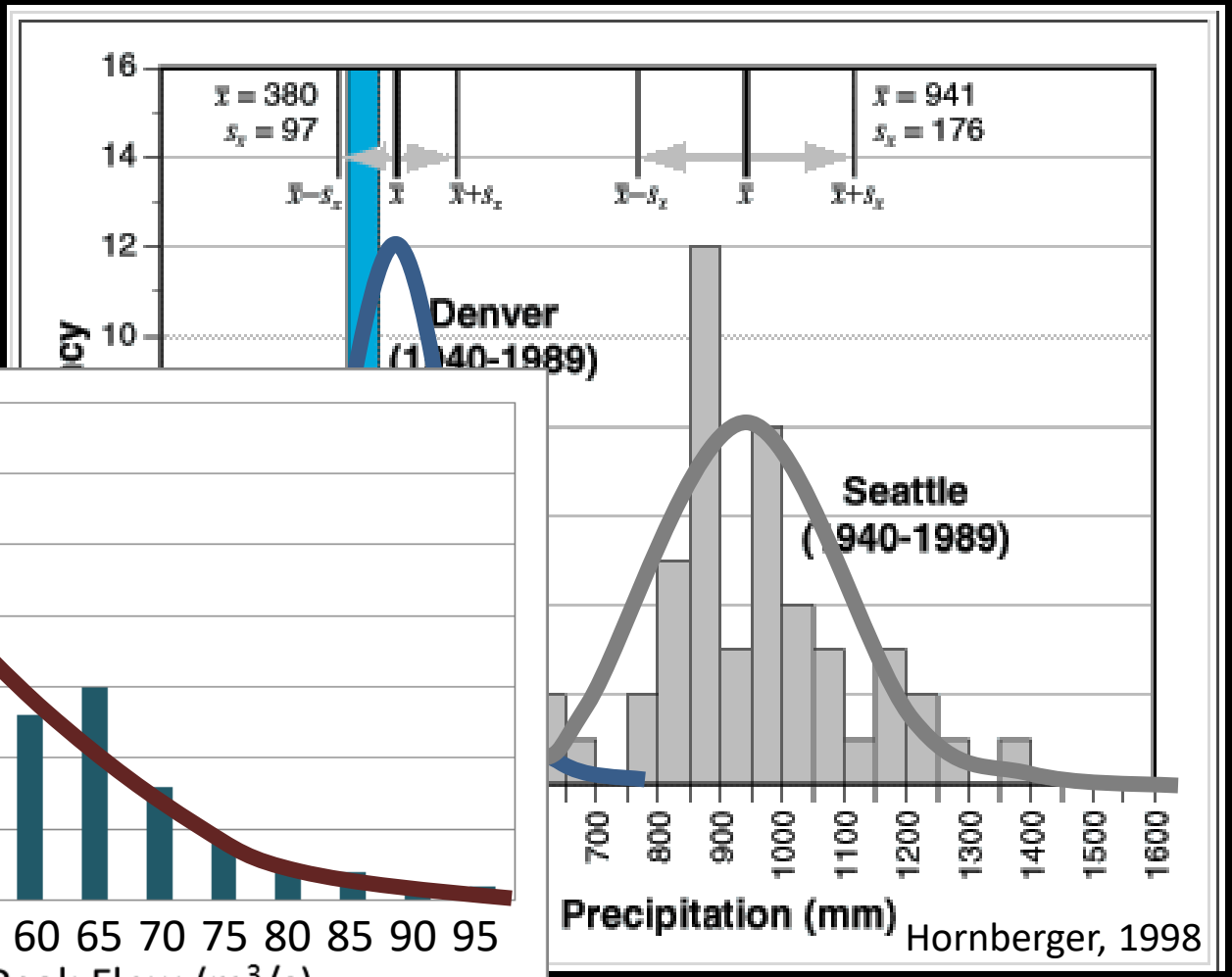
USDA Flood Frequency Calculation
http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?&cid=stelprdb1042910

The stationarity assumption in hydrology

Frequencies of hydrologic phenomena (e.g., precipitation, streamflow) can be represented by a time-invariant PDF that can be estimated from historic record.

These PDFs provide the basis for evaluation of risks to water supplies, floodplain development, infrastructure.



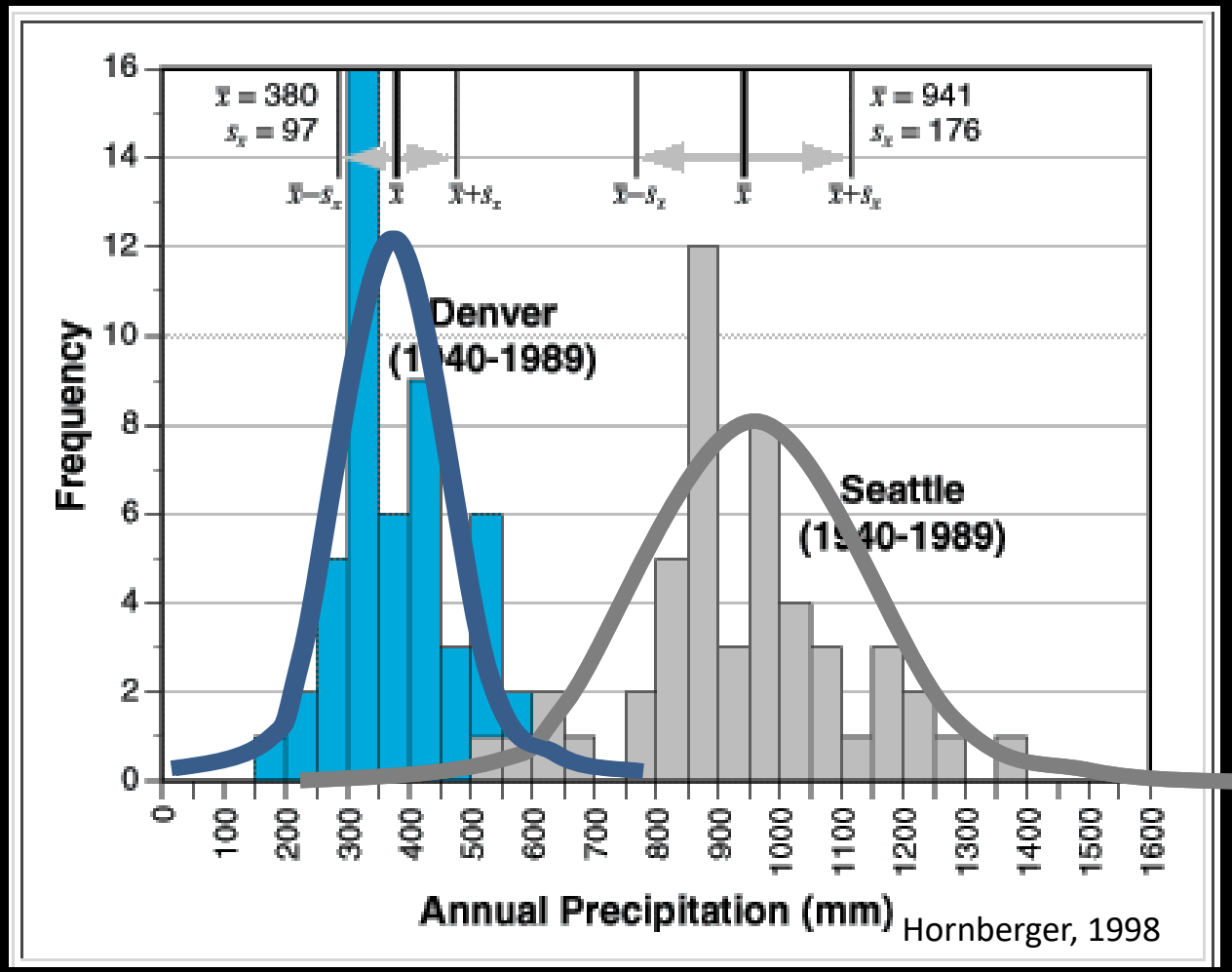


Hornberger, 1998

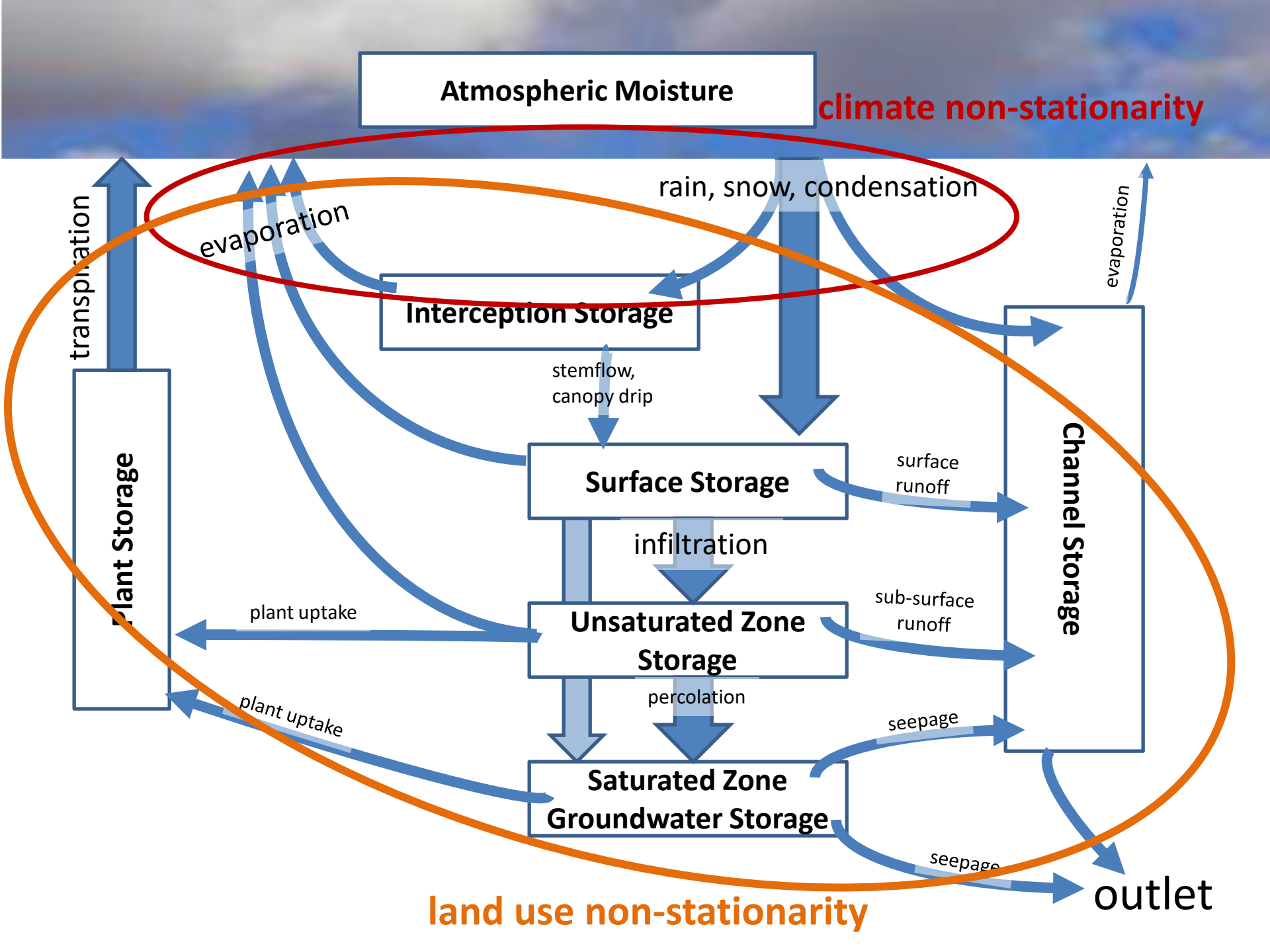
The stationarity assumption in hydrology

In some places, these PDFs are systematically changing

Non-stationary conditions



Hornberger, 1998


Atmospheric Moisture
climate non-stationarity
rain, snow, condensation
evaporation
transpiration
evaporation
Interception Storage
stemflow,
canopy drip
Plant Storage
Surface Storage
surface
runoff
Channel Storage
infiltration
plant uptake
Unsaturated Zone
Storage
sub-surface
runoff
percolation
plant uptake
seepage
Saturated Zone
Groundwater Storage
seepage
outlet
land use non-stationarity

Stuck on stationarity?

Standard practice for predicting flood frequency/magnitude assumes stationarity (Interagency, 1982)

FEMA

POLICYFORUM

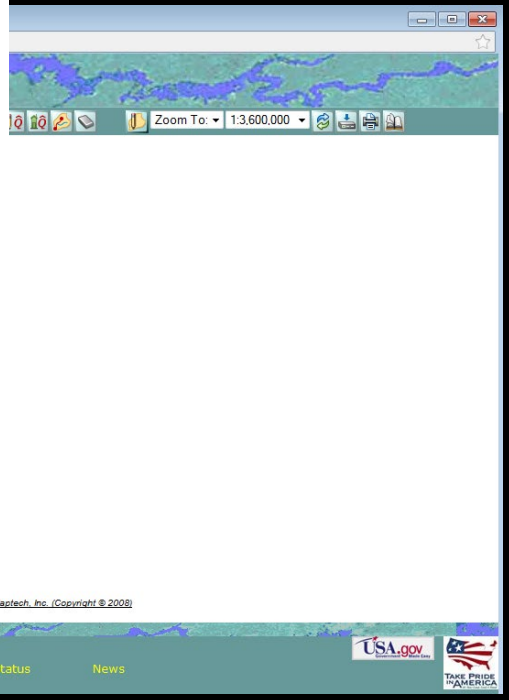
CLIMATE CHANGE

Stationarity Is A Zombie Whither Water Management?

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.



ats assumes stationarity



Review of techniques to adjust for non-stationarity provided by Gilroy & McCuen (2012)

Finding Hydrologic Data



Precipitation:

PRISM
http://www.prism.oregonstate.edu/

NOAA: Frequency Duration Data
http://hdsc.nws.noaa.gov/hdsc/pfds/

NOAA: NNDC data
http://www7.ncdc.noaa.gov/CDO/dataproduct

NRCS: Snotel
http://www.wcc.nrcs.usda.gov/snow/

NRCS: SCAN
http://www.wcc.nrcs.usda.gov/scan/

Soil Moisture:

NWS: CPC
http://www.cpc.ncep.noaa.gov/soilmst/w.shtml

Streamflow:

USGS: Water Watch
http://waterwatch.usgs.gov/

USGS: NWIS
http://waterdata.usgs.gov/nwis

Many state agencies, consortiums

Groundwater:

USGS: NWIS
http://waterdata.usgs.gov/nwis/gw

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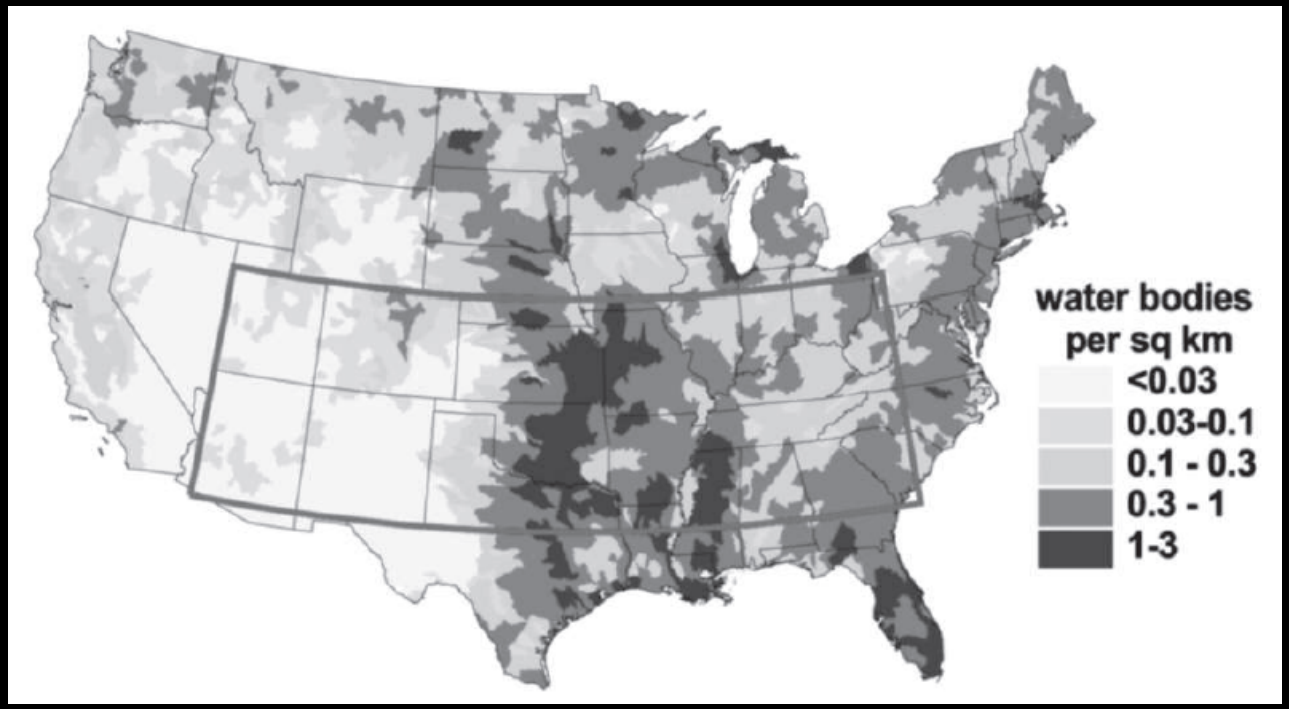
Targeted modeling and metrics. Stationarity Assumption?

Reservoir and pond sedimentation rates

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

Small water bodies distributed throughout US

2-9 million ponds < 10^4 m^2



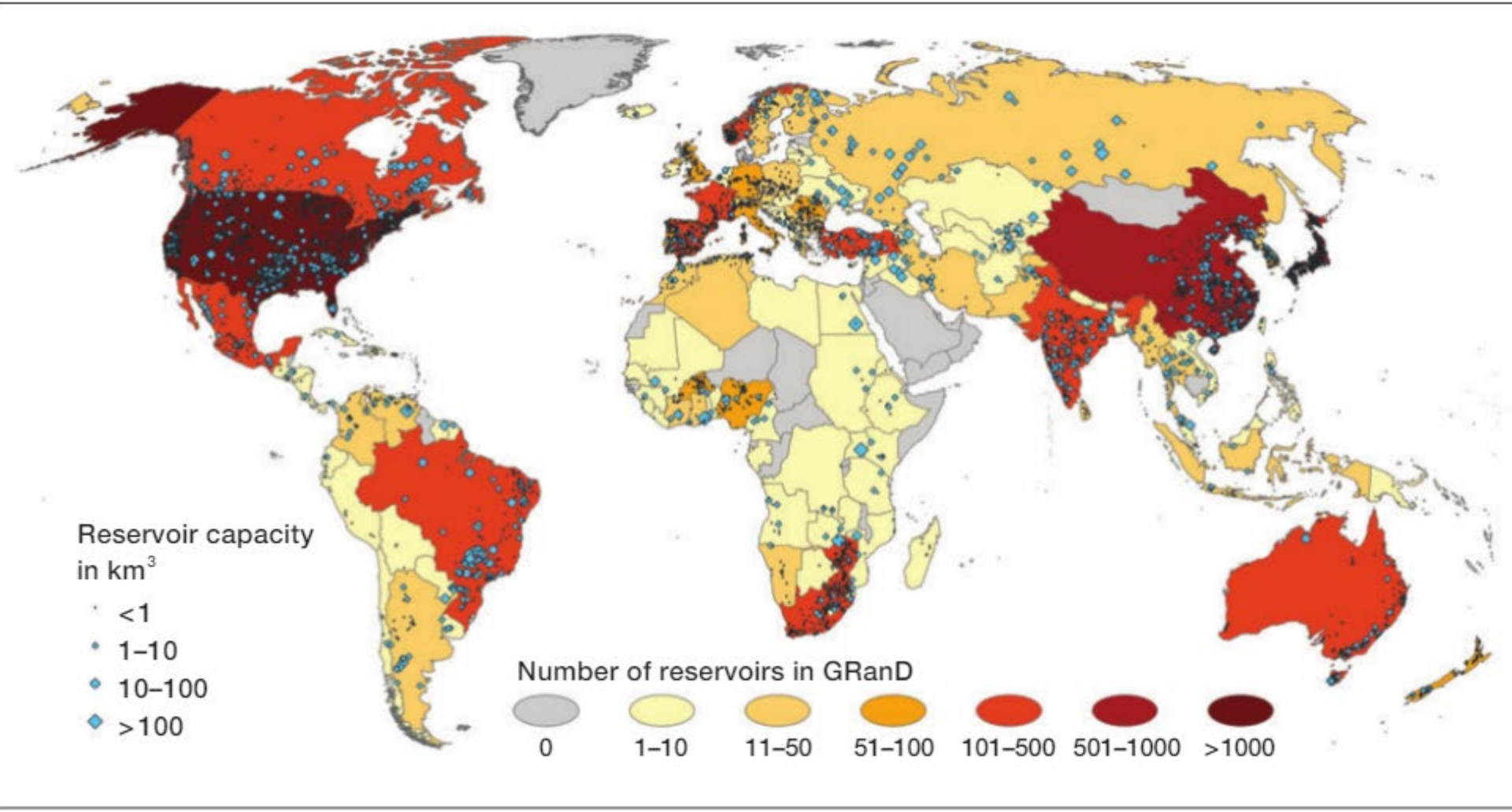
Smith et al., 2002

Relevant because reservoirs/ponds may:

1. serve as sediment traps
2. be useful for estimating space- and time-integrated sediment yields

Humans have simultaneously:
Increased sediment transport by global rivers by 2.3 ± 0.6 B Mg/yr via soil erosion, and
Decreased delivery to global oceans by 1.4 ± 0.3 B Mg/yr via retention within reservoirs
-Syvitski et al., 2007

Global Reservoir and Dam (GRanD) Database



http://globaldamwatch.org/grand/

7320 reservoirs

Lehner et al., 2011

ormation

UNITED STATES
DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

RESERVOIR SEDIMENTATION DATA SUMMARY

Echo Asgn.
NAME OF RESERVOIR

65-2
DATA SHEET NO.

DAM

1. OWNER Weber River Water Users/	2. RIVER Weber	3. STATE Utah	
4. SEC. 30 TWP. 3N RANGE 5E	5. NEAREST TOWN Echo & Coalville	6. COUNTY Summit	
7. STREAM BED ELEV. 5450	8. TOP OF DAM ELEV. 5570	9. SPILLWAY CREST ELEV. 1/ 5560	

RESERVOIR

10. STORAGE ALLOCATION	11. ELEVATION TOP OF POOL	12. SURFACE AREA ACRES	13. STORAGE ACRE-FEET	14. ACCUMULATED ACRE-FEET	15. DATE STORAGE BEGAN
a. FLOOD CONTROL	-	-	-	-	Oct.
b. POWER	-	-	-	-	1930
c. WATER SUPPLY	-	-	-	-	16. DATE NORMAL OPER. BEGAN
d. IRRIGATION	5560	1,470	75,718	75,718	
e. CONSERVATION	-	-	-		May
f. INACTIVE	5450	0	0	0	1931

17. LENGTH OF RESERVOIR 4 MILES; AV. WIDTH OF RESERVOIR .57 MILES

WATERSHED

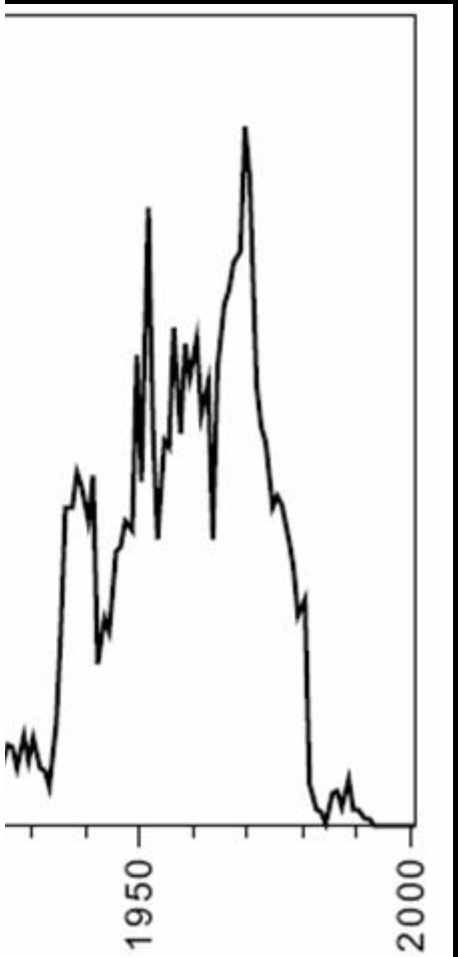
18. TOTAL DRAINAGE AREA	732 SQ. MI.	22. MEAN ANNUAL PRECIPITATION	14.5 - 35* INCHES
19. NET SEDIMENT CONTRIBUTING AREA	732 SQ. MI.	23. MEAN ANNUAL RUNOFF	5.2 INCHES
20. LENGTH 47 MILES; AV. WIDTH	16 MILES	24. MEAN ANNUAL RUNOFF	203,100 AC.-FT.
21. MAX. ELEV. 11,947 MIN. ELEV.	5450	25. CLIMATIC CLASSIFICATION	semi-arid

SURVEY DATA

26. DATE OF SURVEY	27. PERIOD YEARS	28. ACCL. YEARS	29. TYPE OF SURVEY	30. NO. OF RANGES OR CONTOUR INT.	31. SURFACE AREA ACRES	32. CAPACITY ACRE-FEET	33. C/W RATIO AC-FT. PER SQ. MI.
Oct. 1930					1,470	75,718	103
Oct. 1954	24.0	24.0	R	16 (M)	1,445	73,900	101

26. DATE OF SURVEY	34. PERIOD ANNUAL PRECIPITATION	35. PERIOD WATER INFLOW ACRE-FEET			36. WATER INFL. TO DATE AC-FT.	
		a. MEAN ANNUAL	b. MAX. ANNUAL	c. PERIOD TOTAL	a. MEAN ANNUAL	b. TOTAL TO DATE
Oct. 1954	14.5 - 35*	203,125	415,700	4,875,000	203,125	4,875,000

26. DATE OF SURVEY	37. PERIOD SEDIMENT DEPOSITS ACRE-FEET			38. TOTAL SED. DEPOSITS TO DATE ACRE-FEET		
	a. PERIOD TOTAL	b. AV. ANNUAL	c. PER SQ. MI-YEAR	a. TOTAL TO DATE	b. AV. ANNUAL	c. PER SQ. MI-YEAR
Oct. 1954	1818	76	.104	1818	76	.104



rvoirs

Estimating trapping efficiency of reservoirs

$$TE = \frac{S_{in} - S_{out}}{S_{in}} = \frac{S_{set}}{S_{in}}$$

S_{in} = sediment mass entering a reservoir

S_{out} = sediment mass leaving a reservoir

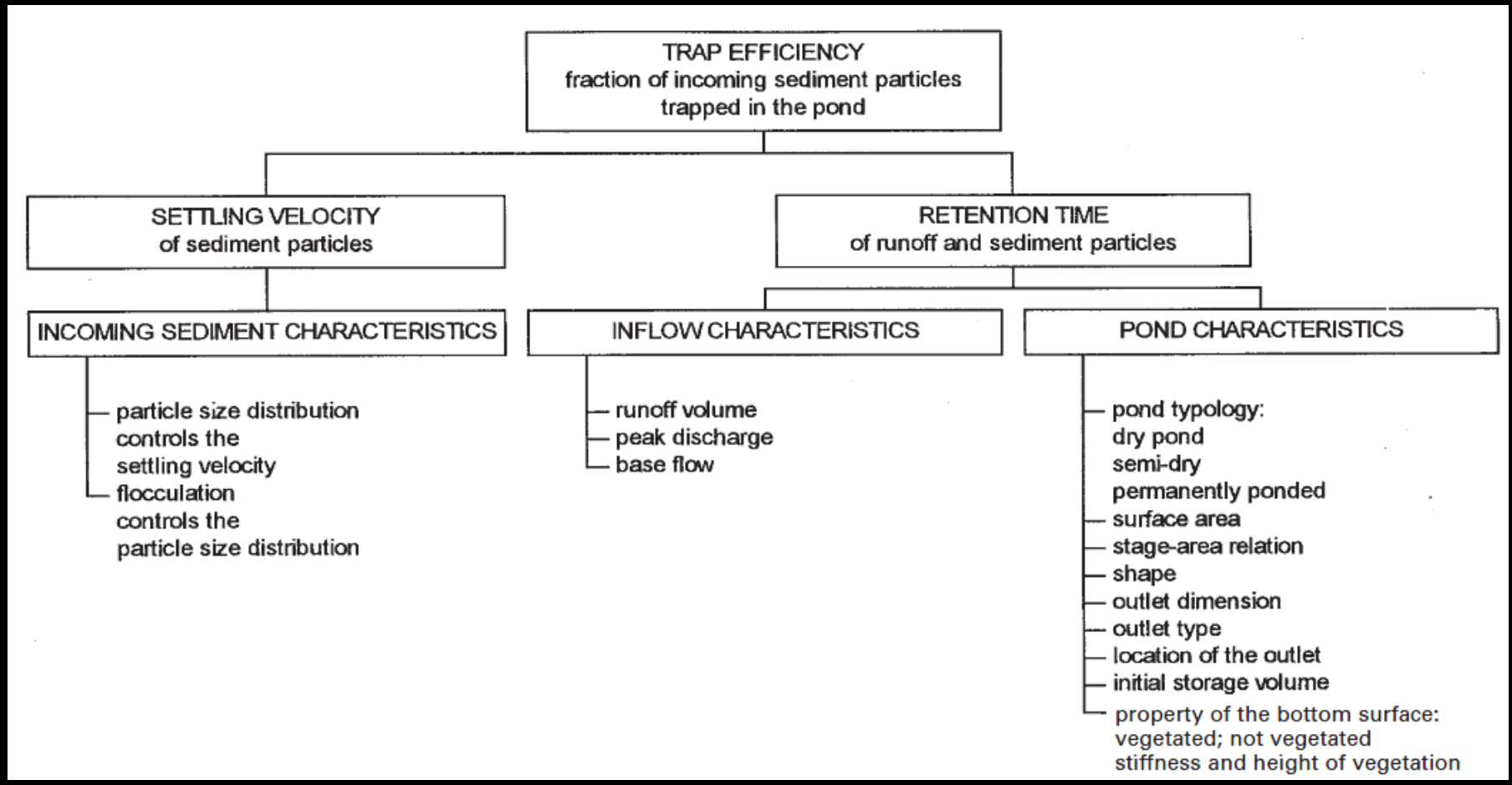
S_{set} = sediment mass deposited within the reservoir

Controls on TE:
Particle size distribution of S_{in} relative to water retention time

Retention time depends on:
1) characteristics of inflow hydrograph and
2) geometric characteristics, including storage capacity, shape and outlet type

See review by Verstraeten and Poesen, 2000
Spreadsheet model: Minear and Kondolf, 2009

Controls on reservoir trapping efficiency



Verstraeten and Poesen 2000

Empirical techniques for estimating TE

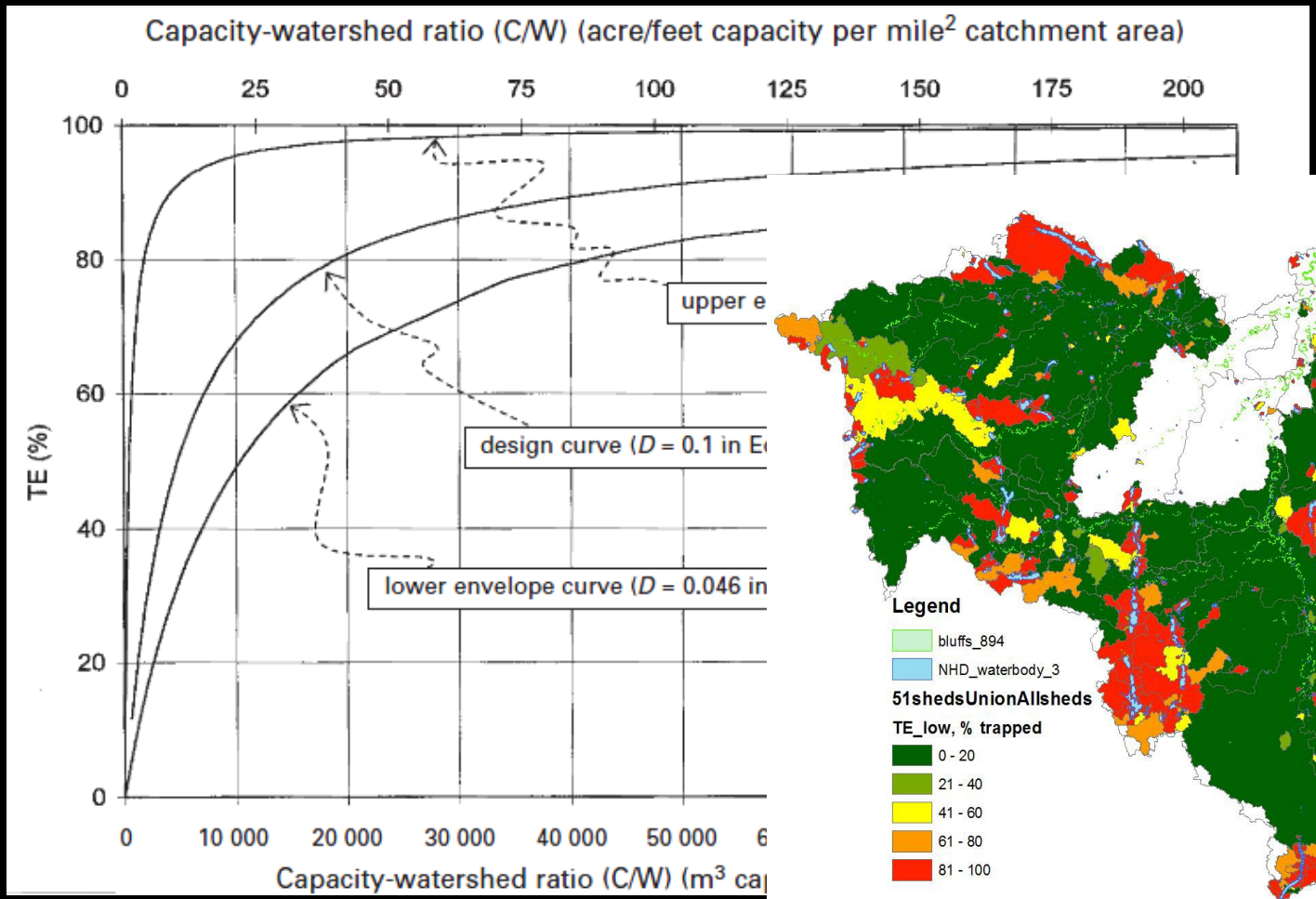
$$TE = 100\left(1 - \frac{1}{1 + 0.0021D\frac{C}{W}}\right)$$

Brown (1943)

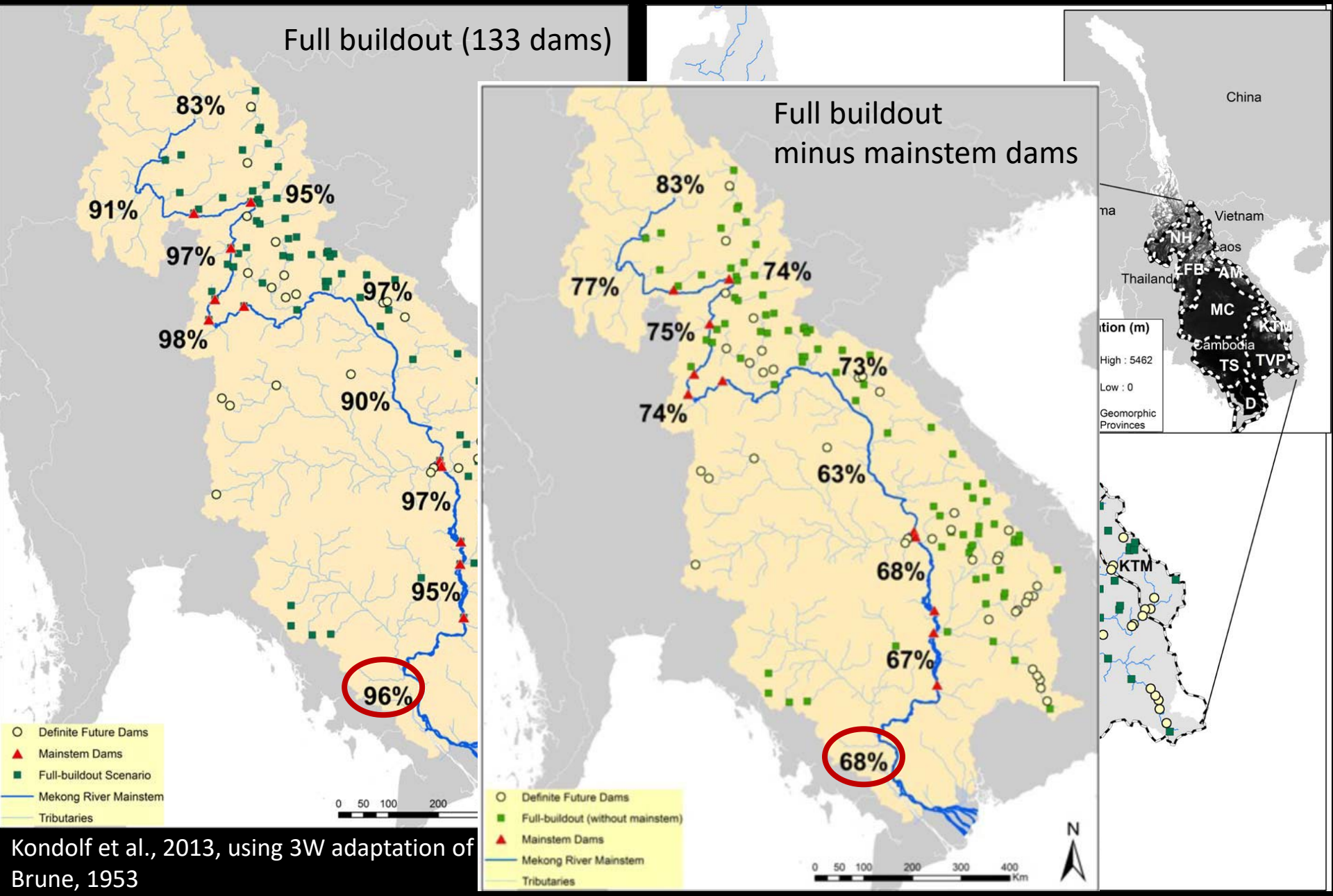
C = reservoir storage capacity in m^3

W = watershed area in km^2

D = empirical form factor (range 0.046 – 1)



Cumulative effects of many dams?



Kondolf et al., 2013, using 3W adaptation of Brune, 1953

Quasi-physical techniques for estimating TE

Ward et al., 1980: for ephemeral flow-through ponds

$$TE = 91.5 + 13.2\frac{S}{Q} + 1.9(P_{20} - P_5)\left(\frac{T_D}{T_S}\right) - 1.4\left(\frac{q_e}{q_i}\right)^{0.3} P_{20} \quad (30)$$

where:

S is the pond capacity up to the riser crest (m^3);
Q is the inflow volume (m^3);
P_{20} and P_5 are the percentage finer than 20 μm and 5 μm, respectively, at peak inflow rate;
T_D is detention time (h);
T_S is storm duration (h);
q_e is peak outflow rate (m^3/s); and
q_i is peak inflow rate (m^3/s).

Ward et al., 1980: for perennial ponds with baseflow

$$TE = 93.1 + 27.6\frac{S}{Q} + 0.046(P_{20} - P_5)\left(\frac{T_D}{T_S}\right) - 1.4\left(\frac{q_e}{q_i}\right)^{0.3}$$

Lewis et al., 2013 adapted Brune (1953) and Churchill (1948) for tropical rivers with high flow CV

Some take-away points:

1. Hydrology is inherently complex. Immense variability in space and time, myriad non-linear and interacting processes. Be targeted in your analysis. Beware of nonstationarity.

2. Be a geek, it's okay. Appropriate models, thoughtfully applied, can provide useful info. But be aware of (and transparent about) the simplifications and uncertainties in your model.

3. Cosmogenic nuclides measure long-term erosion rates and can be used to quantify erosion integrated over millennial timescales. Lots of existing data, use it!

4. Reservoirs may contain useful sedimentation records. Much data available, but may require additional analysis.