Connecting Process and Form:
New Results on Scaling and Implications for Modeling and Prediction in Ungauged Basins

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University of Minnesota

Grenoble
November, 2006

National Center for Earth-surface Dynamics
A National Science Foundation Science & Technology Center

St. Anthony Falls Laboratory
University of Minnesota

HYDROLOGY AND EARTH-SURFACE DYNAMICS RESEARCH @

SAFL and NCED

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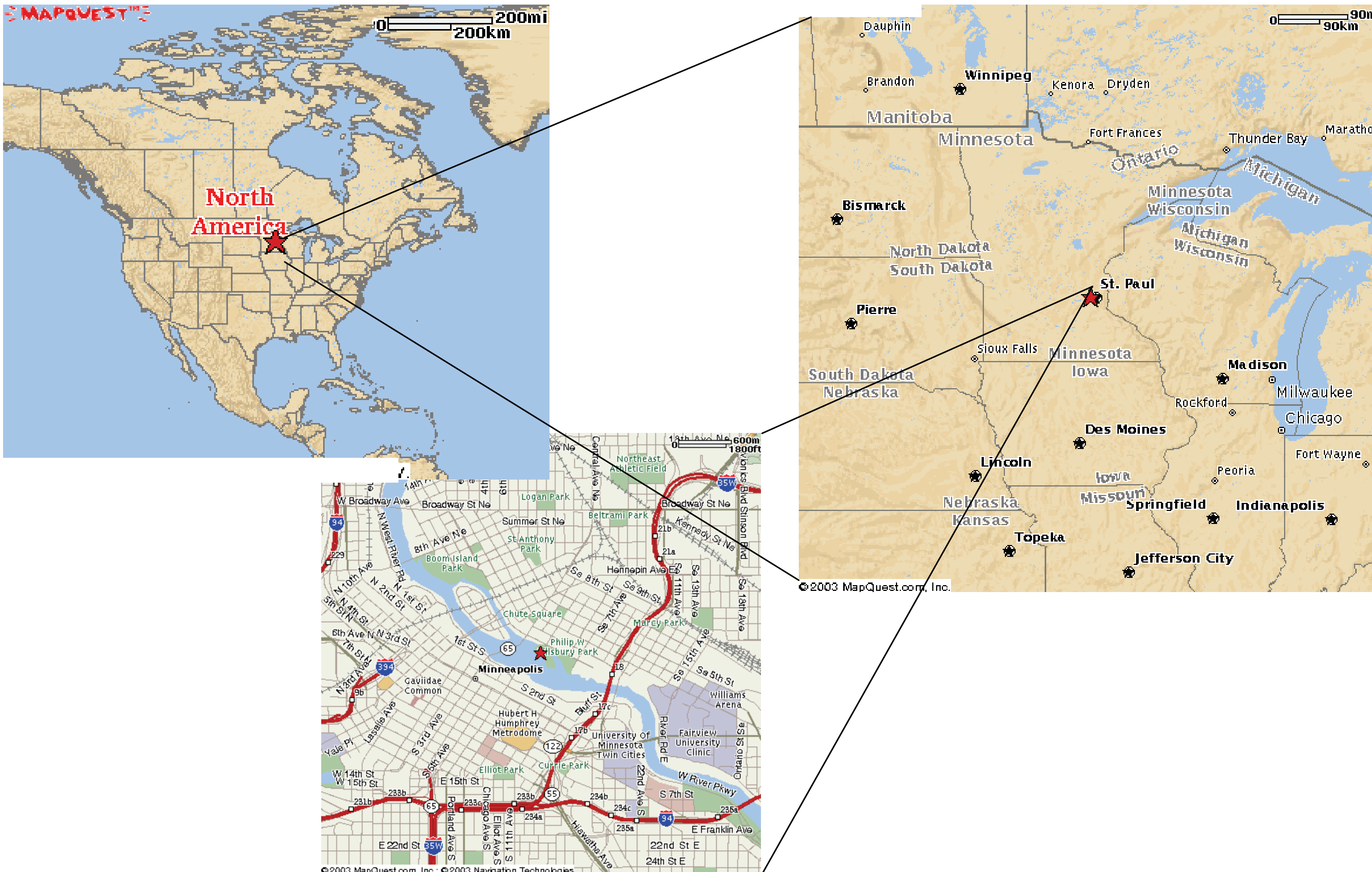
St. Anthony Falls Laboratory (SAFL)
National Center for Earth-Surface Dynamics (NCED)
Department of Civil Engineering

University of Minnesota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University Of Minnesota Twin Cities
Fairview University Clinic
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S 7th St
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St. Anthony Falls Laboratory University of Minnesota (1938-present)

SAFL's goal is to advance the knowledge of environmental hydrology and hydraulics, turbulence, earthscape evolution, and climate/ ecosystem dynamics via high quality experimental, theoretical and computational research.

Transfer this knowledge to the engineering community and to the public through applied research and outreach activities

St. Anthony Falls Laboratory University of Minnesota (1938-present)

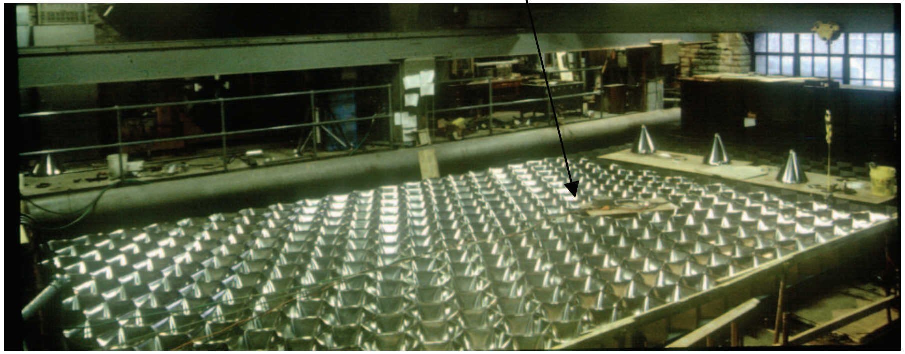
- 5000 m^2 of flumes, basins, tanks and offices
- Main channel (84 x 2.7m, 300 cfs)
- Recirculating turbidity-current flume
- Boundary layer wind tunnel (16x1.5x2.5m)
- 3m deep aquarium-grade tank with suspended inner channel for subaqueous flow experiments
- Environmental and Sediment laboratories
- Jurassic Tank (XES - eXperimental EarthScape basin)

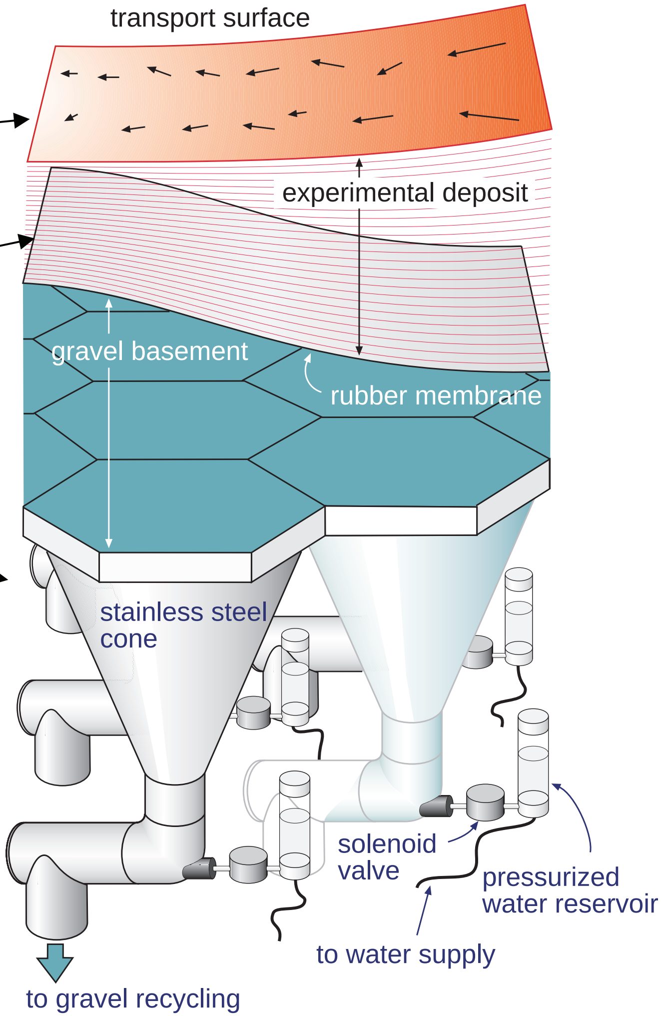
Experimental EarthScapes in “Jurassic Tank”

This surface remains near its initial level, while…

…this surface subsides…

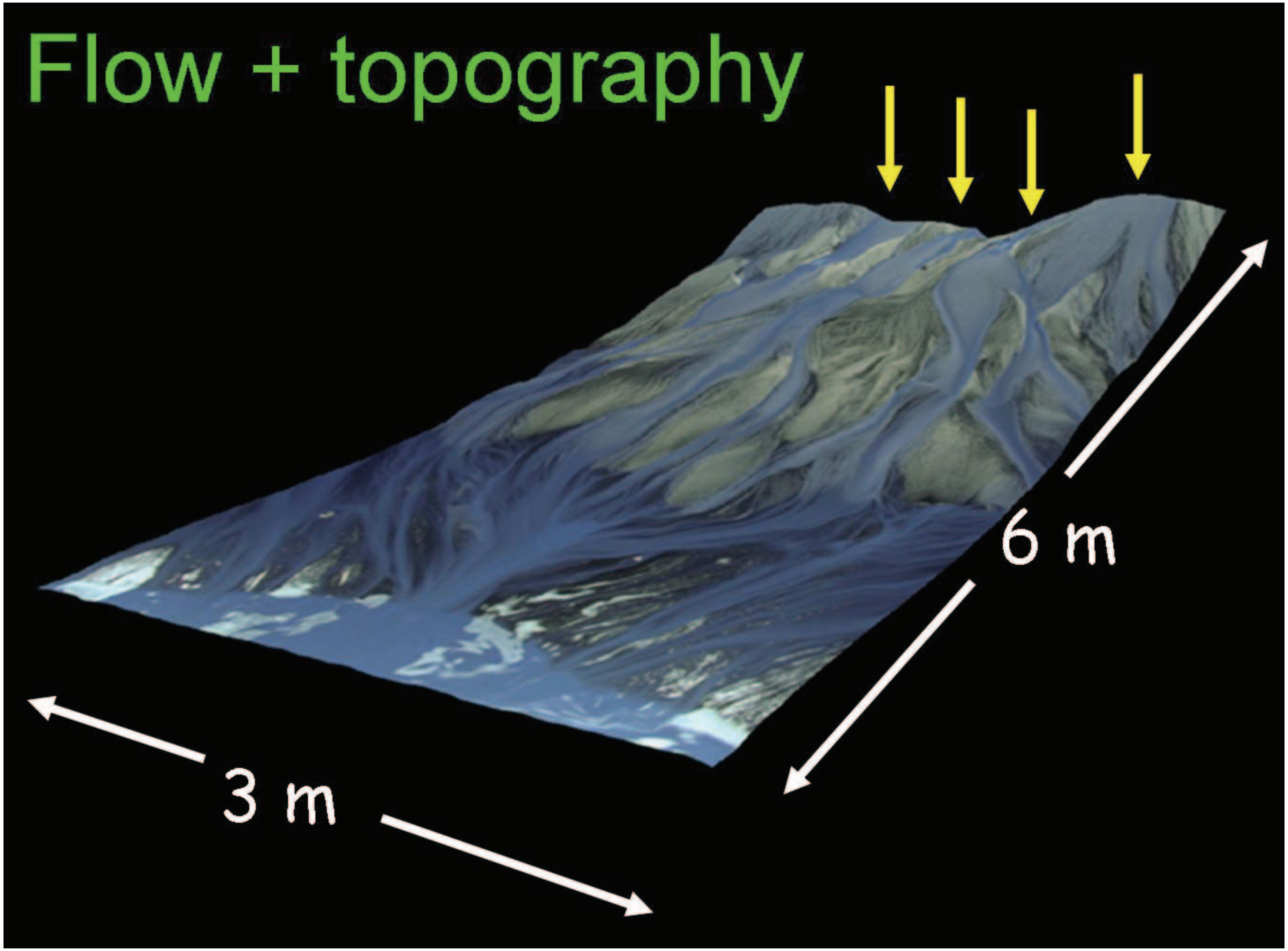
…via these cells





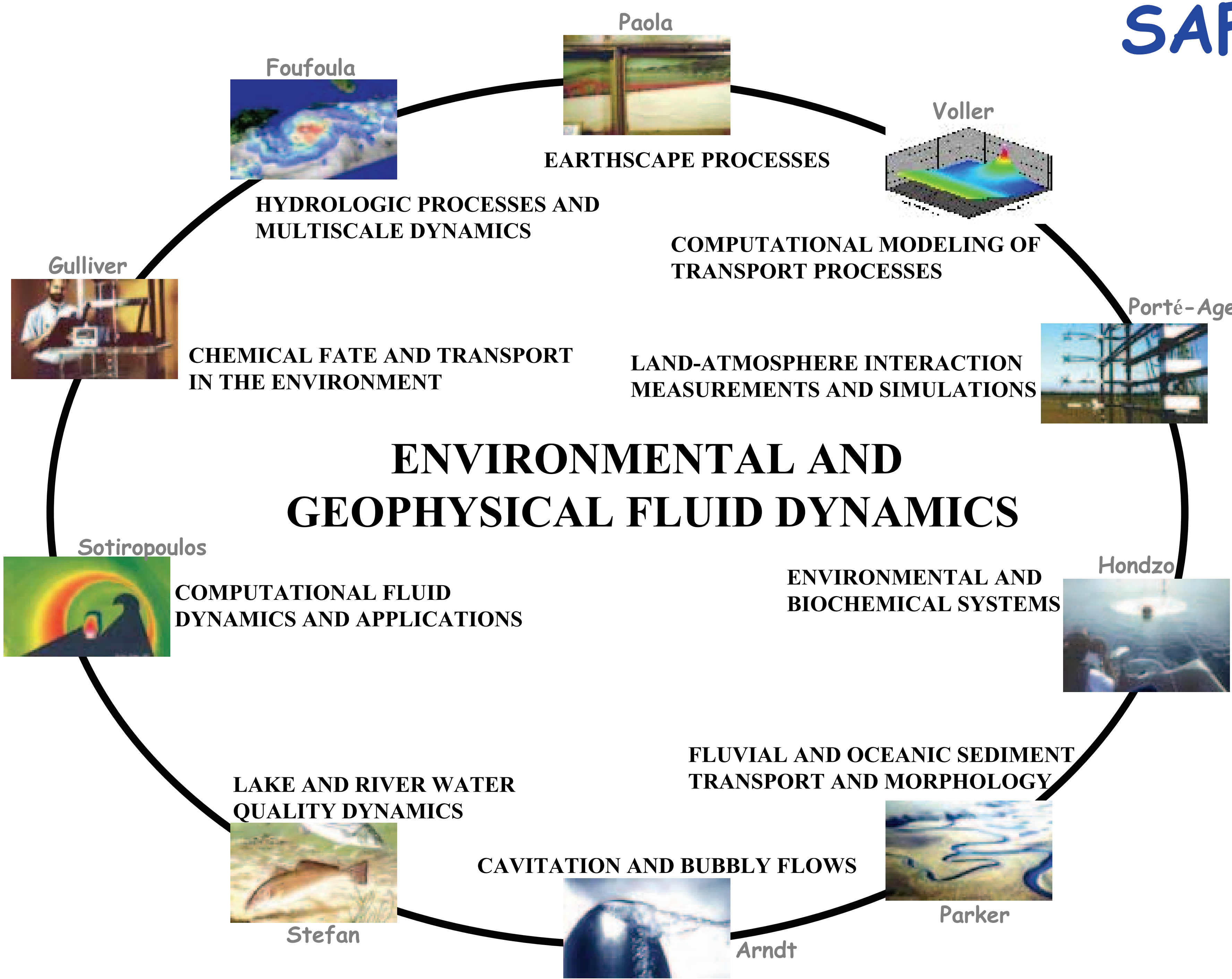
13 x 6.5m; 432 subsidence cells

Experimental EarthScapes in "Jurassic Tank"



Stratigraphy, Morphodynamics, Continental Margins

SAFL


ENVIRONMENTAL AND
GEOPHYSICAL FLUID DYNAMICS
Paola
EARTHSCAPE PROCESSES
Voller
COMPUTATIONAL MODELING OF
TRANSPORT PROCESSES
Porté-Agel
LAND-ATMOSPHERE INTERACTION
MEASUREMENTS AND SIMULATIONS
Hondzo
ENVIRONMENTAL AND
BIOCHEMICAL SYSTEMS
FLUVIAL AND OCEANIC SEDIMENT
TRANSPORT AND MORPHOLOGY
Parker
CAVITATION AND BUBBLY FLOWS
Arndt
LAKE AND RIVER WATER
QUALITY DYNAMICS
Stefan
Sotiropoulos
COMPUTATIONAL FLUID
DYNAMICS AND APPLICATIONS
Gulliver
CHEMICAL FATE AND TRANSPORT
IN THE ENVIRONMENT
Foufoula
HYDROLOGIC PROCESSES AND
MULTISCALE DYNAMICS

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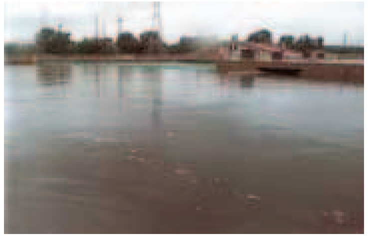
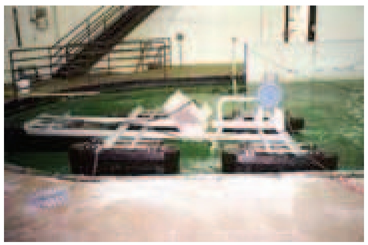
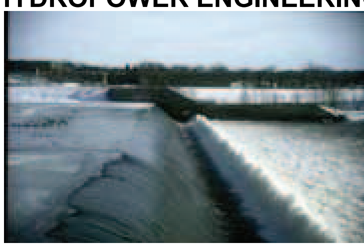
WATER AND WASTEWATER TREATMENT



AERATION TECHNIQUES



HYDROPOWER ENGINEERING

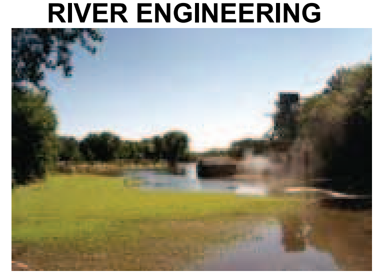


HYDRAULIC STRUCTURES

The St. Anthony Falls Laboratory is involved in a wide variety of **APPLIED RESEARCH AND ENGINEERING** projects commissioned by government agencies, private companies, and consultants. These projects span the areas of river modeling for environmental protection and restoration; water and wastewater treatment; water quality of lakes, rivers and reservoirs; hydropower plants and hydraulic structures; wind engineering; and various performance and calibration testing.

SURFACE WATER QUALITY

RIVER ENGINEERING



CALIBRATION AND PERFORMANCE TESTING

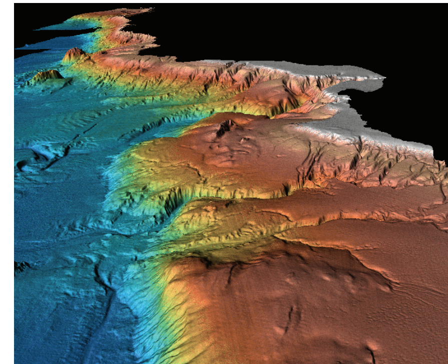
WIND ENGINEERING

National Center for Earth-surface Dynamics (NCED)

A NSF Science and Technology Center
Established at U of M in 2002

NCED's purpose is to catalyze the development of an integrated predictive science of the processes shaping the surface of the Earth, in order to transform management of ecosystems, resources, and land use

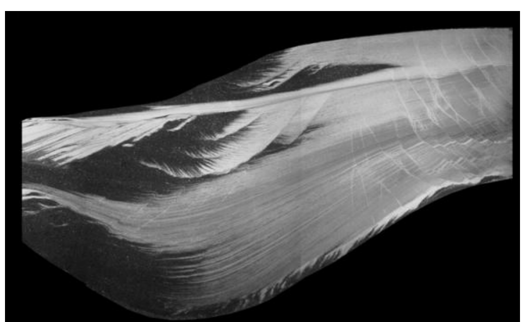
sediment transport



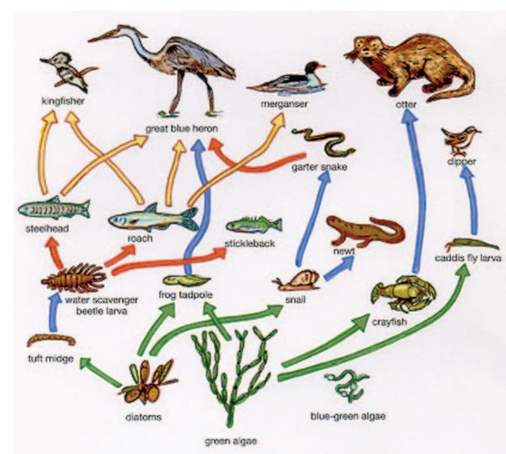
scaling

hydrology

geomorphology

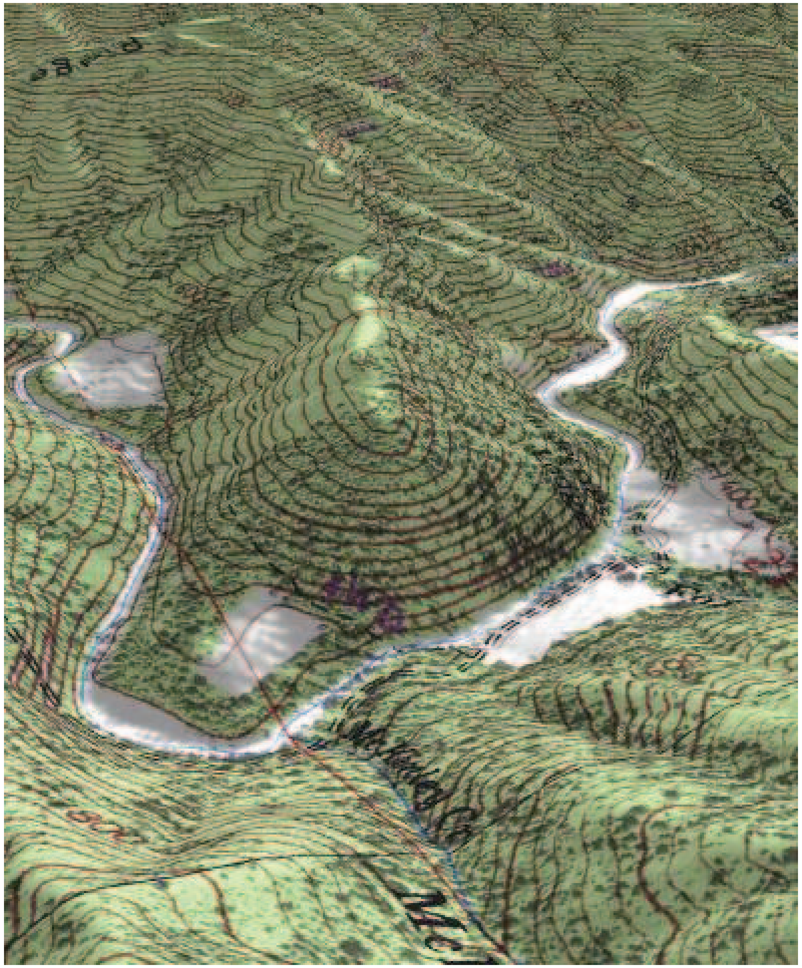


sedimentology



ecology

Landscape and ecosystem response to extreme stress



GCMs predict a reduction of precipitation here. How will the system respond (sediment yield, hydrology, ecosystem, landsliding...)?

Sustainable solutions to stream restoration

View downstream from Santa Teresa bridge (courtesy Matt Kondolf, UC Berkeley)

Jan 1996

Sustainable solutions to stream restoration

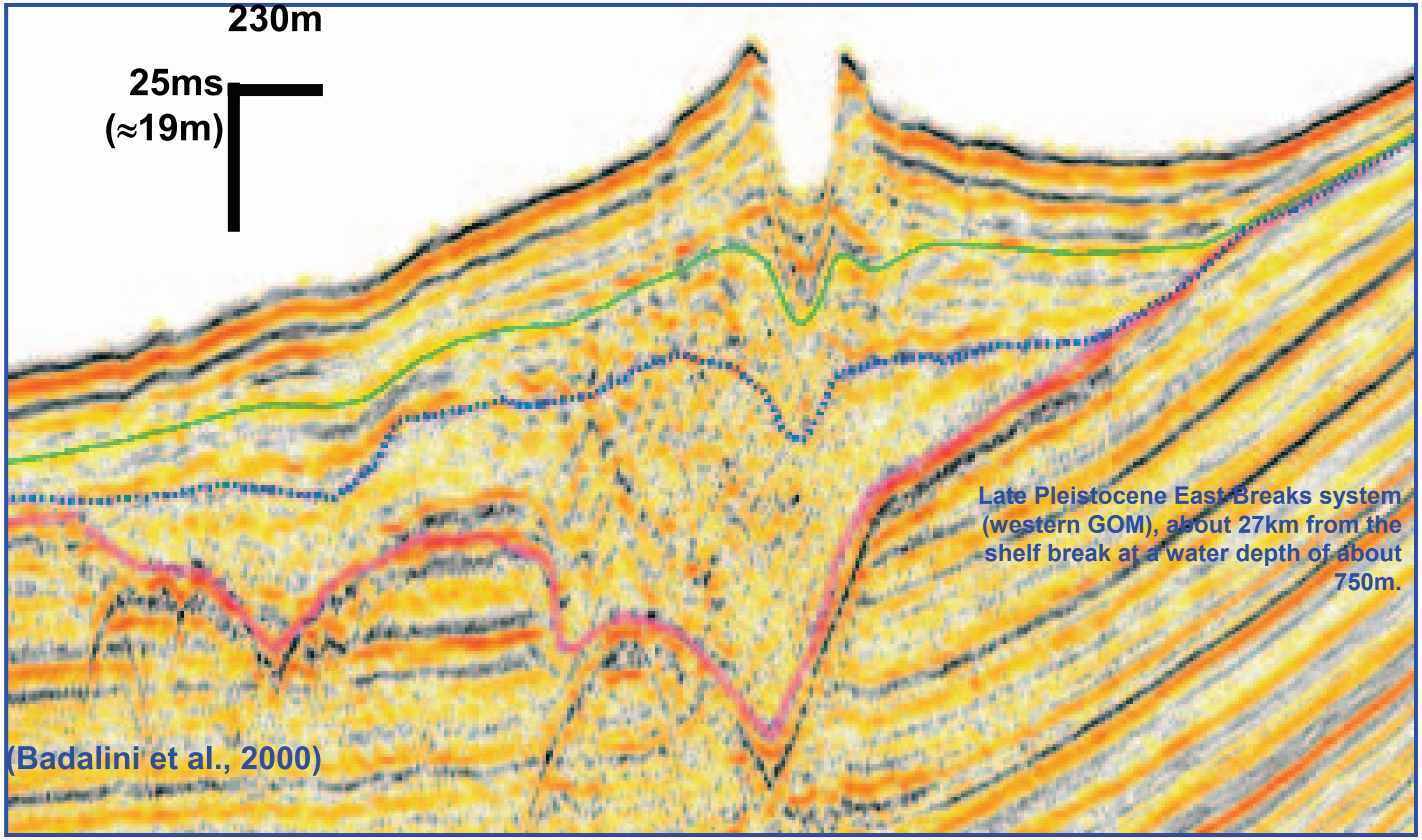
View downstream from Santa Teresa bridge (courtesy Matt Kondolf, UC Berkeley)

Jan 1996

July 1997 – After flood of Feb 1996

Could this have been prevented?

Exploration of natural resources



- Can climatic variations be inferred from this deposit?
- Is there recoverable oil in this deposit?
- Can the history of the channel be used for landscape prediction?

Participating Institutions

University of Minnesota (SAFL)

University of California, Berkeley

University of Colorado, Boulder

Fond du Lac Tribal and Community College

University of Illinois, Urbana/Champaign

Johns Hopkins University

Massachusetts Institute of Technology

Princeton University

Science Museum of Minnesota

Research Focus of my group

Hydrology/Geomorphology with emphasis on quantifying the space-time organization and interactions of precipitation, landforms and streamflow over a range of scales

For the purpose of:

1. Subgrid-scale parameterizations of predictive models, including downscaling

2. Upscaling of flux laws (water and sediment) in view of small-scale variability

3. Statistical prediction of "extremes" (precipitation depth, floods, large scour in a channelized system, large migration of a channel in a braided river system, etc.) based on observations of more common events

Current Research

1. Precipitation (NASA, NSF)

- Multiscale characterization and downscaling methodologies
- Multisensor estimation
- NWP model verification and quantification of forecast prediction uncertainty via ensembles

2. Hydro-geomorphology (NSF)

- Evolution of braided river systems
- Channel/floodplain dynamics and effect on hydrologic response
- Process signatures in high resolution topography

3. Atmospheric boundary layer turbulence (NASA, NSF)

- Subgrid-scale parameterizations and LES closures
- Stable boundary layer

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Overarching Questions

1. How much of the physical/mechanistic behavior of the coupled hydrologic/geomorphologic system is reflected in the observed statistical patterns of landscapes and streamflows?

2. Are statistical patterns distinct across physical boundaries and how can they be used in assisting modeling, prediction and observatory design across scales and across environments?

3. Where/what to sample to get the most out of a limited number of observations?

MAIN MESSAGES

1. Physical processes do leave important signatures on the statistics of landscapes and streamflows and thus provide a powerful means of inference

   [to guide modeling and observatory design, to further pose and test hypotheses, etc . . .]

2. High resolution topography offers new opportunities for connecting process and form at an ever increasing range of scales

   [hillslope to watershed scales, explicit extraction of channel heads, verification of mechanistic transport laws, spatially-distributed hydrologic modeling, etc…]

Examples to discuss

1. The scaling break in floods reflects important fluvial regime transitions and a channel-floodplain exchange process that is scale & frequency dependent.
   [Implications for modeling and prediction]

2. High-resolution DEMs offer new opportunities, e.g., objective and explicit identification of the hillslope-to-valley-to-channel transition.
   [Implications for modeling and subgrid-scale parameterizations]

3. Bedload size distributions and mass flux along river networks are less controlled by the flow pathways and more by the sediment production at the hillslope.
   [Implications for monitoring, theories of scale-dependent channel formation]

4. New ways of looking at landscapes, e.g., river corridor width functions, highlight the ability to depict important physical boundaries in valley forming processes from the presence of statistical boundaries.
   [Implications for spatially-distributed modeling]

Related Publications

1. Dodov B., E. Foufoula-Georgiou, Fluvial processes and streamflow variability: Interplay in the scale-frequency continuum and implications for scaling, *Water Resources Research*, 41, W05005, doi:10.1029/2004WR003408, 2005

2. Theodoratos, N., I. Iorgulescu, E. Foufoula-Georgiou, A geomorphologic interpretation of the statistical scaling in floods, *Water Resources Research*, under review, 2006.

3. Passalacqua P., F. Porté-Agel, E. Foufoula-Georgiou, C. Paola, Application of dynamic subgrid-scale concepts from large-eddy simulation to modeling landscape evolution, *Water Resources Research*, 42, W06D11, doi:10.1029/2006WR004879, 2006

4. Sklar L. S., W. E. Dietrich, E. Foufoula-Georgiou, B. Lashermes, D. Bellugi, Do gravel bed river size distributions record channel network structure?, *Water Resources Research*, 42, W06D18, doi:10.1029/2006WR005035, 2006

5. Lashermes, B., E. Foufoula-Georgiou, and W. Dietrich, Objective delineation of valleys in canyon systems: a methodology based on wavelets and high resolution DEMs, in preparation, 2006.

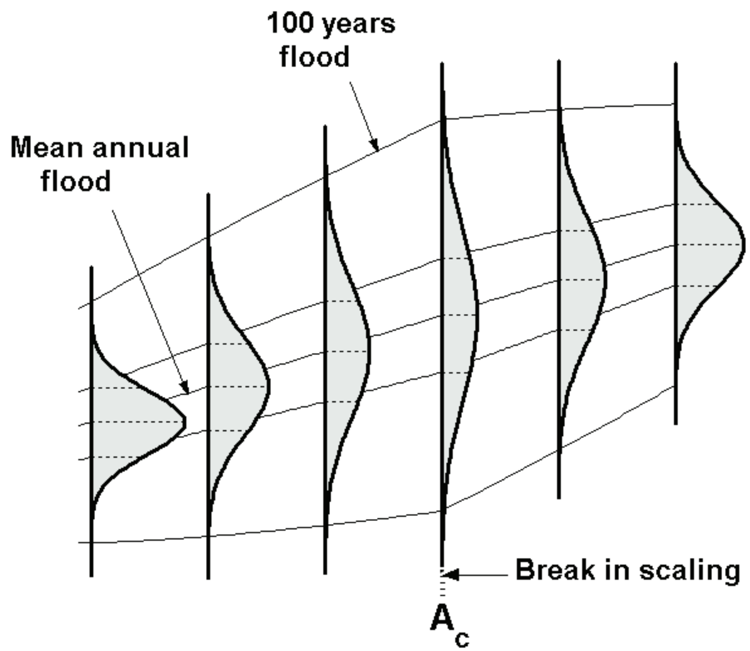
6. Lashermes, B. and E. Foufoula-Georgiou, Area and width functions of river networks: new results on multifractal properties, *Water Resources Research*, under review, 2006

7. Gangodagamage C., E. Barnes, and E. Foufoula-Georgiou, Anomalous scaling in river corridor widths reflects localized nonlinearities in valley forming processes, under review, 2006.

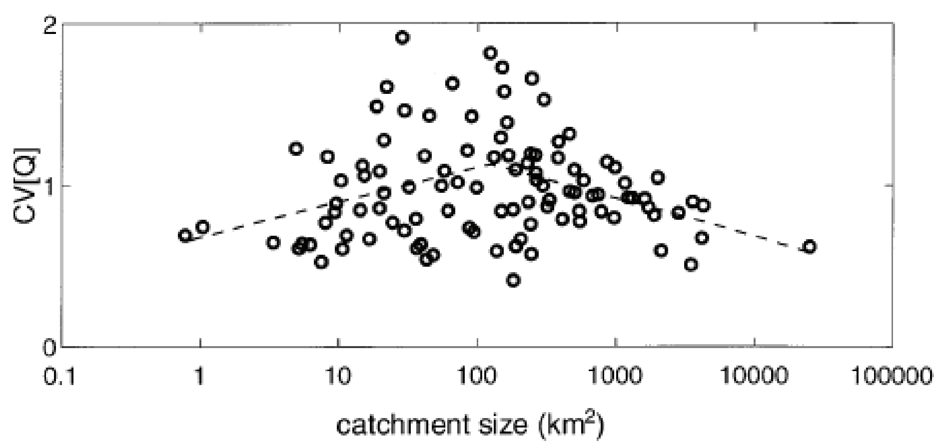
1. SCALING BREAK IN FLOODS

Multiscaling theory of flood peaks, *Gupta et al.* [1994]:

$$Q(\lambda A) =^d G(\lambda)\, Q(A)$$

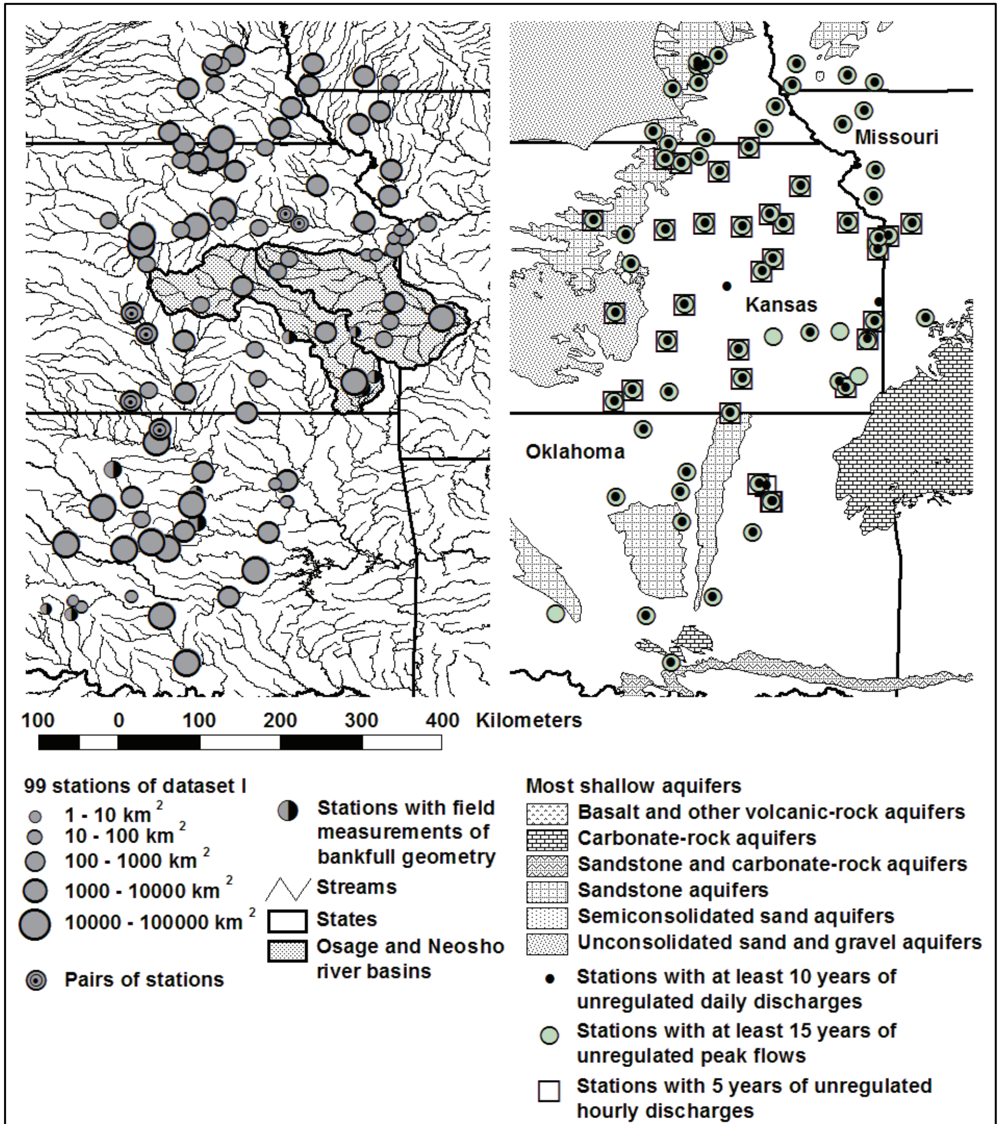


$CV(A)$



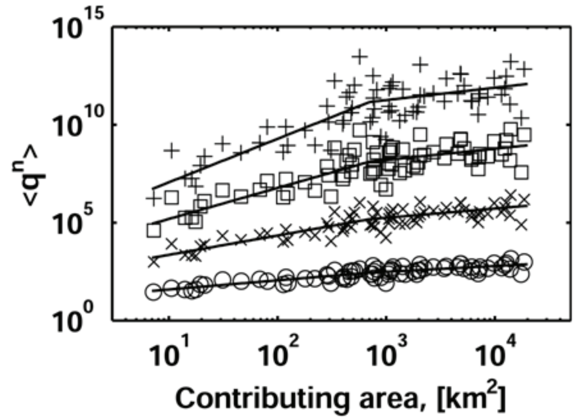
(reproduced from *Smith*, 1992)

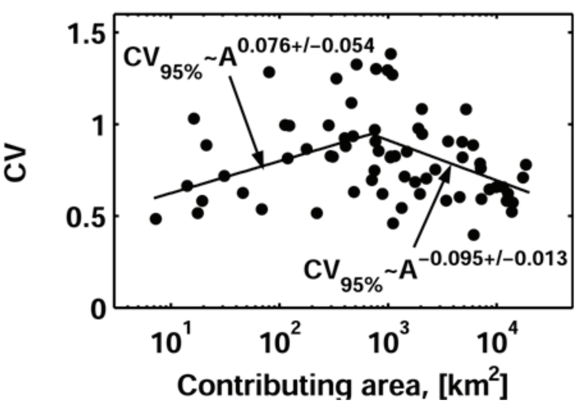
Midwest Region



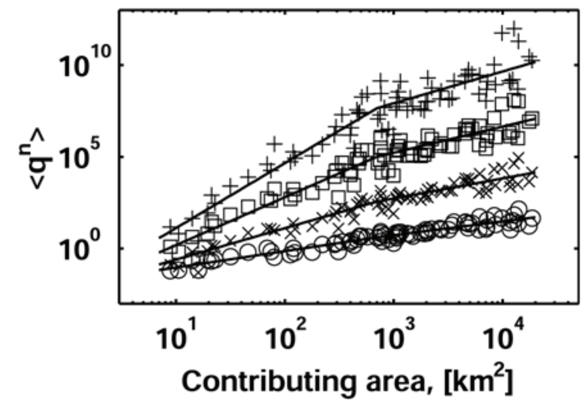
- •99 stations for HG (100's of measurements for different Q/ station)
- •72 stations for max annual flows (>15 yrs)
- •70 stations for daily flows (>10 yrs)
- •72 stations for hourly flows (>5 yrs)
- •High resolution hydrography data for Osage and Neosho basins, KS
- •Stratigraphic logs for 420 water wells
- •115 stations of suspended sediment (100's measurements for different Q/station)

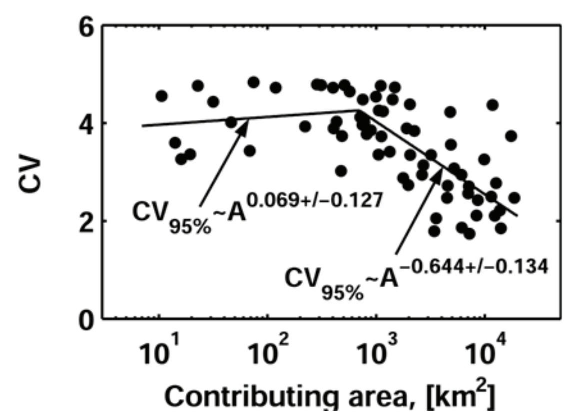
Scaling of Maximum Annual Floods





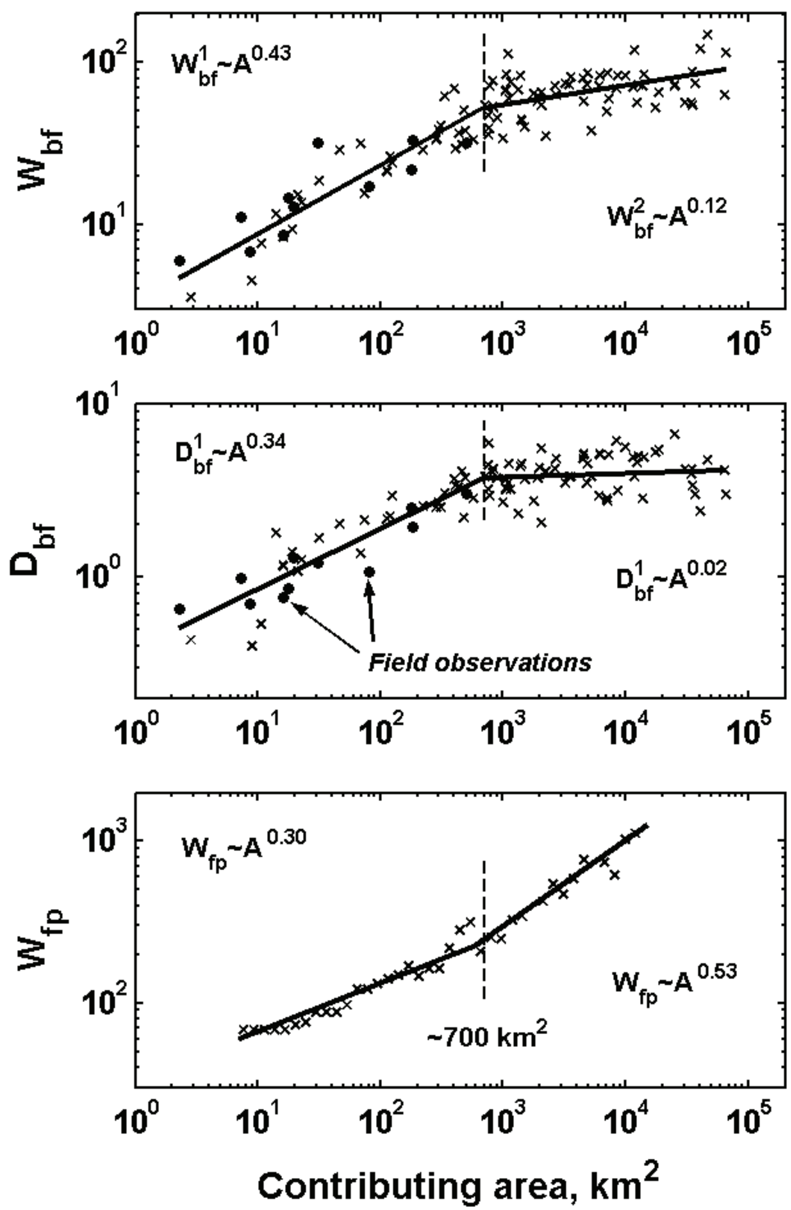
Scaling of Daily Discharges





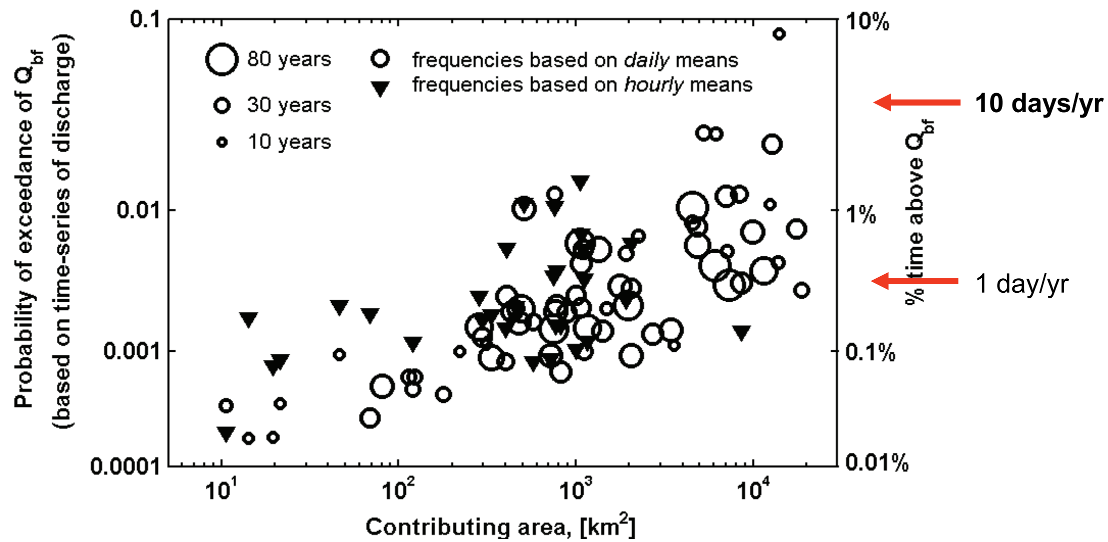
What controls the scaling break?

Channel Bankfull and Floodplain Geometry

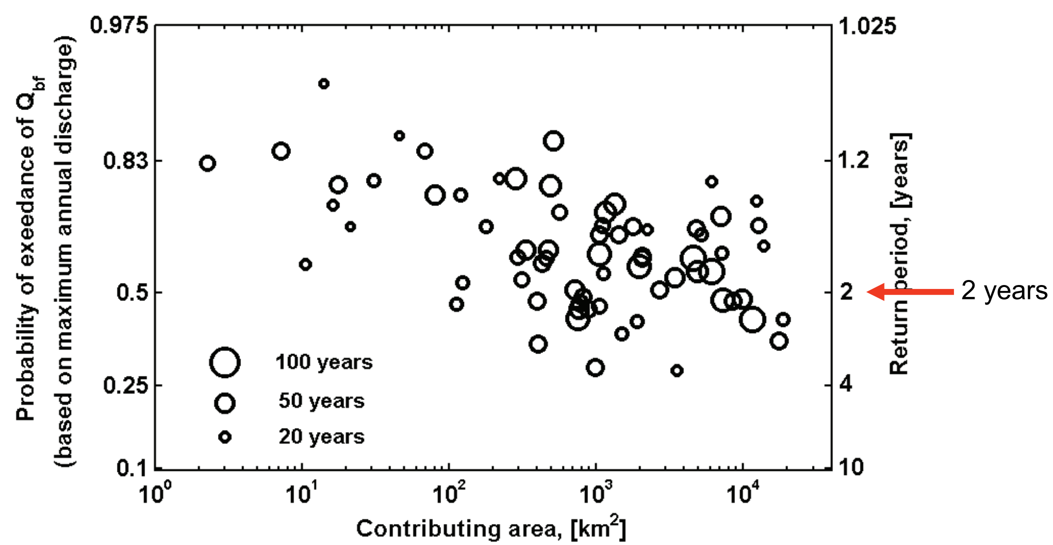


Frequency of Bankfull Discharge

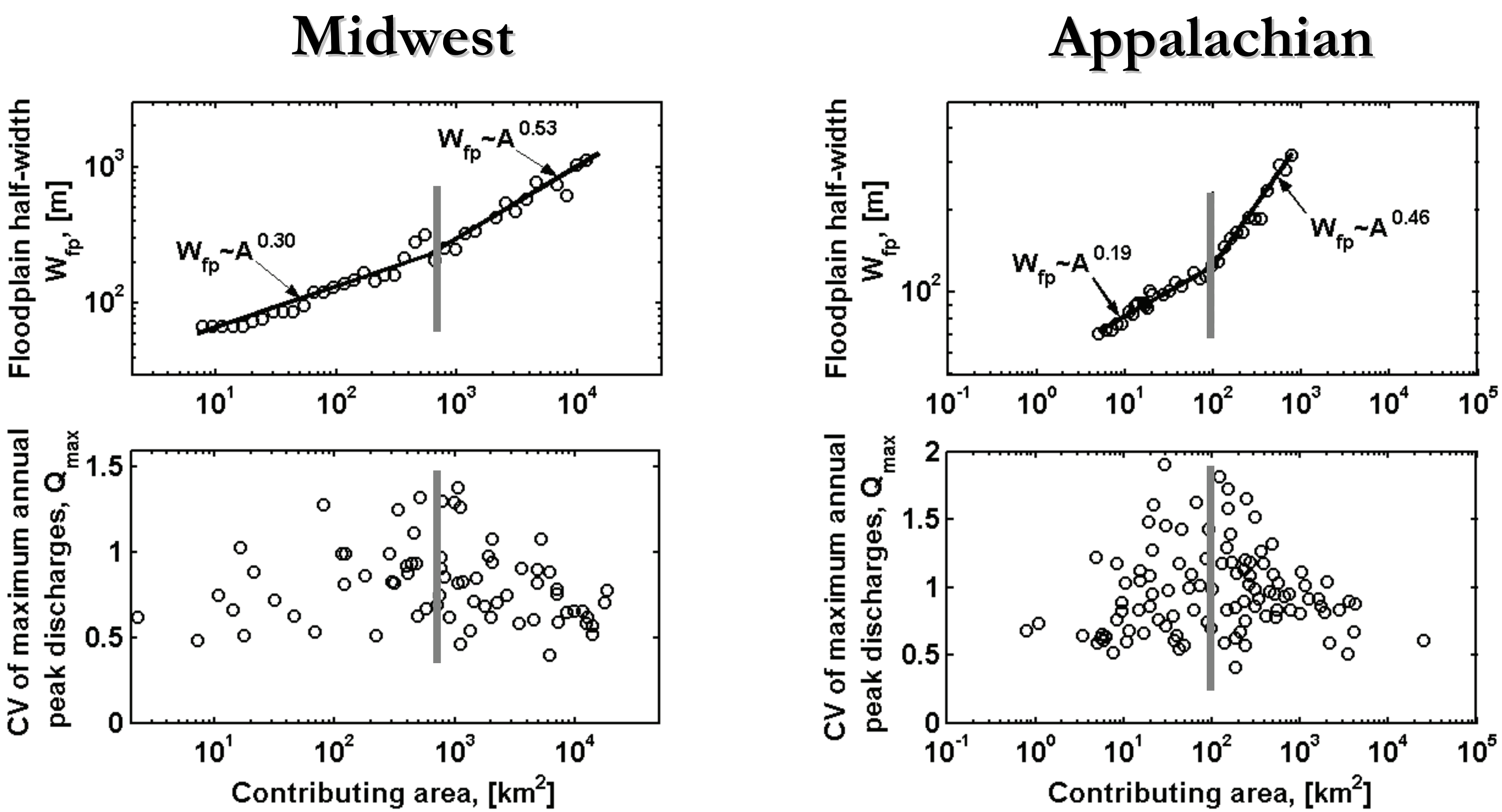
(1)From daily/hourly time-series



(2) From maximum annual discharges



The scaling break in floods is controlled by the channel/floodplain geometry and interactions



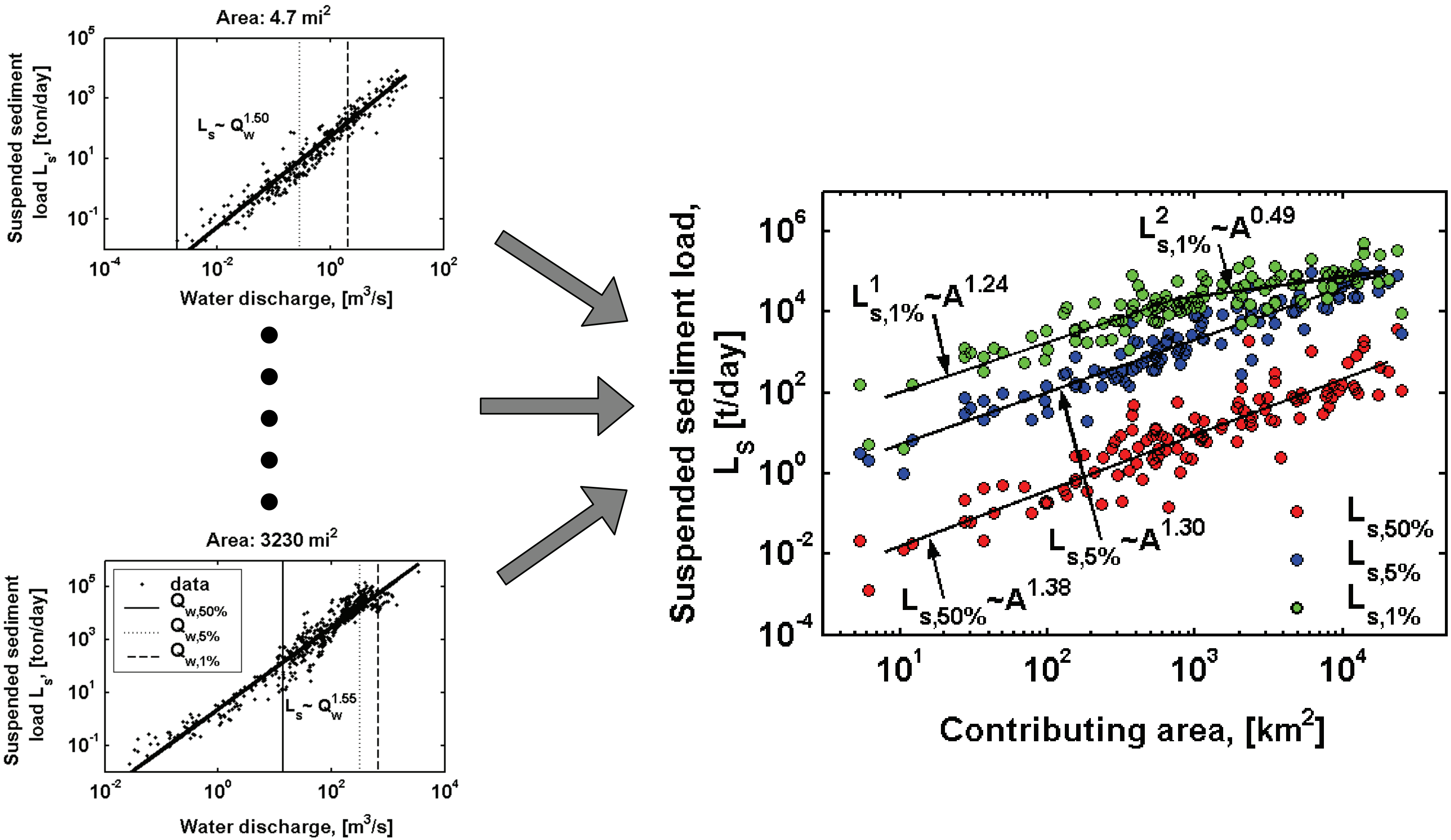
Implications for Flood Prediction

- Hydrologic transitions are imprinted in geomorphologic transitions

- High resolution DEMs offer potential to explicitly extract channel-floodplain morphometry which can:

  - (a) *guide* hydrologic predictions over a range of scales, and
  - (b) *guide* spatially-distributed modeling over large domains

Implications for Suspended Sediment Loads



2. Objective Extraction of Hillslope-to-Valley Transition from High Resolution DEMs (LIDAR)?

-Computation of local slope and curvature

$$h(x,y)$$

<u>Gradient magnitude</u>: <u>direction</u>: <u>curvature:</u>

$$\left|\nabla h(x,y)\right| = \sqrt{\left(\frac{\partial h}{\partial x}\right)^2 + \left(\frac{\partial h}{\partial y}\right)^2} \qquad \theta(x,y) = \tan^{-1}\left(\frac{\frac{\partial h}{\partial y}}{\frac{\partial h}{\partial x}}\right) \qquad \nabla^2 h(x,y) = \frac{\partial^2 h(x,y)}{\partial x^2} + \frac{\partial^2 h(x,y)}{\partial y^2}$$

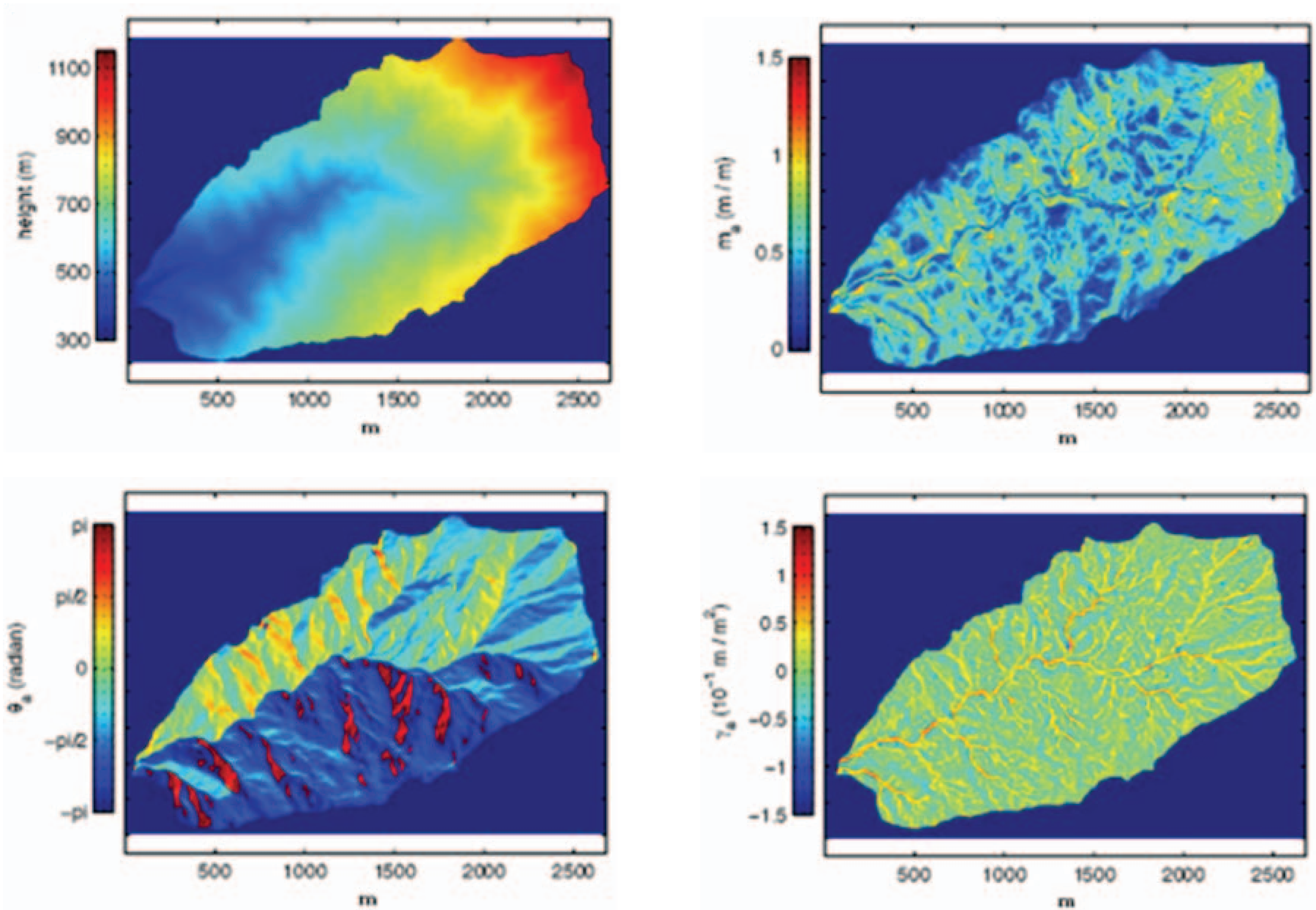
-Typically, smooth topography and then take ∇h, $\nabla^2 h$ or smooth local ∇h, $\nabla^2 h$ by spatial averaging.

-Propose a wavelet-based formalism (**compute attributes at a range of scales**):

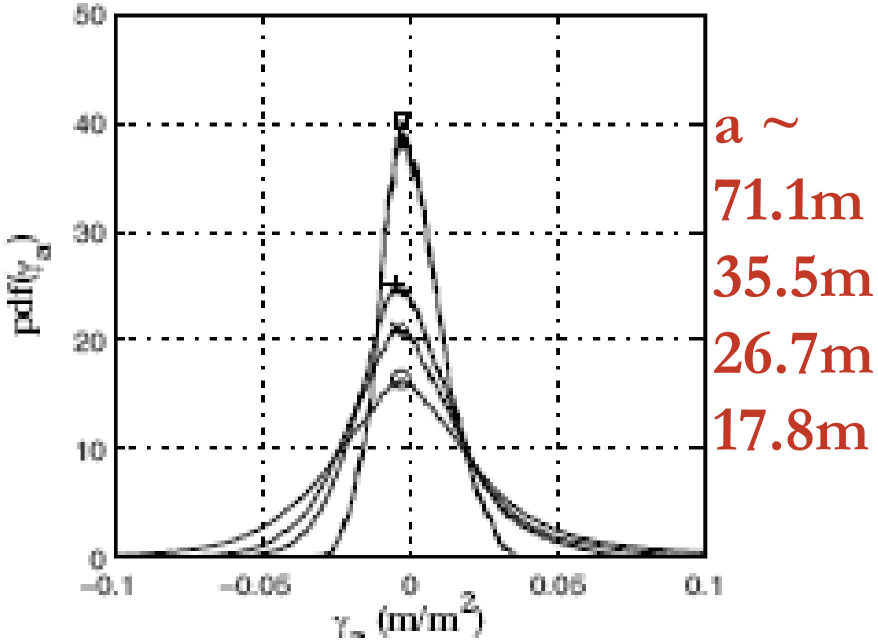
$$\frac{\partial}{\partial x}(h * g) \quad = \quad \frac{\partial h}{\partial x} * g \quad = \quad \mathrm{h} * \frac{\partial g}{\partial x}$$

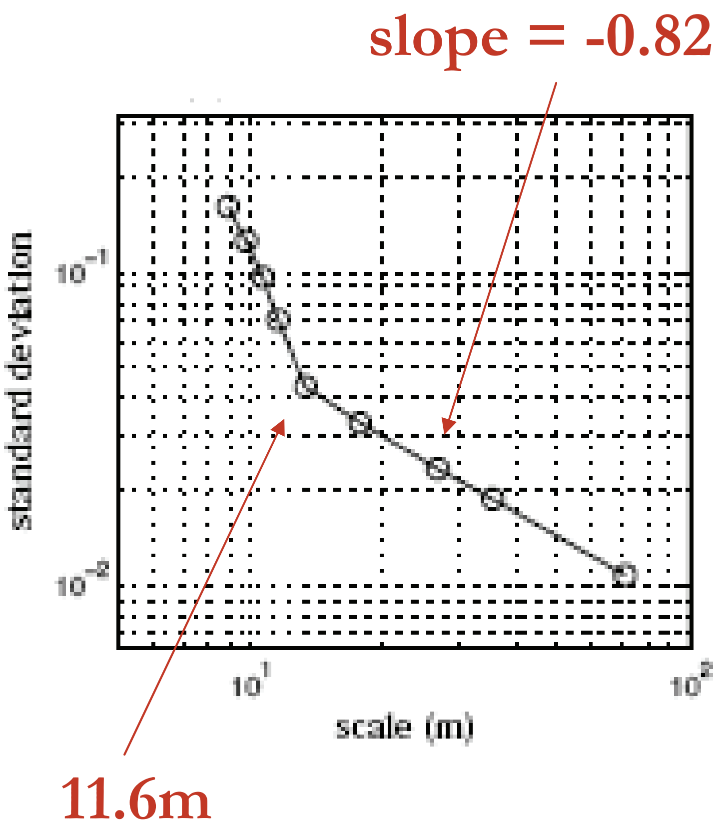
Ref: Lashermes, Foufoula-Georgiou, Dietrich (2006)

Angelo Coast Reserve

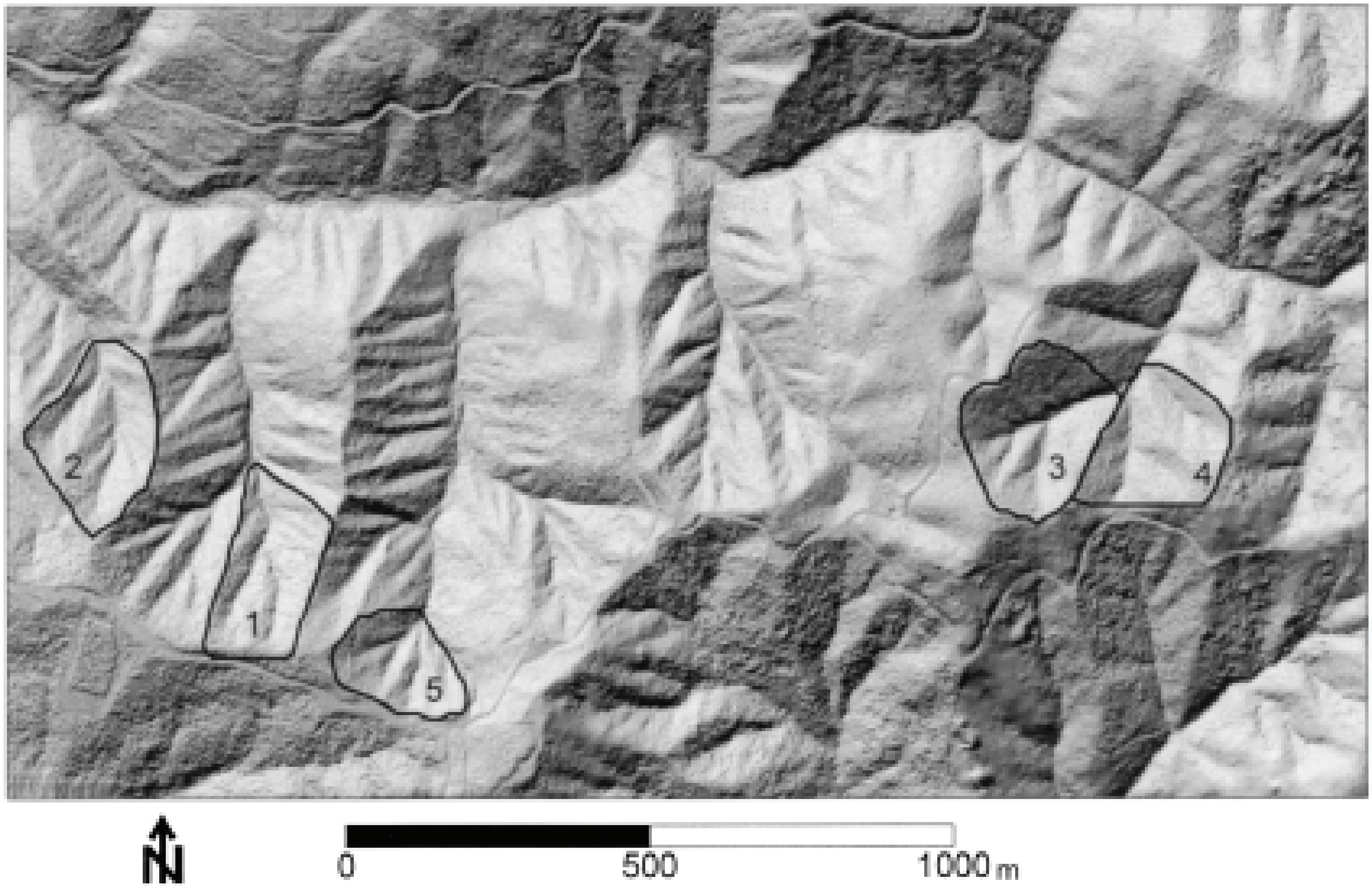


Minimum Scale for Curvature Interpretation?

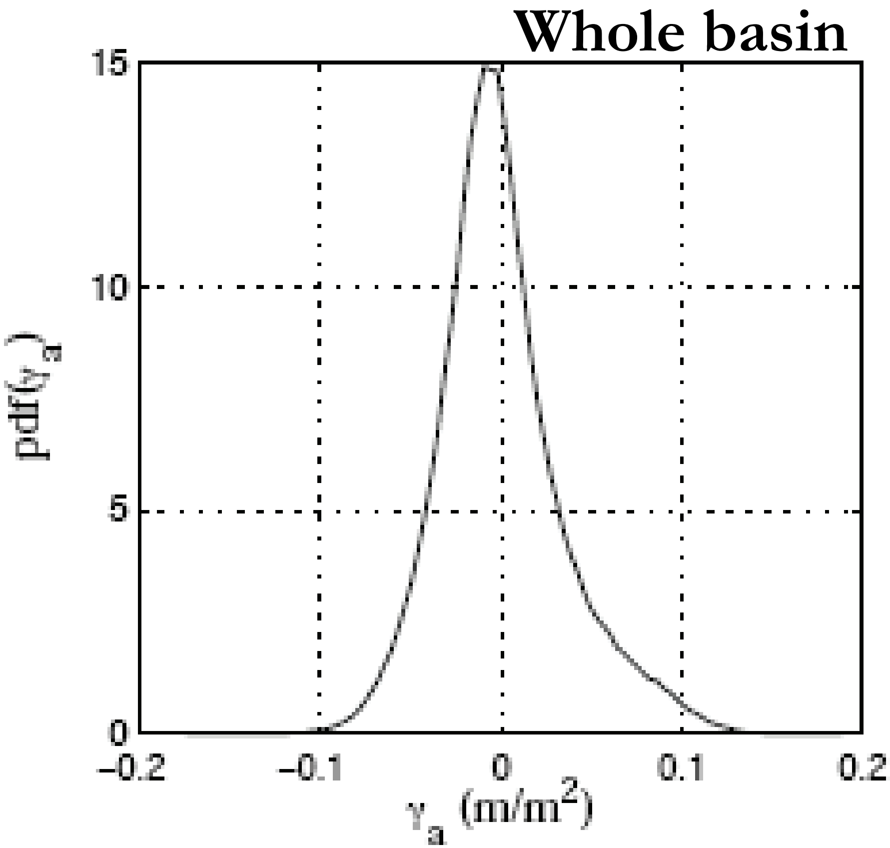


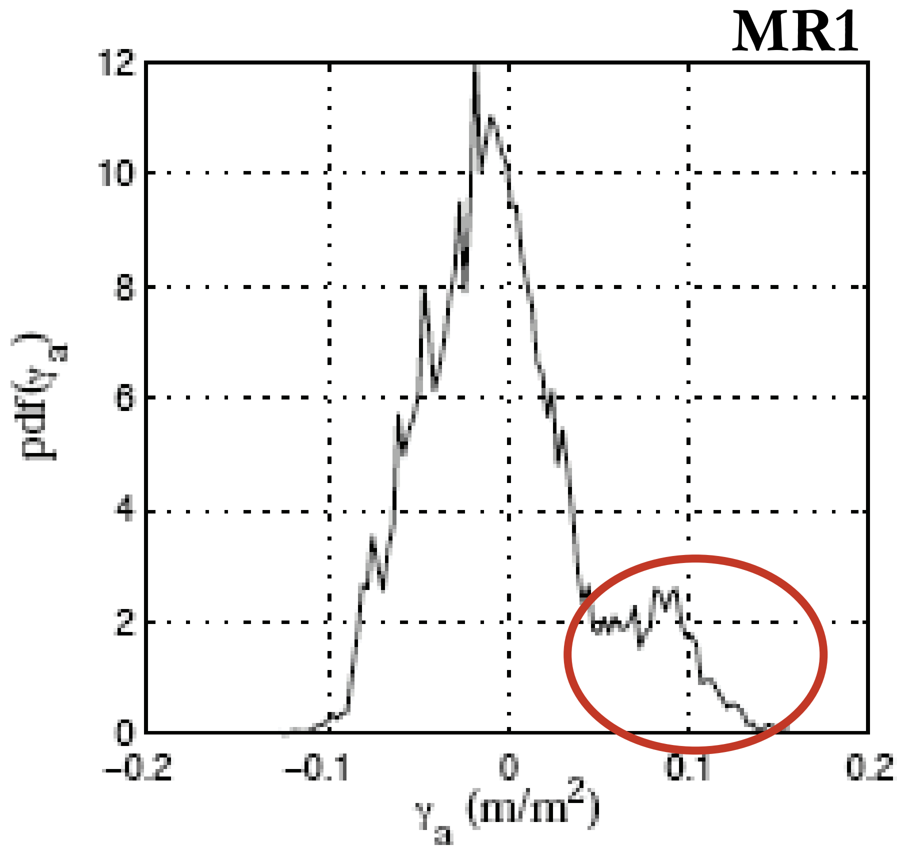


Oregon Coast Range

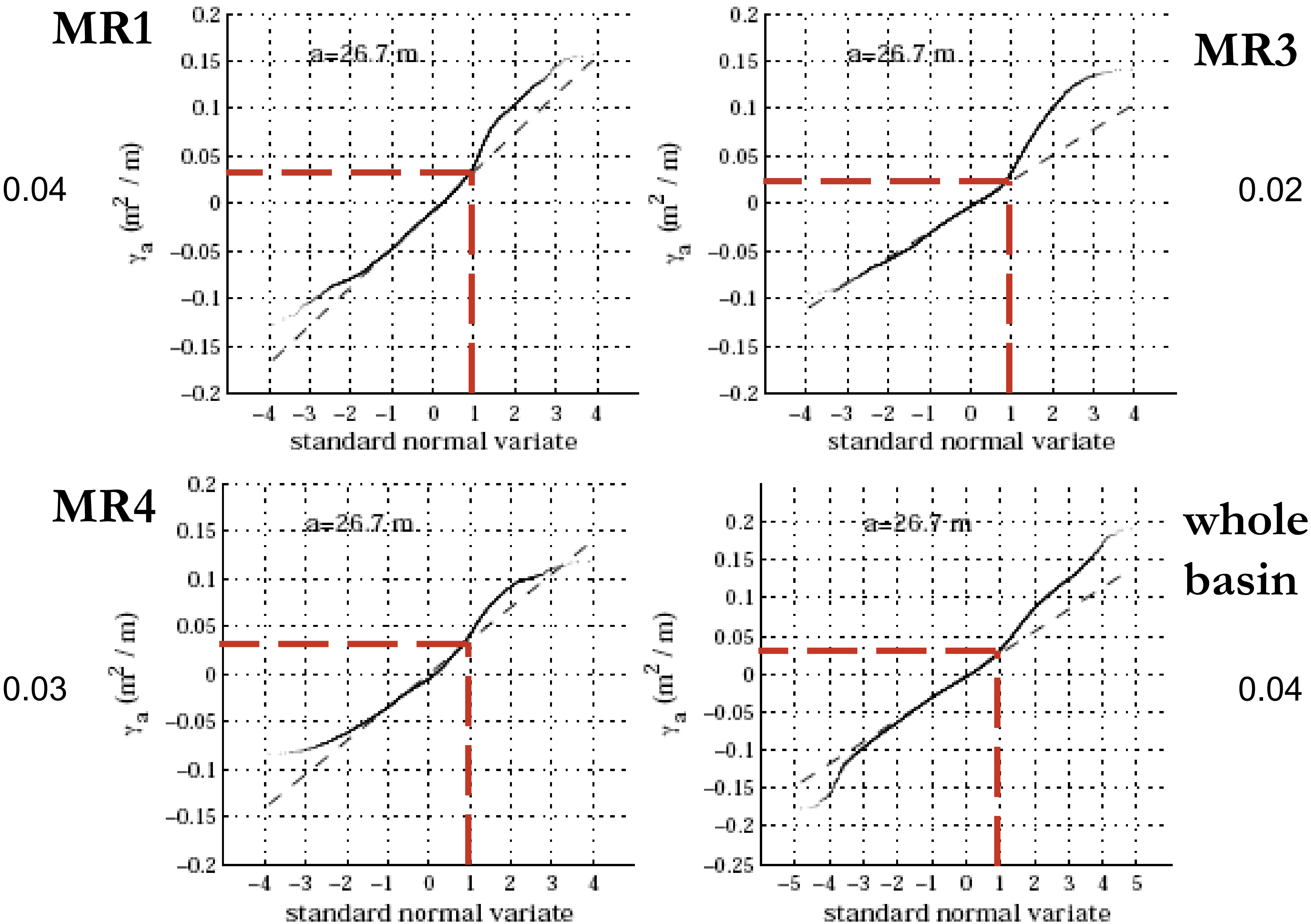


Pdf of γa for OCR (a=26.7m)



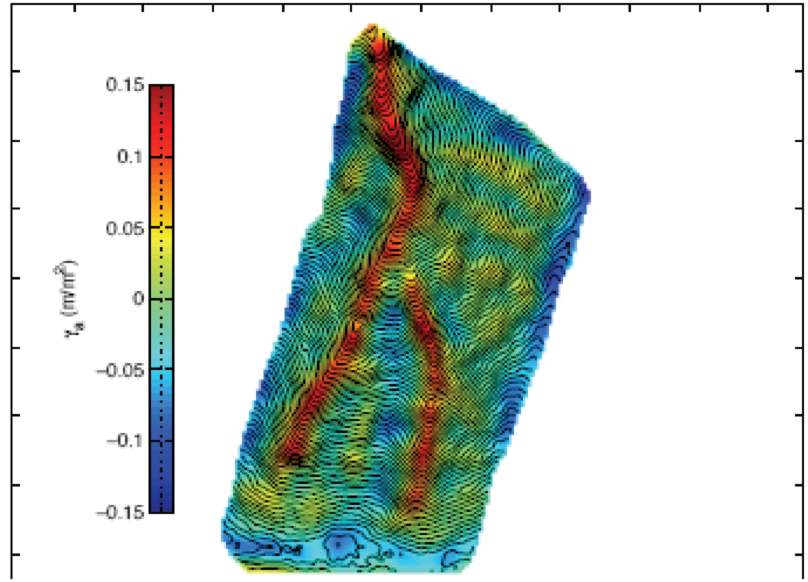


OCR: Q-q plots for γa

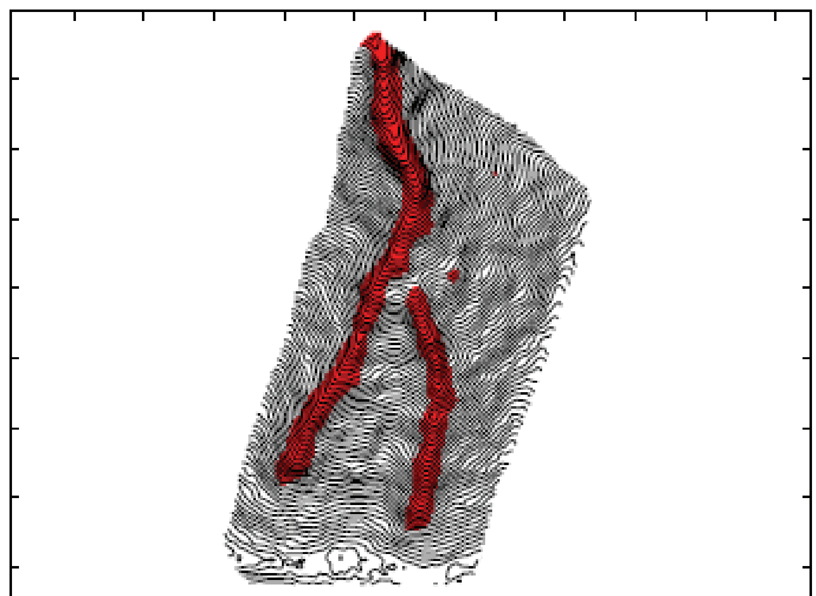


MR1 Subbasin

$$\gamma_a$$



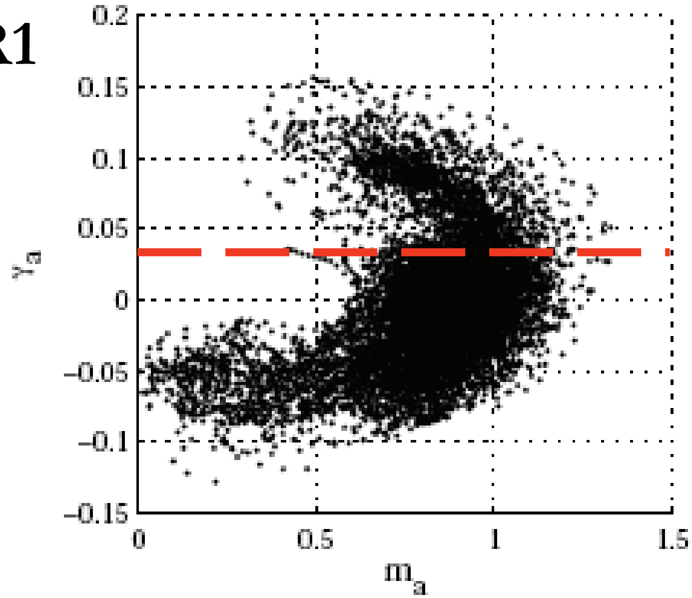
$$\gamma_a \geq \gamma_{a,th}$$



Curvature vs. Gradient for OCR

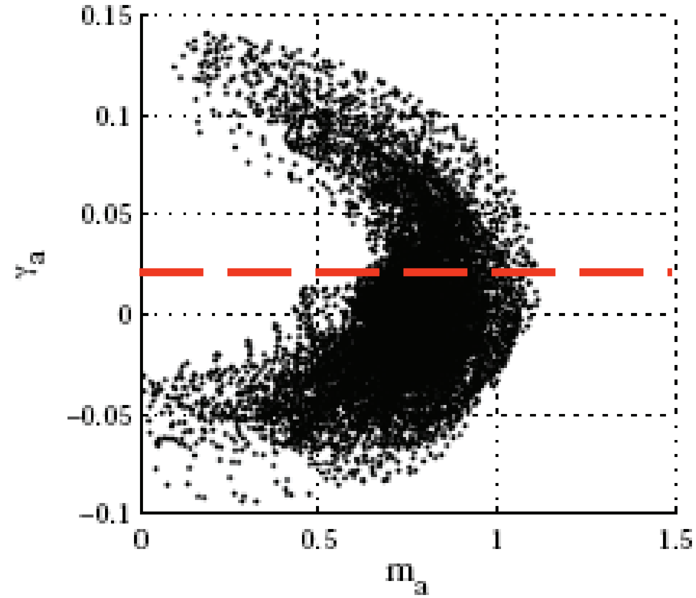
MR1

0.04



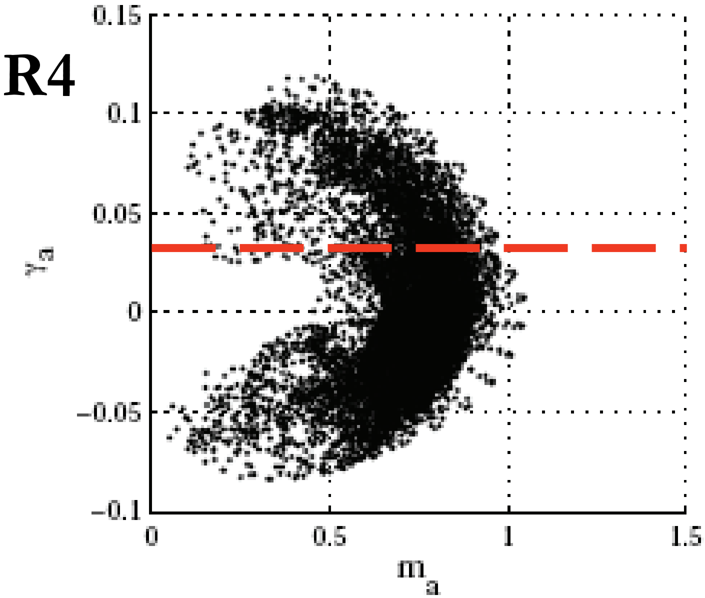
MR3

0.02



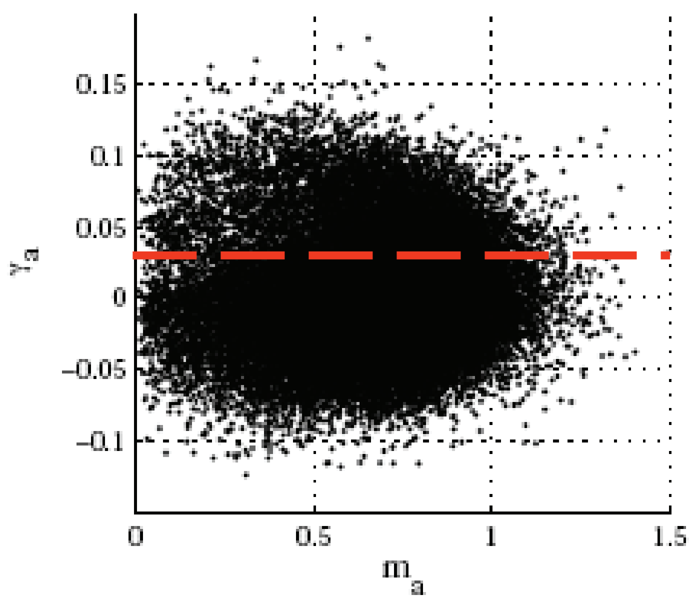
MR4

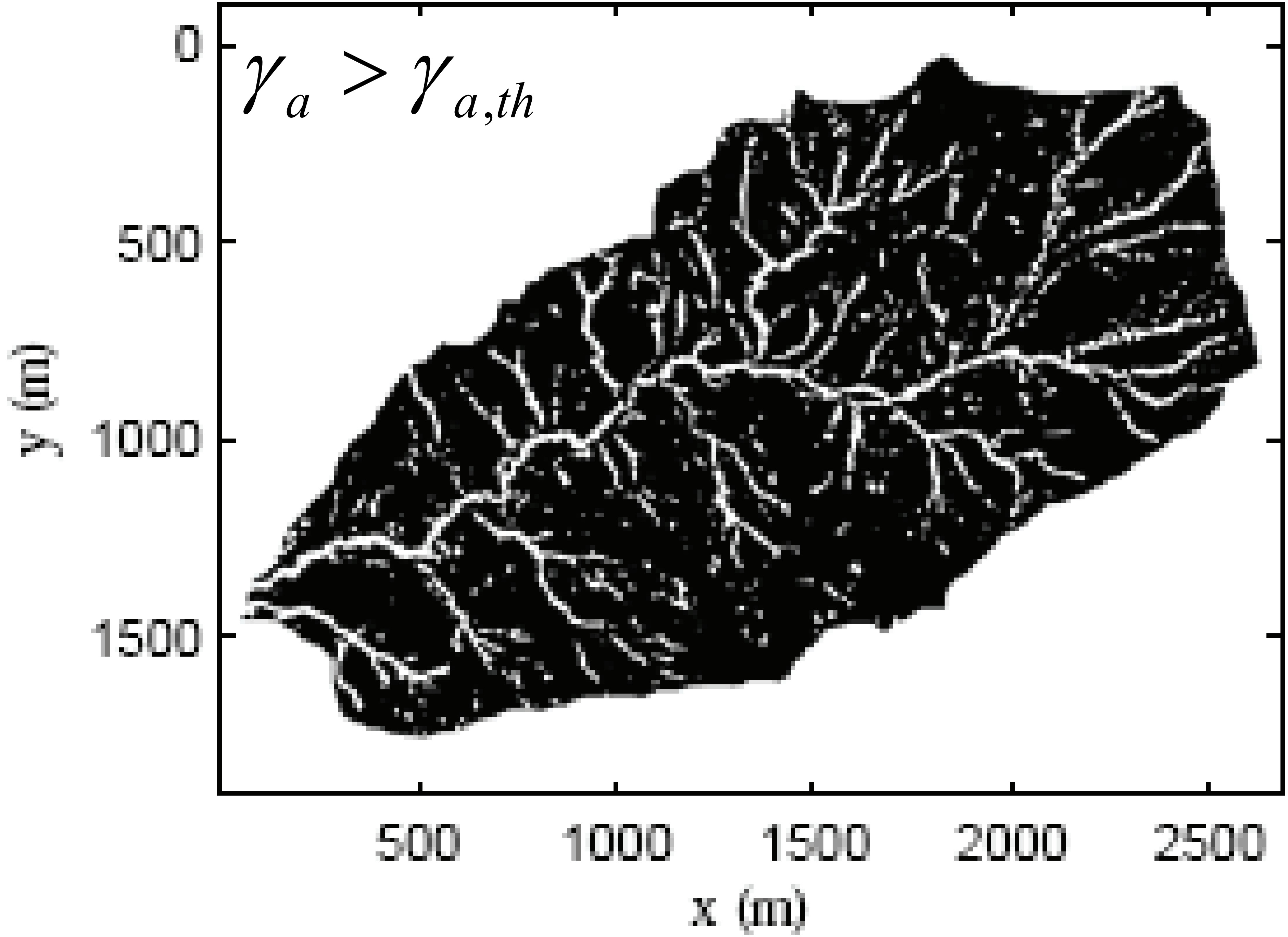
0.03



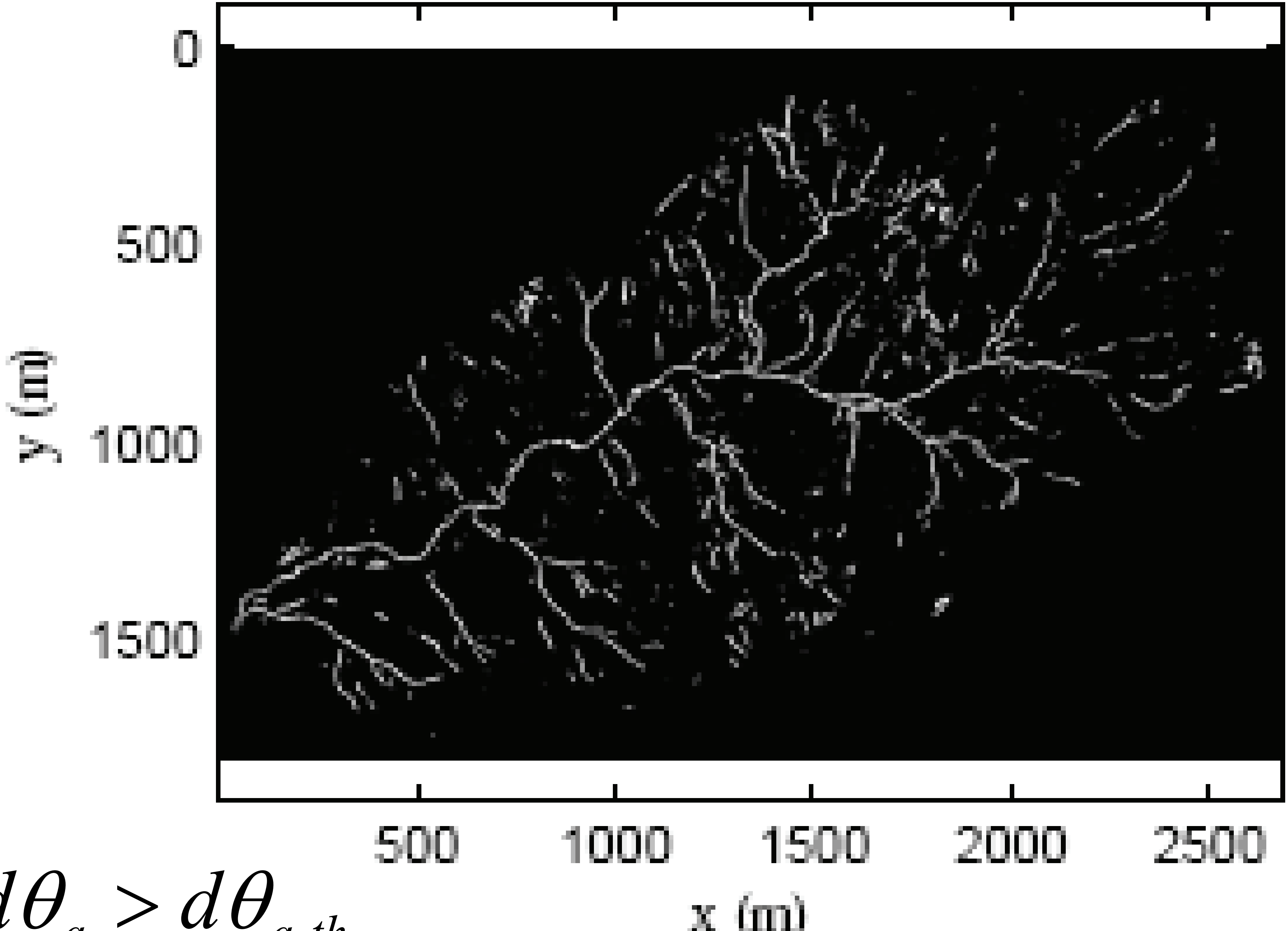
whole basin

0.04

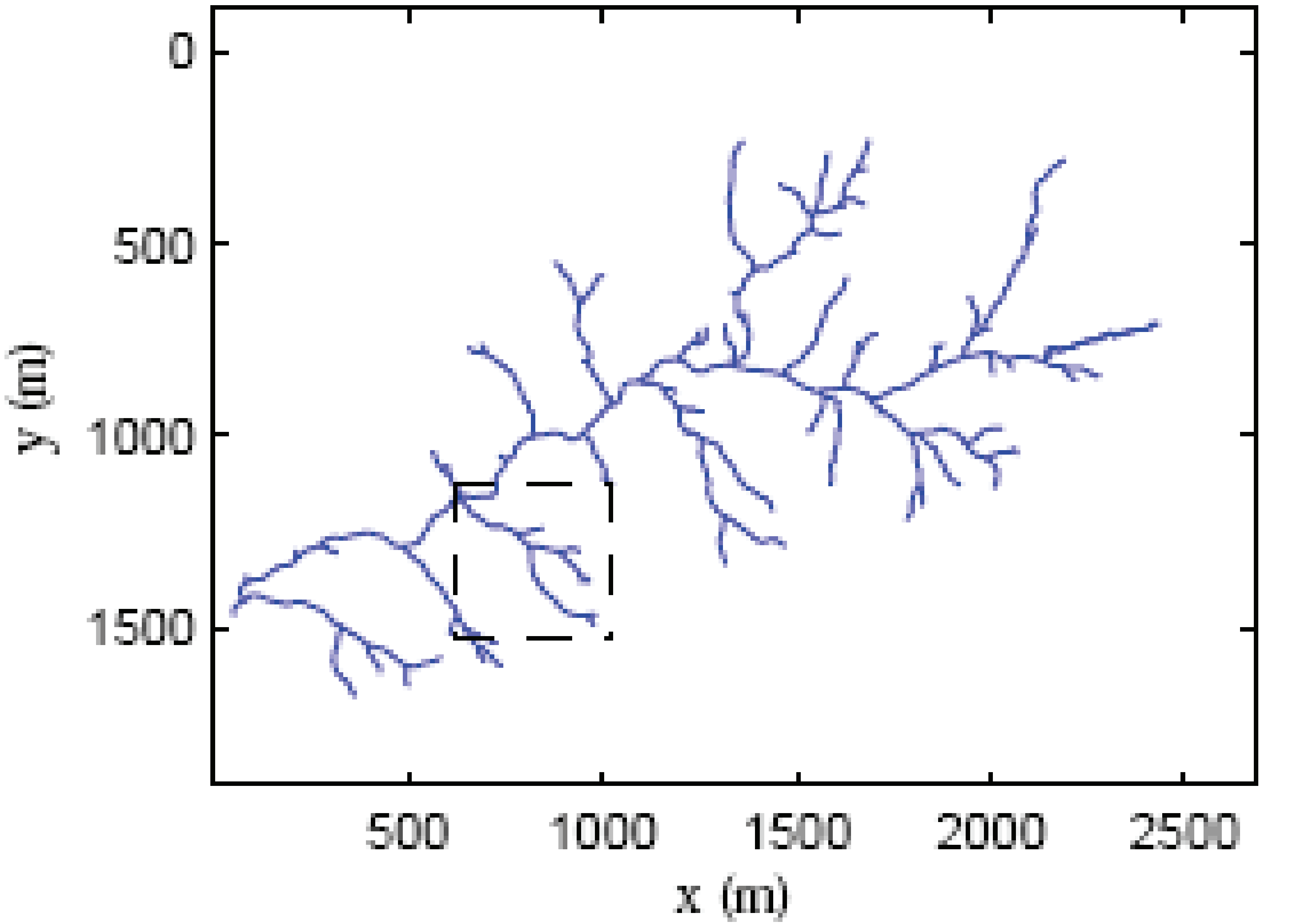




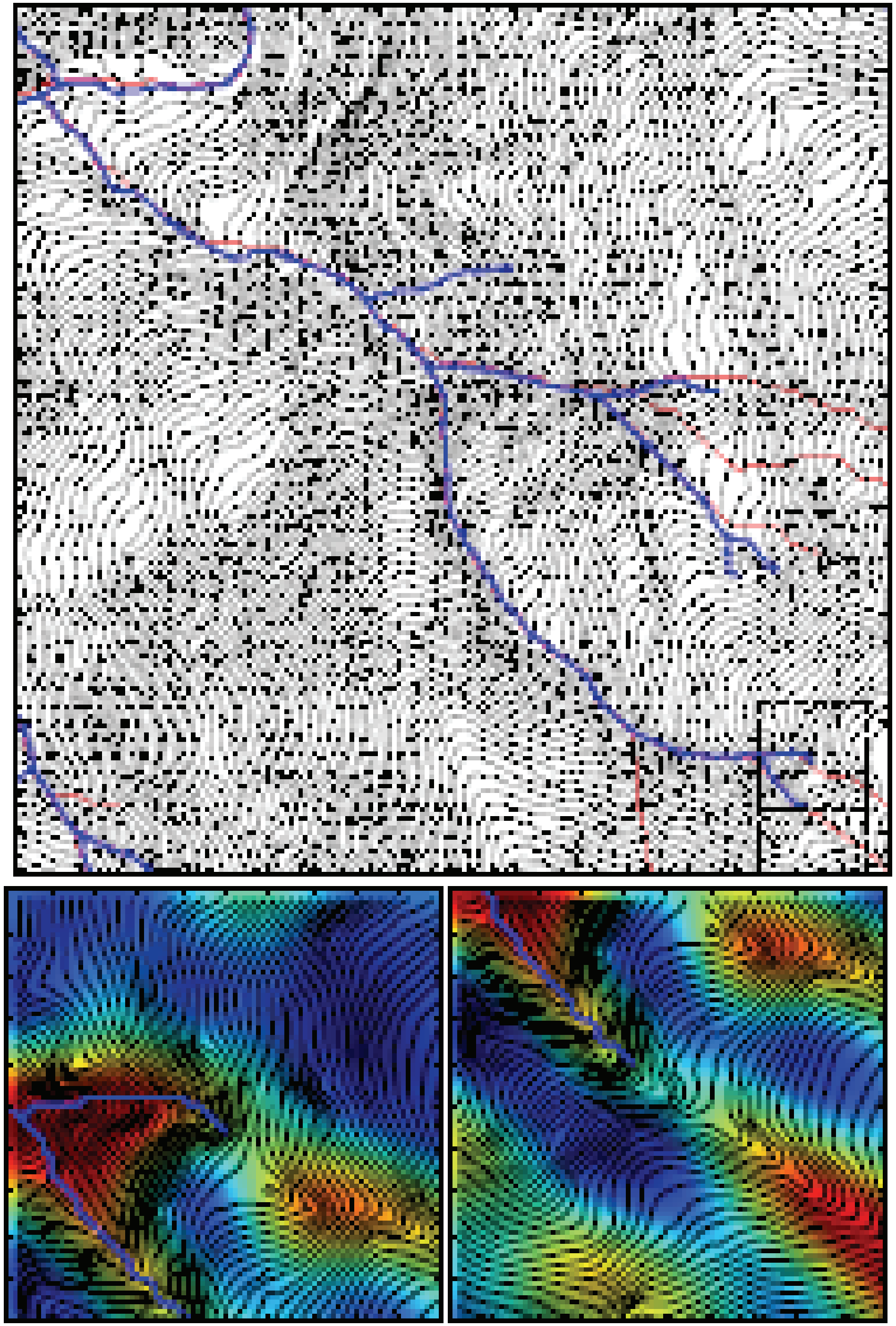
$\gamma_a > \gamma_{a,th}$
0
500
1000
1500
y (m)
500
1000
1500
2000
2500
x (m)



$$d\theta_a > d\theta_{a,th}$$



0
500
1000
1500
y (m)
500
1000
1500
2000
2500
x (m)

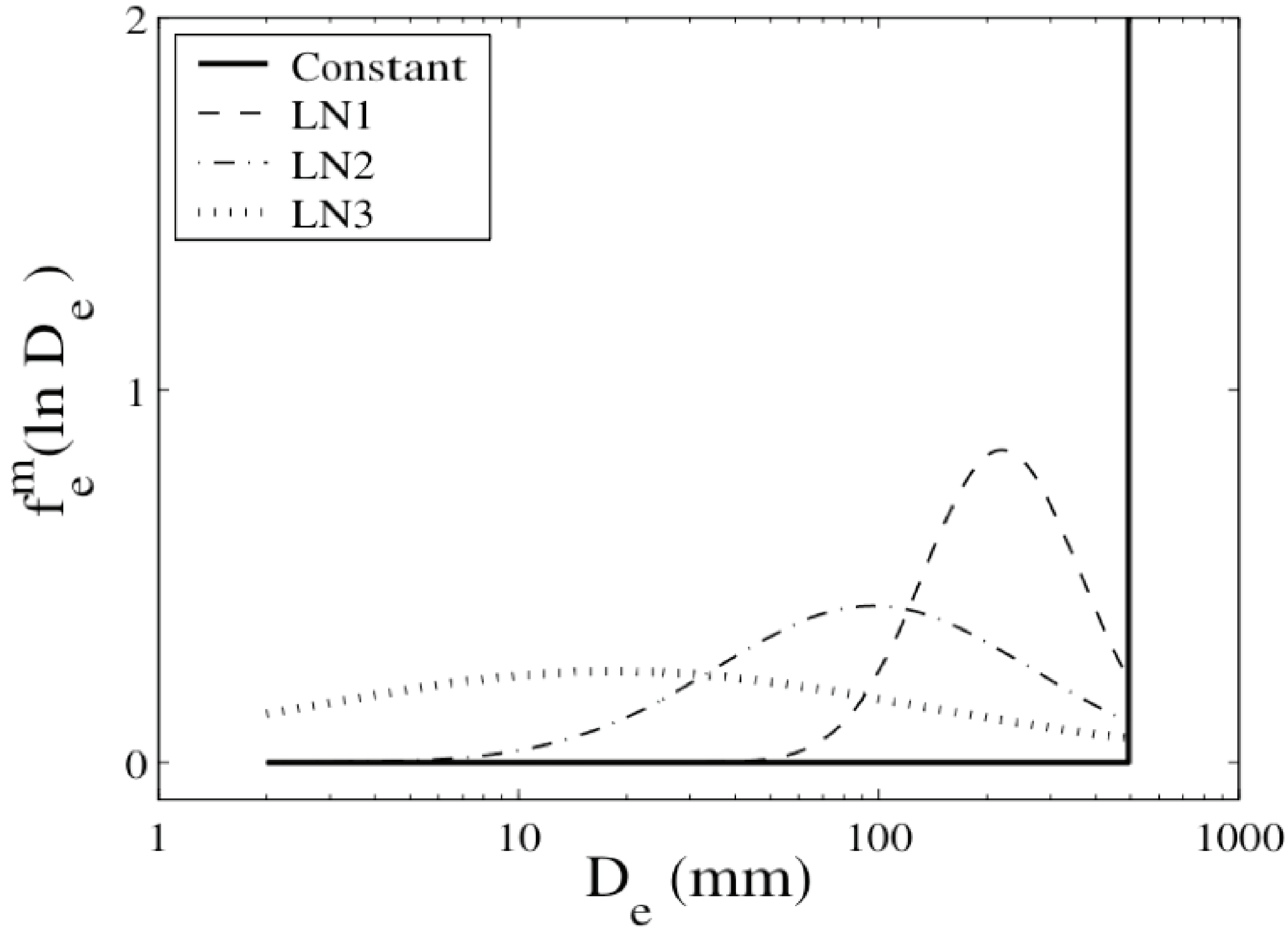


3. Bedload size distributions:
Importance of hillslope sediment production

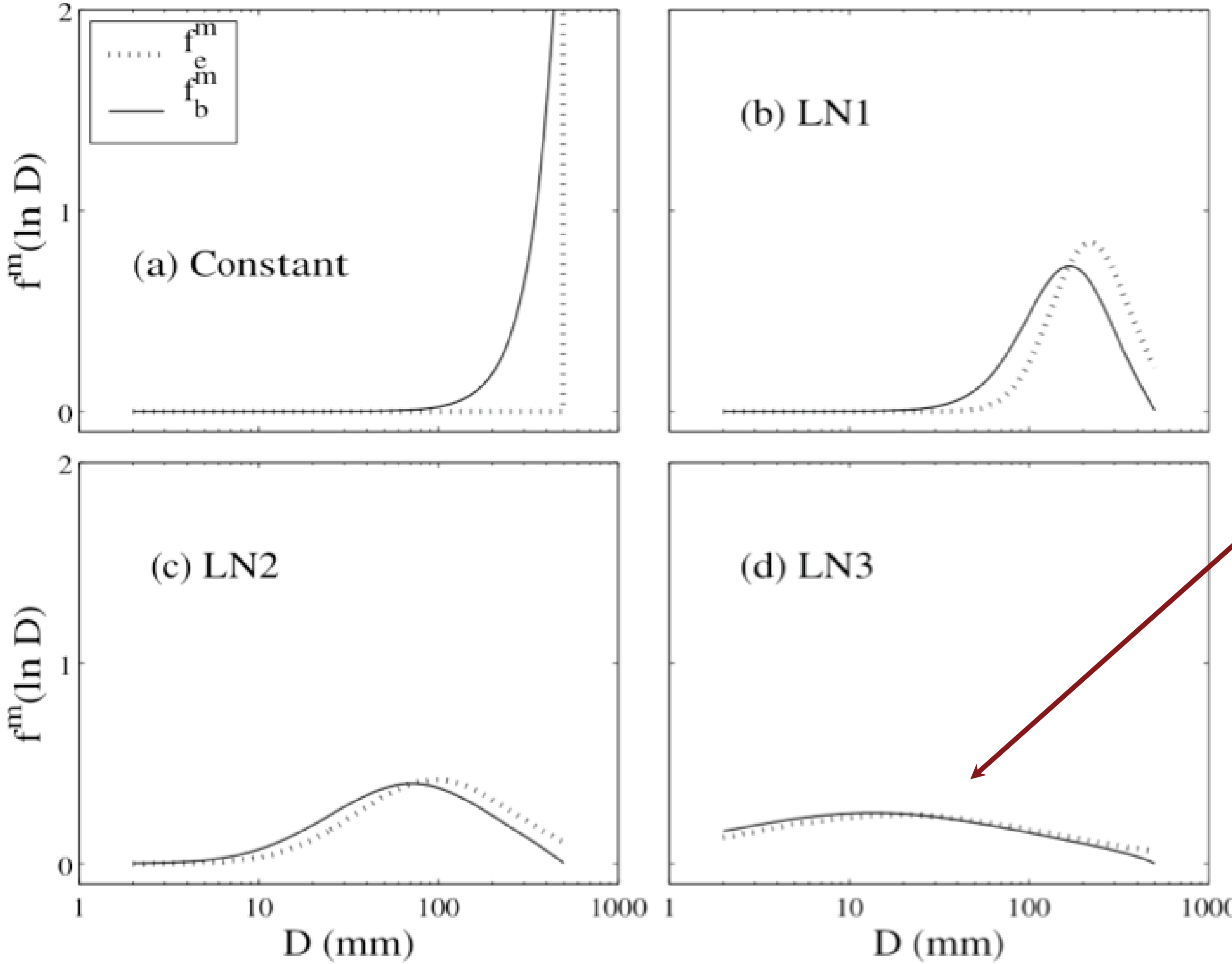
Do gravel bed size distributions record channel network structure?

Ref: Sklar L. S., W. E. Dietrich, E. Foufoula-Georgiou, B. Lashermes, D. Bellugi, Do gravel bed river size distributions record channel network structure?, *Water Resources Research*, 42, W06D18, doi:10.1029/2006WR005035, 2006.

Pdfs of entering sediment



Pdfs of entering sediment & steady-state bedload sediment



As variance of entering sediment distribution increases, bedload steady-state pdf approaches entering pdf

Conclusions and Implications

Bedload mass flux equilibrates with supply over length scale of 1/alpha, and then it becomes *independent* of drainage area

How do channel cross sections develop under flow which scales with area but bedload mass flux that is constant?

The bedload steady-state grain size distribution differs little from the hillslope supply distribution in the case of poorly sorted hillslope sediments

Large-scale variability in bed material is due primarily to spatial gradients in hillslope sediment production and transport characteristics

Need theory and data to predict the grain size distribution supplied to channels by hillslopes

4. River Corridor Geometry:
Can statistics reveal the underlying physics?

Ref: Gangodagomage, Bamer, Foufoula-Georgiou, et al.

4. River Corridor Geometry:

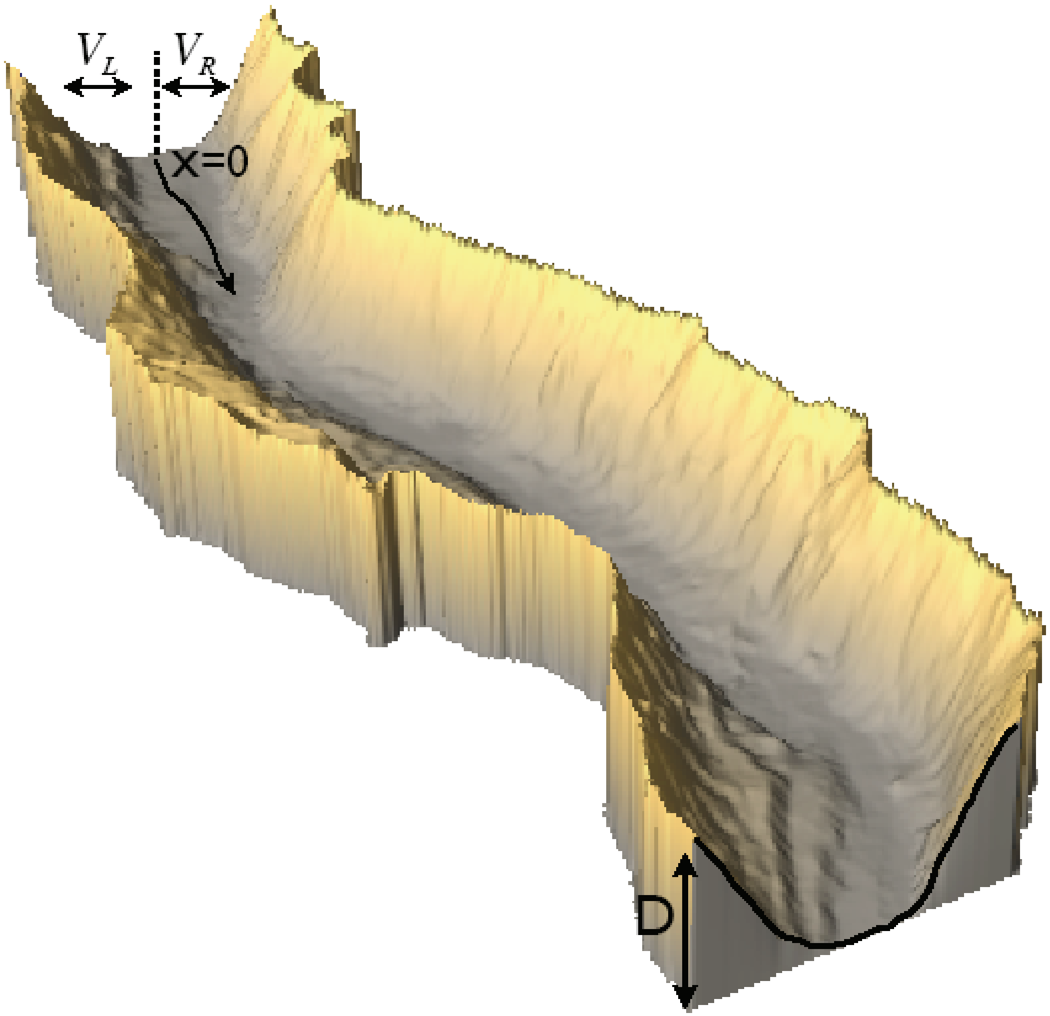
Can statistics reveal the underlying physics?

- Do differences in mechanistic laws governing valley-forming processes leave their signature on the statistical properties of valley geometry?

- Are statistically-distinct regimes the result of physically-distinct valley-forming processes?

Ref: Gangodagomage, Bamer, Foufoula-Georgiou, et al.

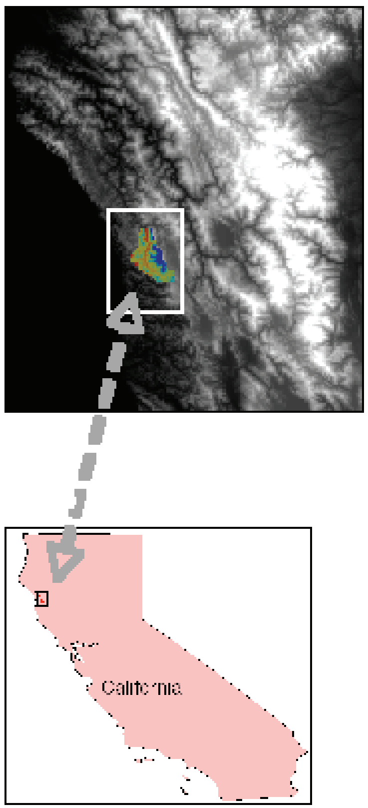
River Corridor Width Functions

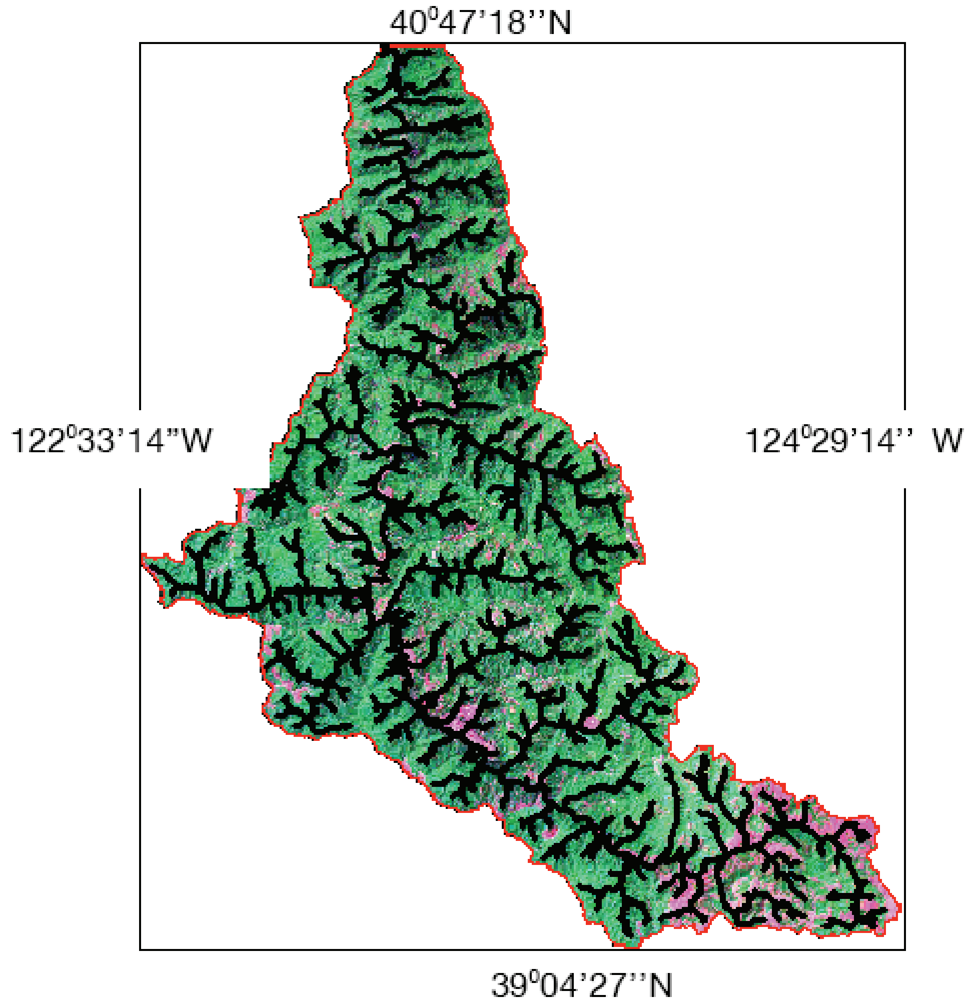


$$V_L\left(x;D\right)$$

$$V_R\left(x;D\right)$$

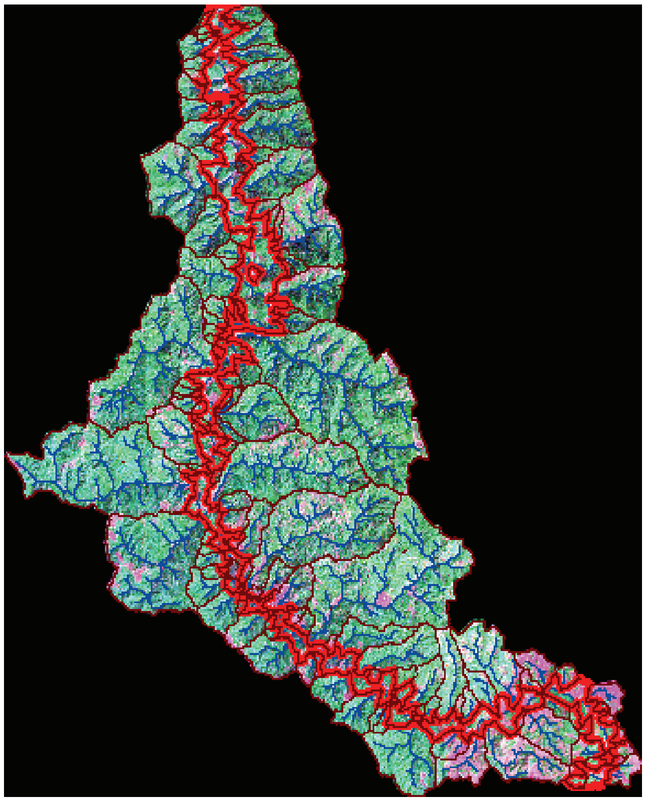
South Fork Eel River, CA

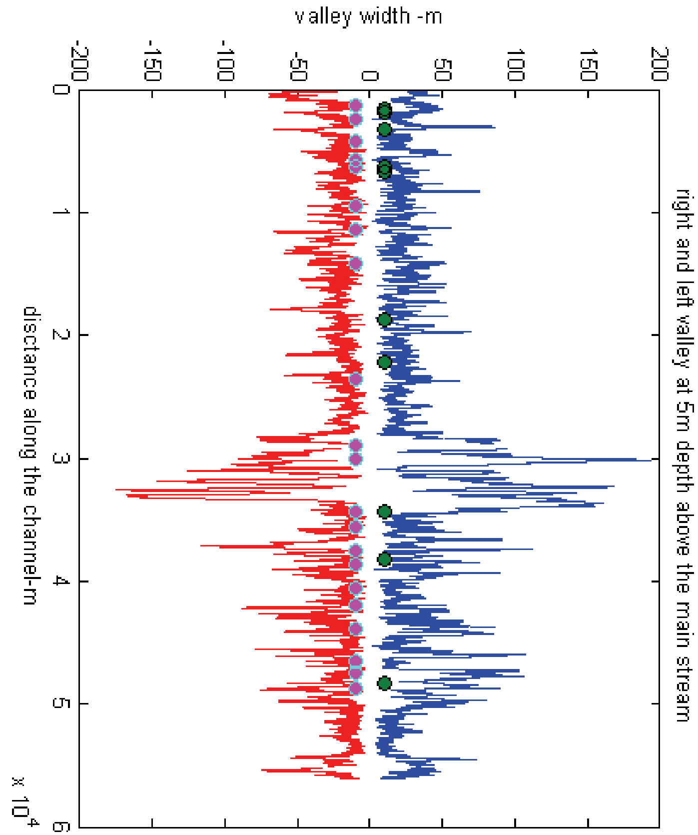




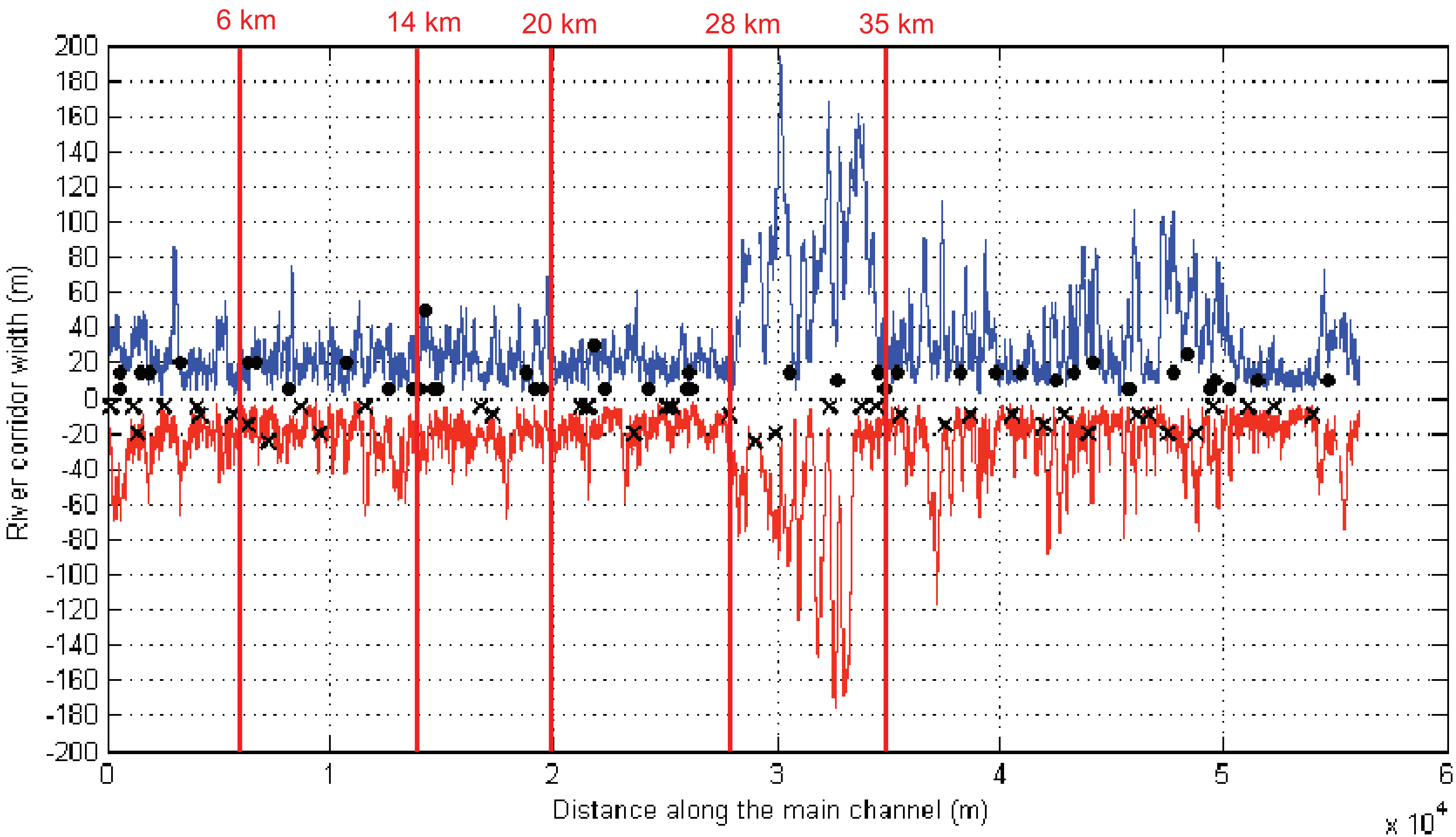
Area = 351 km^2

River Corridor Width Function (D=5m)



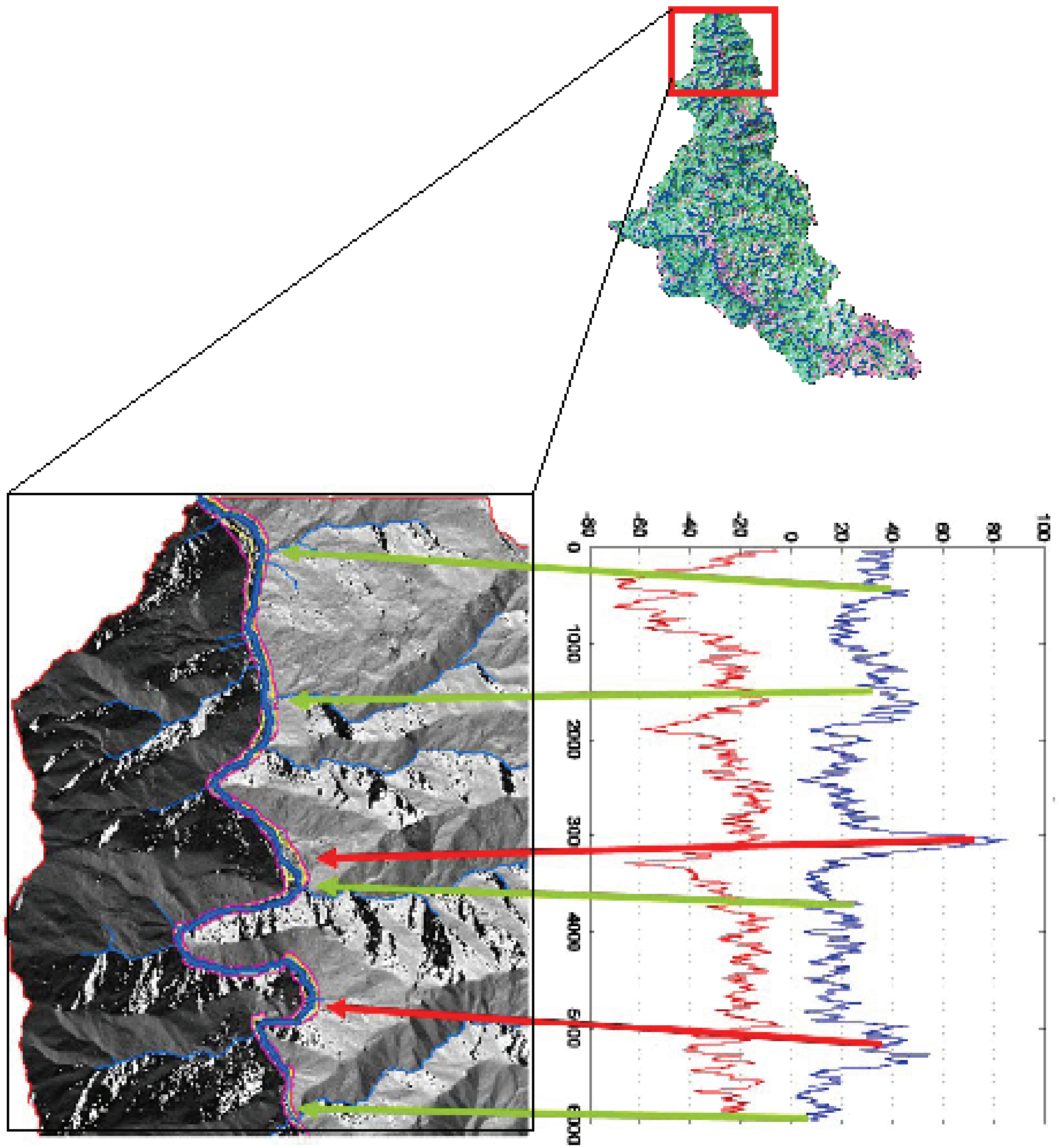


River Corridor Width Function: South Fork Eel River



89 tributaries: (1 km^2 – 150 km^2)

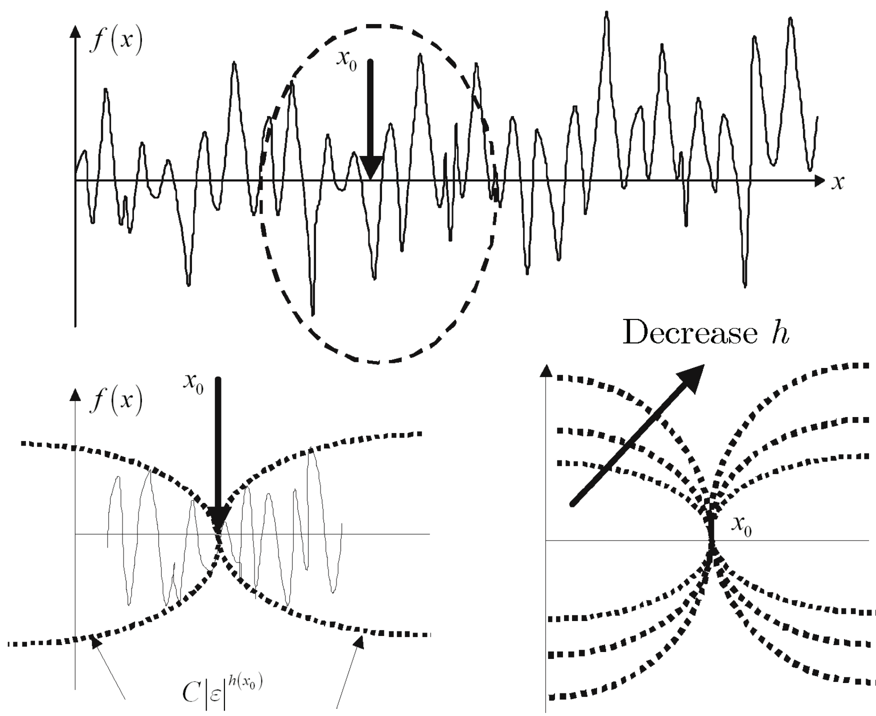
River Reach: 0-6 Km



MULTIFRACTAL FORMALISM

- Characterize a signal f(x) in terms of its local singularities

$$\left|f\left(x_0\right)-f\left(x_0+\varepsilon\right)\right|\leq C\cdot\left|\varepsilon\right|^{h\left(x_0\right)}$$

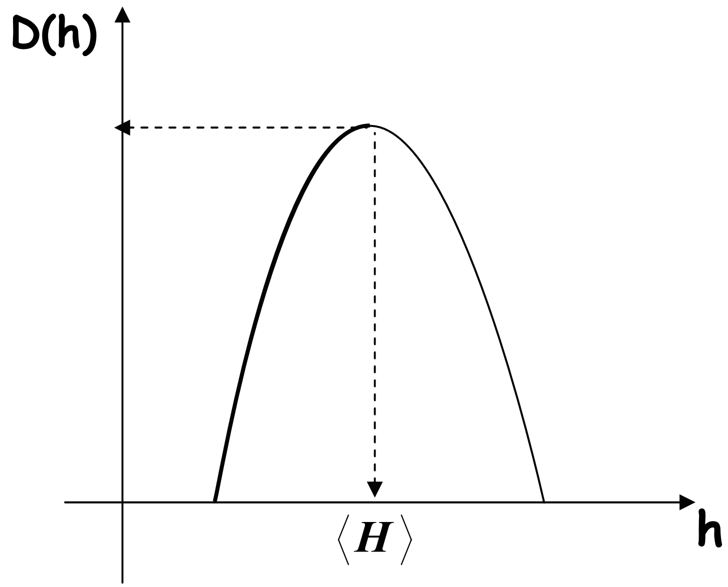


Ex: $h(x_0) = 0.3$ implies f(x) is very rough around x_0.

$h(x_0) = 0.7$ implies a “smoother” function around xo.

Multifractal Formalism

- Spectrum of singularities D(h)



- D(h) can be estimated from the statistical moments of the fluctuations.

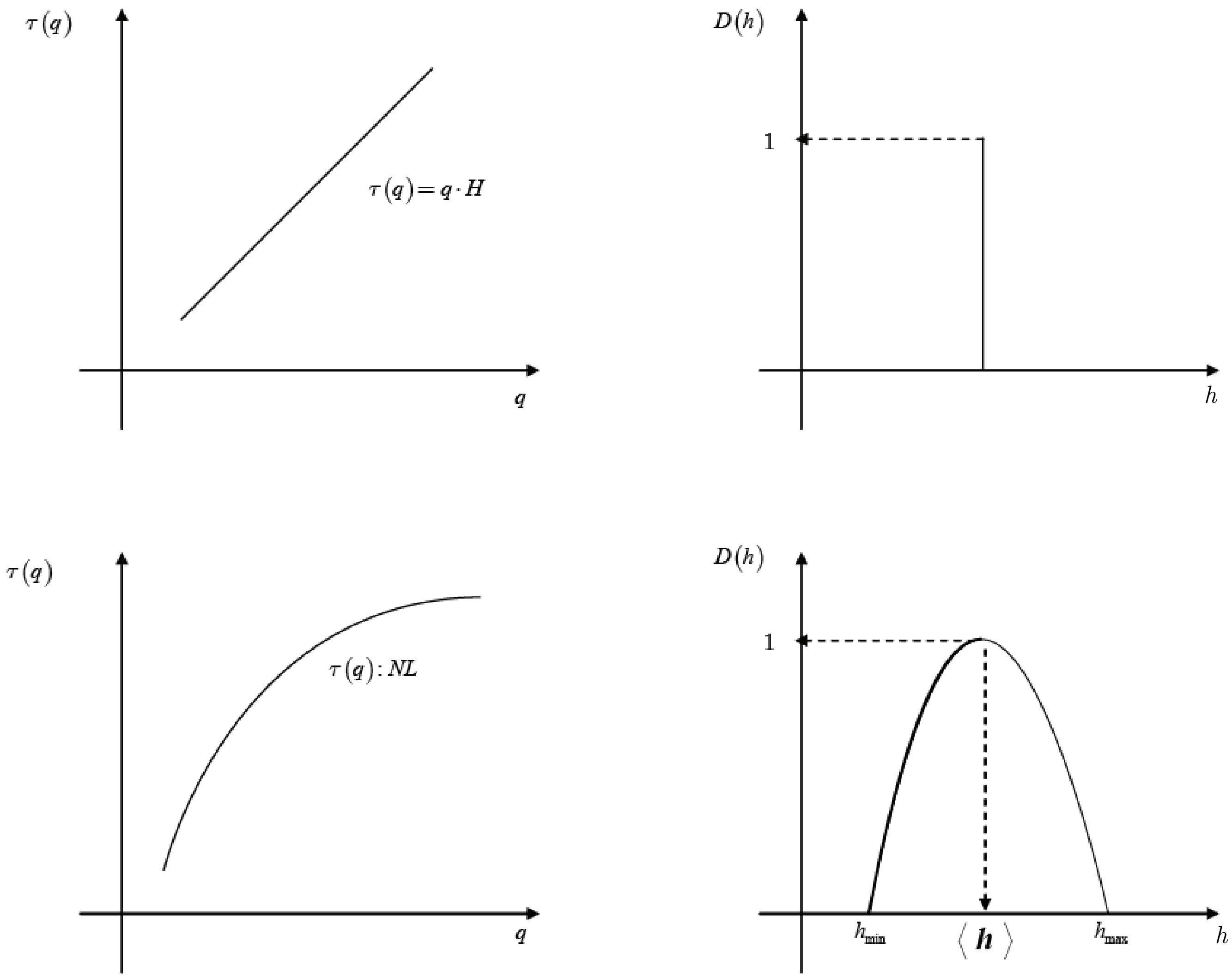
$$M(q,a) = \left\langle \left| f(x) - f(x+a) \right| \right\rangle^{q} \sim a^{\tau(q)}$$

$$D(h) = \min_{q}\left[qh - \tau(q) + 1 \right]$$

Legendre Transform

Multifractal Formalism

- Spectrum of scaling exponents $\tau(q)$



monofractal

multifractal

Implications of Multifractality

-Normalized moments depend on scale

e.g., $$CV(a)^2 = \frac{M_2(a) - M_1^2(a)}{M_1^2(a)} = \frac{M_2(a)}{M_1^2(a)} - 1 = a^{\tau(2)-2\tau(1)} - 1$$

mono-scaling: $$\tau(q) = q \cdot H \rightarrow CV(a) = \text{ constant}$$

multi-scaling: $$\tau(\mathrm{q}) \neq q \cdot H \rightarrow CV(a) \text{ depends on } a$$

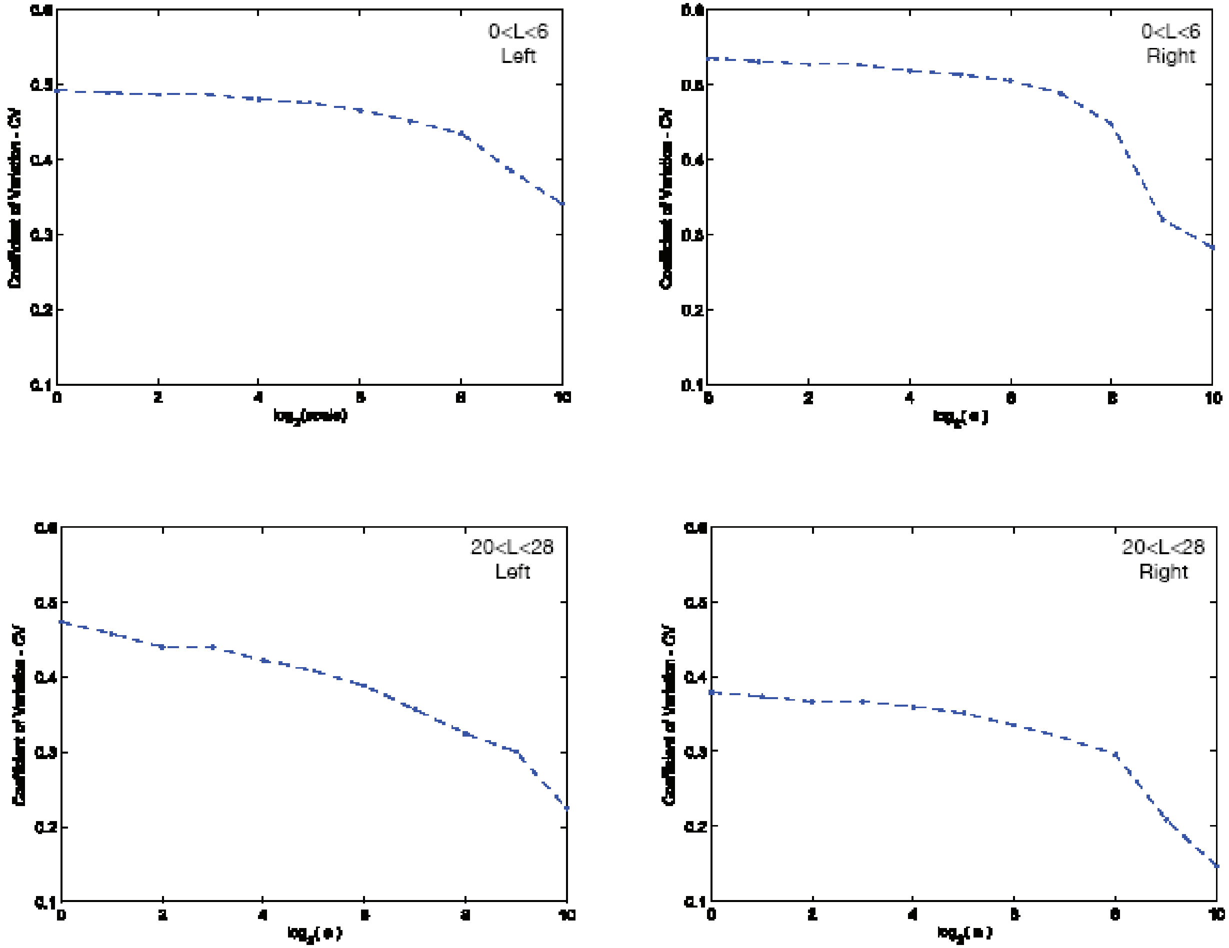
-Statistical moments of fluctuations increase faster as scale decreases (at very small scales, pdfs have heavy tails)

-Chance of getting very high fluctuations locally, although sparsely.

-More than one degree of singularities is present.

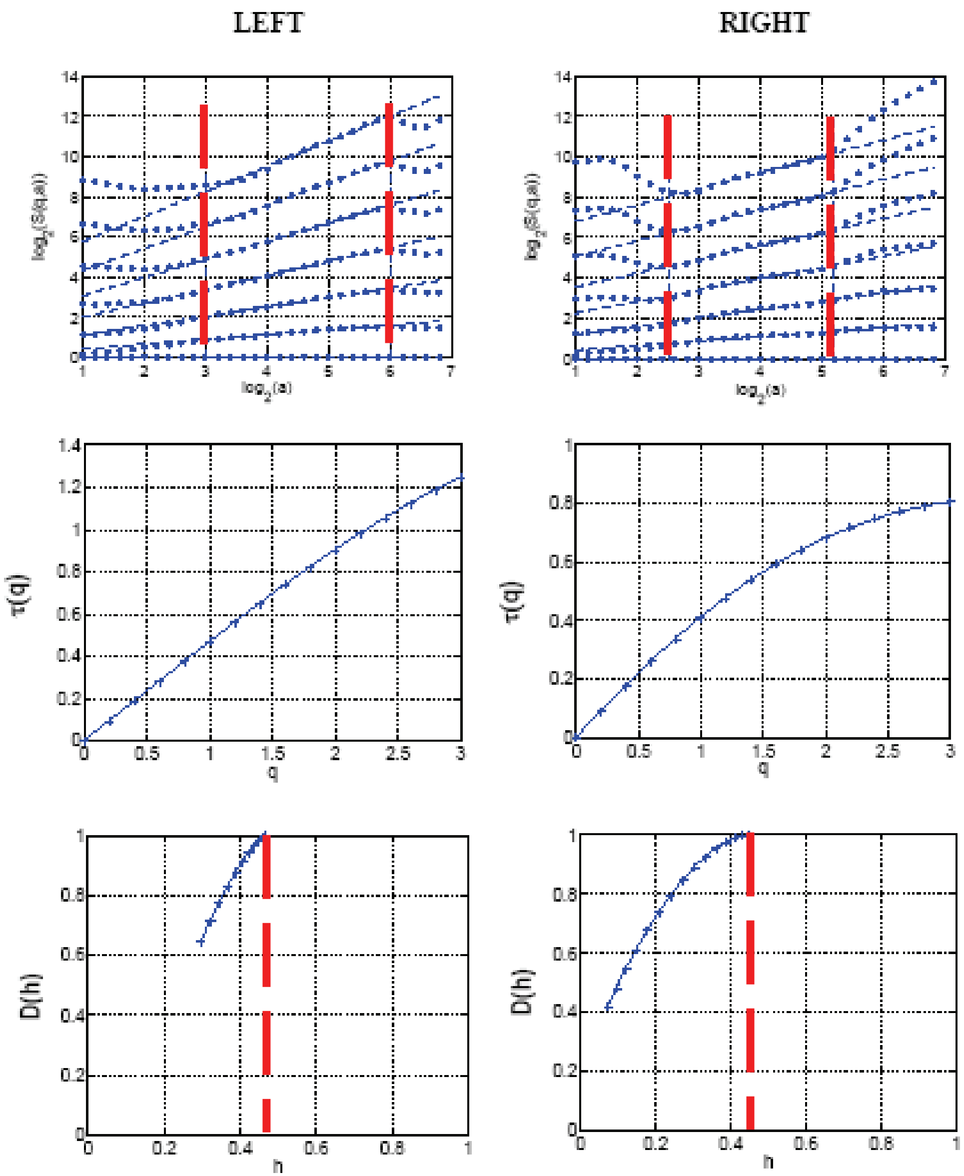
-These singularities are spread throughout the signal intermittently

CV of River Corridor Widths



Suggests multifractality

River Reach: 0-6 km

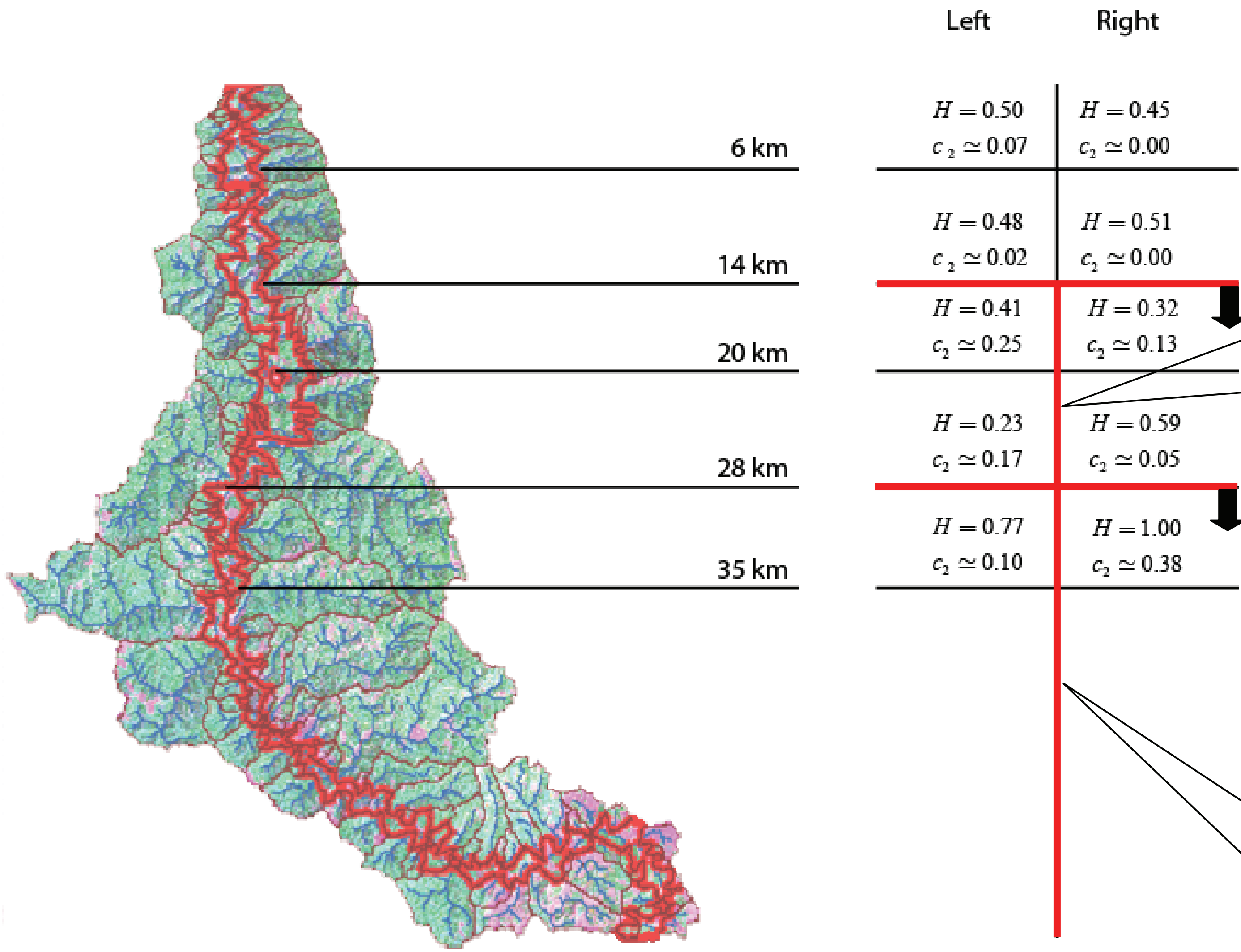


Summary of Results

distance from outlet (km)	along-stream slope (deg)	side of the corridor (Left/Right)	spectral slope	scaling range (m)	scaling range (Octaves)	Hölder exponent <H>	(h_{min}, h_{max})	c_1	c_2
$0 < x < 6$	0.40	Right	1.27	5.0 – 36.8	2.5 – 5.2	0.45	(–0.1, 1.18)	0.45	0.07
		Left	1.36	9.2 – 64	3.2 – 6.0	0.47	(0.02, 1.02)	0.50	$\simeq$ 0.0
$6 < x < 14$	0.47	Right	1.63	9.2 – 56	3.2 – 5.8	0.51	(0, 1.30)	0.51	$\simeq$ 0.0
		Left	1.45	8.6 – 56	3.1 – 5.8	0.49	(0.1, 1.22)	0.48	0.02
$14 < x < 20$	0.27	Right	1.18	8.0 – 56.0	3.0 – 5.8	0.29	(–0.1, 1.20)	0.32	0.13
		Left	1.19	9.8 – 36.8	3.3 – 5.2	0.39	(0.0, 1.07)	0.41	0.25
$20 < x < 28$	0.24	Right	1.21	8.0 – 64	3.0 – 6.0	0.58	(0.1, 1.10)	0.59	0.05
		Left	1.28	16.0 – 128	4.0 – 7.0	0.22	(–0.1, 0.60)	0.23	0.17
$28 < x < 35$	.124	Right	1.41	8.0 – 128	3.0 – 7.0	0.81	(0.0, 2.00)	1.00	0.38
		Left	1.43	8.0 – 128	3.0 – 7.0	0.76	(0.0, 1.60)	0.77	0.10

Right-Left asymmetry

Physical interpretation of statistical signatures?



More localized transport mechanism

More localized on R than L side?

Smoother overall valleys?

Presence of more terraces in R than L?

Summary of Overarching Questions

1. How much of the physical/mechanistic behavior of the coupled hydrologic/geomorphologic system is reflected in the observed statistical patterns?

2. Are statistical patterns distinct across physical boundaries and how can they be used in assisting modeling, prediction and observatory design across scales and across environments?

3. Where/what to sample to get the most out of a limited number of observations?