Climate and Humans as Amplifiers of Hydro-Ecologic Change:

Science and Policy Implications for Intensively Managed Landscapes

Efi Foufoula-Georgiou

(on behalf of many past, current students and collaborators)

University of Minnesota

Robert E. Horton Lecture
96th AMS meeting
January 13, 2016, New Orleans

ST. ANTHONY FALLS LABORATORY
UNIVERSITY OF MINNESOTA
Driven to Discover℠

A very generous citation – I am honored and humbled -- thank you!

THE ROBERT E. HORTON LECTURER IN HYDROLOGY FOR 2016

Efi Foufoula-Georgiou

For outstanding scientific, programmatic, and educational contributions distinguished by their breadth, quality, sophistication and creativity, advancing the science of hydrometeorology.

1. Horton’s legacy …
2. 30 years overview of my research in 2 mins
3. Problems I am working on now …
4. Challenges in Intensively Managed Landscapes
5. A proposed framework to tackle complex problems
6. AMS has a vital role to play
7. Closing thoughts

Robert E. Horton (1875-1945): "father" of Hydrology

In the United States, proposals to establish a separate Hydrology Section of the AGU had been rejected by the leadership of the Union on the basis that …

…"active scientific interest in the U.S. did not justify a separate section of scientific hydrology within the AGU" (NRC, 1991, 40).

Finally, when the AGU was transformed from a committee of the National Research Council into an independent society in 1930, approval was given to establish a separate Section on Hydrology with R. E. Horton as vice-chairman

Robert E. Horton (1875-1945): "father" of Hydrology

"Defining science as correlated knowledge, it is true that a statement of the field, scope, and status of hydrology at the present time may be little more than a birth-certificate…"

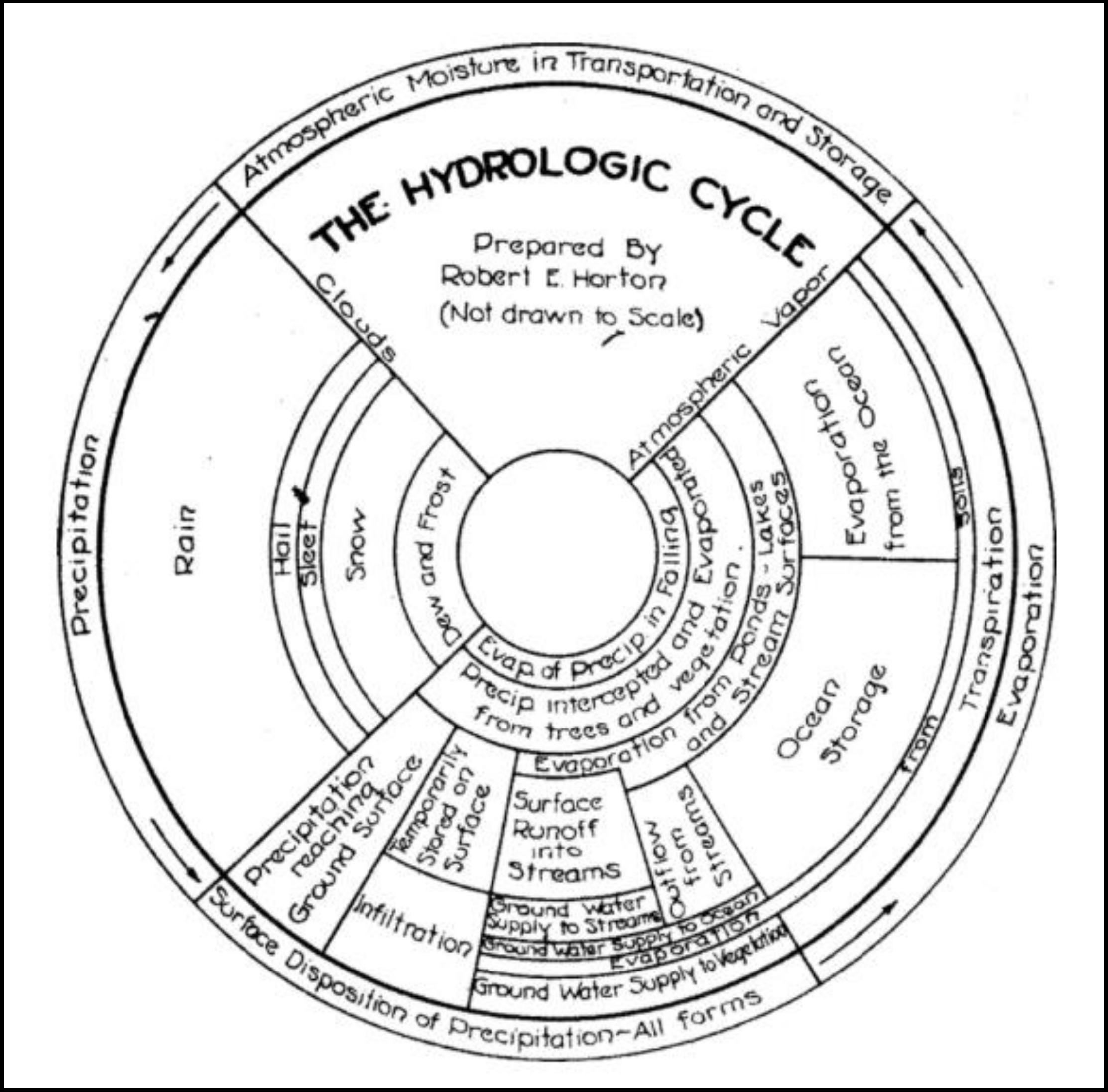
… Hydrology may be regarded as charged with the duty of tracing and explaining the processes and phenomena of the hydrologic cycle, or the course of natural circulation of water in, on, and over the Earth's surface.

This definition has the advantage that it clearly outlines the field of hydrologic science."

From Horton, *The field, scope and status of the science of Hydrology*, Trans. of AGU, 1931 (pages 190-192)

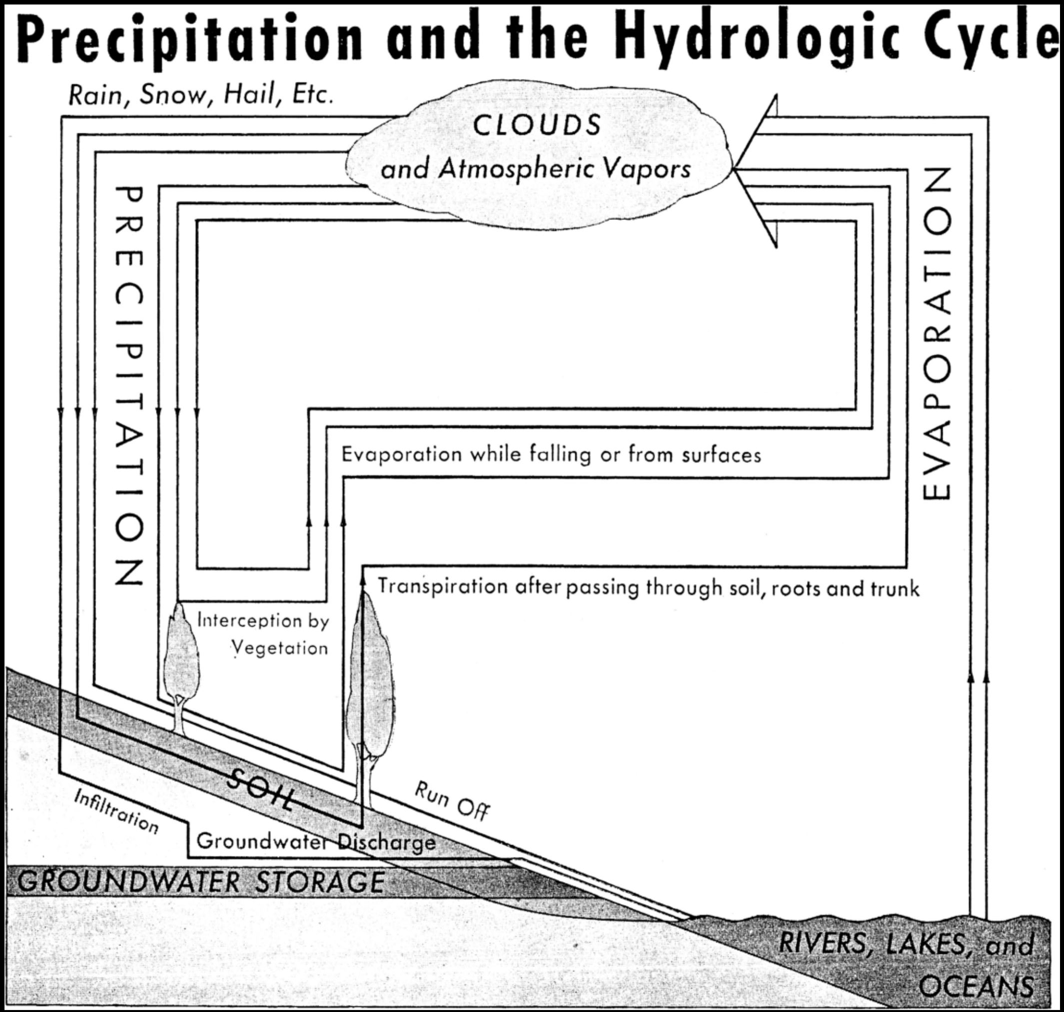
Horton's Illustration of the Hydrologic Cycle

1931



Horton (1931, p.192)

Foundational visual illustration of Hydro-Cycle



1934

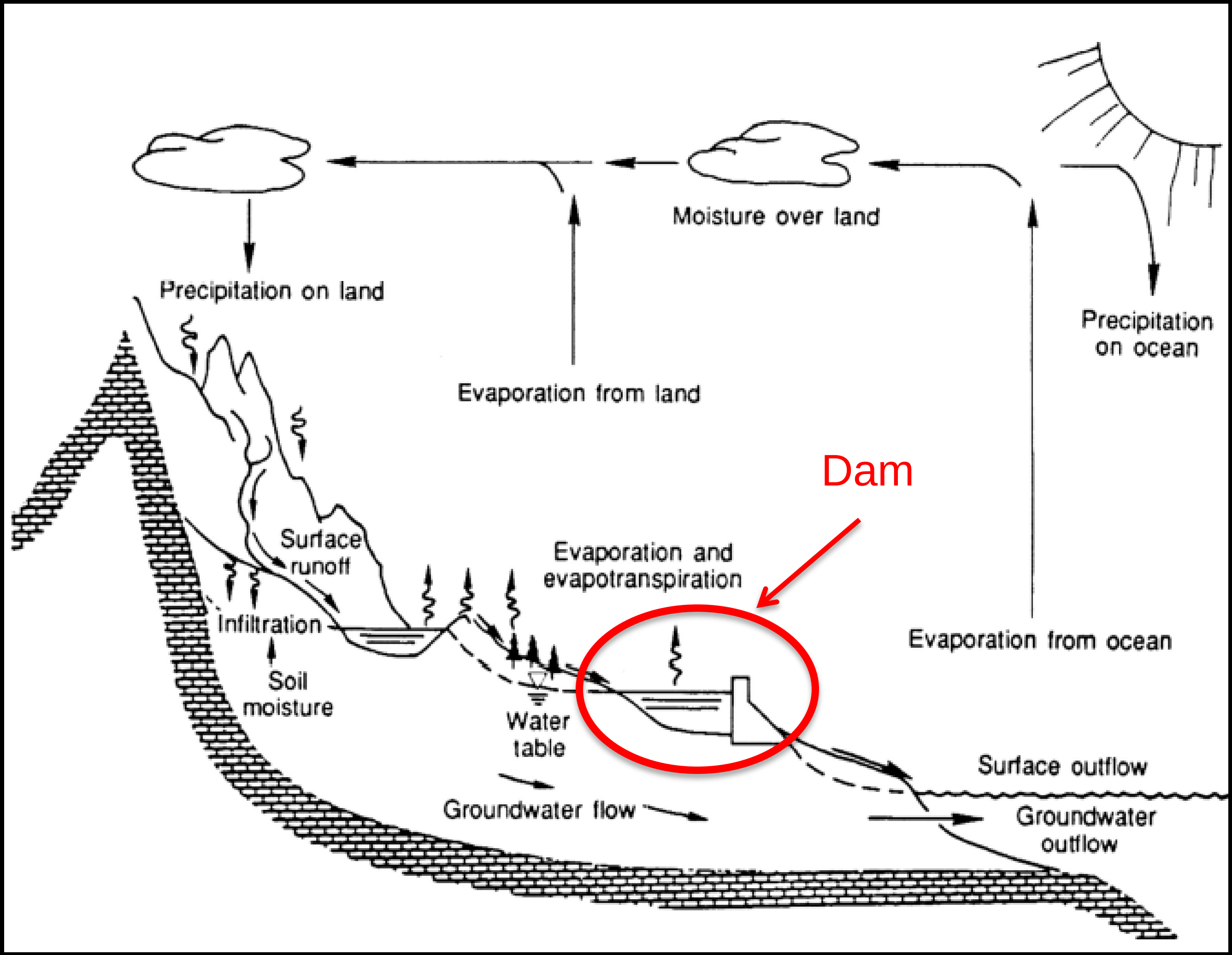
National Resources Board (1934, p. 262)

– strengthening federal government's capacity to control nation's water resources

-- water as a distinct resource

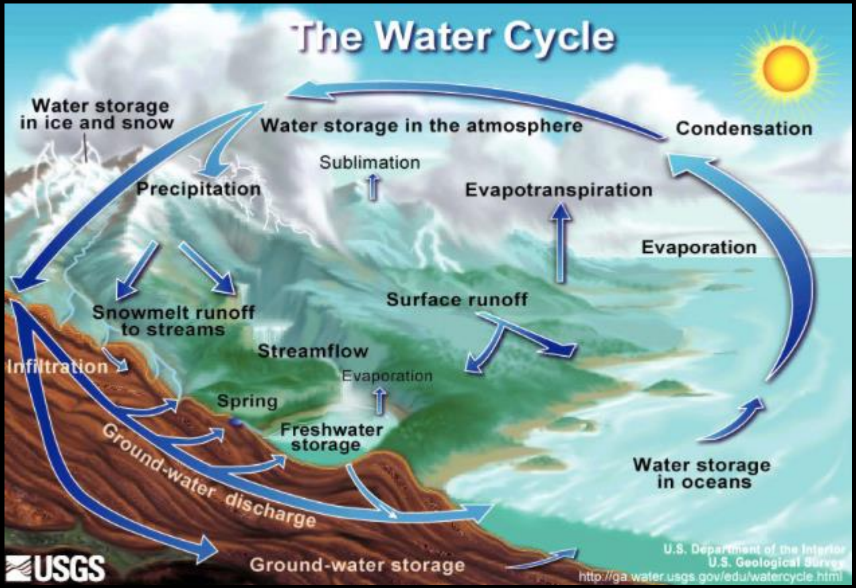
“Blue Book” version of Hydrologic Cycle …

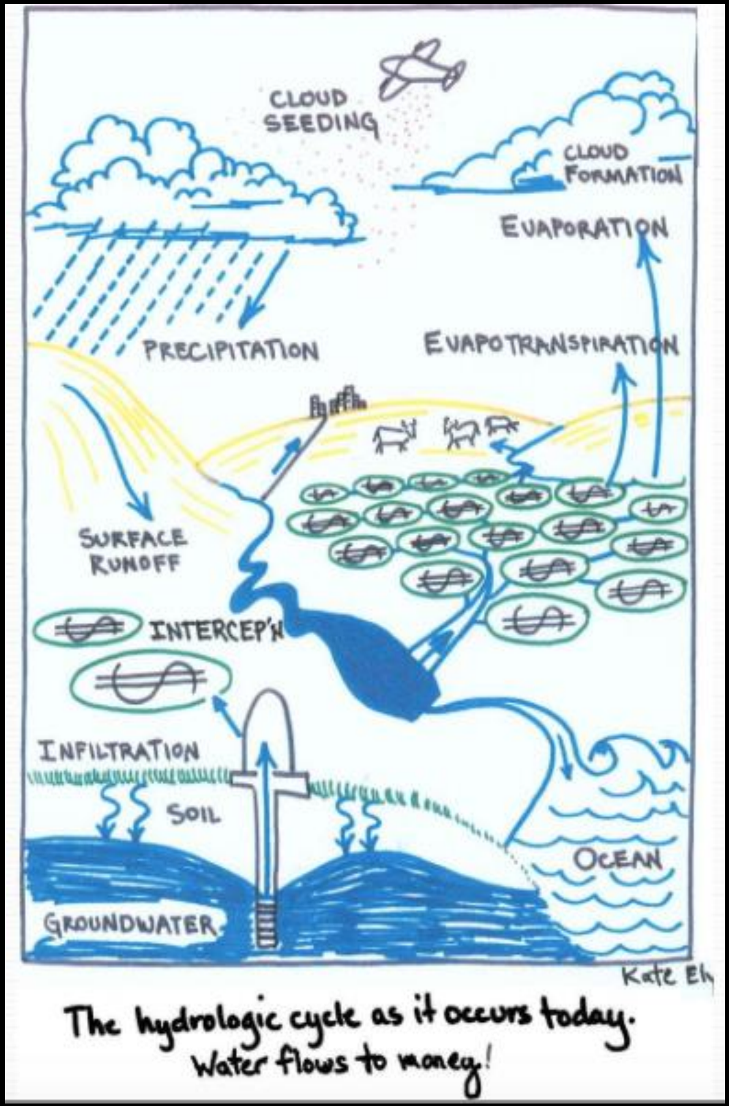
1991

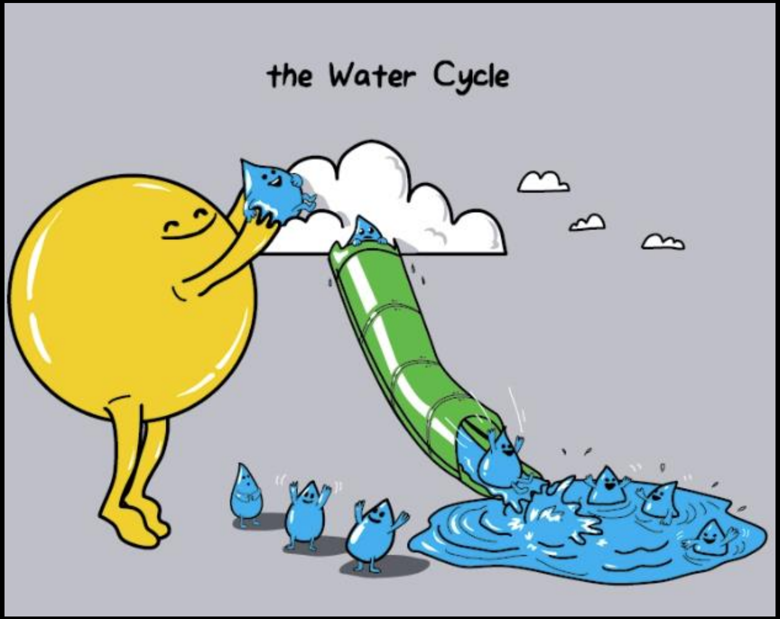


NRC, “Blue Book”, (1991)
– Established HS as a distinct Geoscience & NSF HS Program

A water cycle for all tastes!







http://aquadoc.typepad.com/waterwired/2008/12/postmodern-hydrologic-cycle.htm

Horton's most seminal contributions in hydro-geomorphology

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA

VOL. 56, PP. 275-370, 40 FIGS. MARCH 1945

EROSIONAL DEVELOPMENT OF STREAMS AND THEIR DRAINAGE BASINS; HYDROPHYSICAL APPROACH TO QUANTITATIVE MORPHOLOGY

BY ROBERT E. HORTON

Defined the quantitative basis of geomorphology

-- Introduced Horton laws (scale invariance) in River networks

-- Hydrophysical explanation of channel formation and evolution

… Cited 4329 times so far

Horton’s eminence across disciplines …

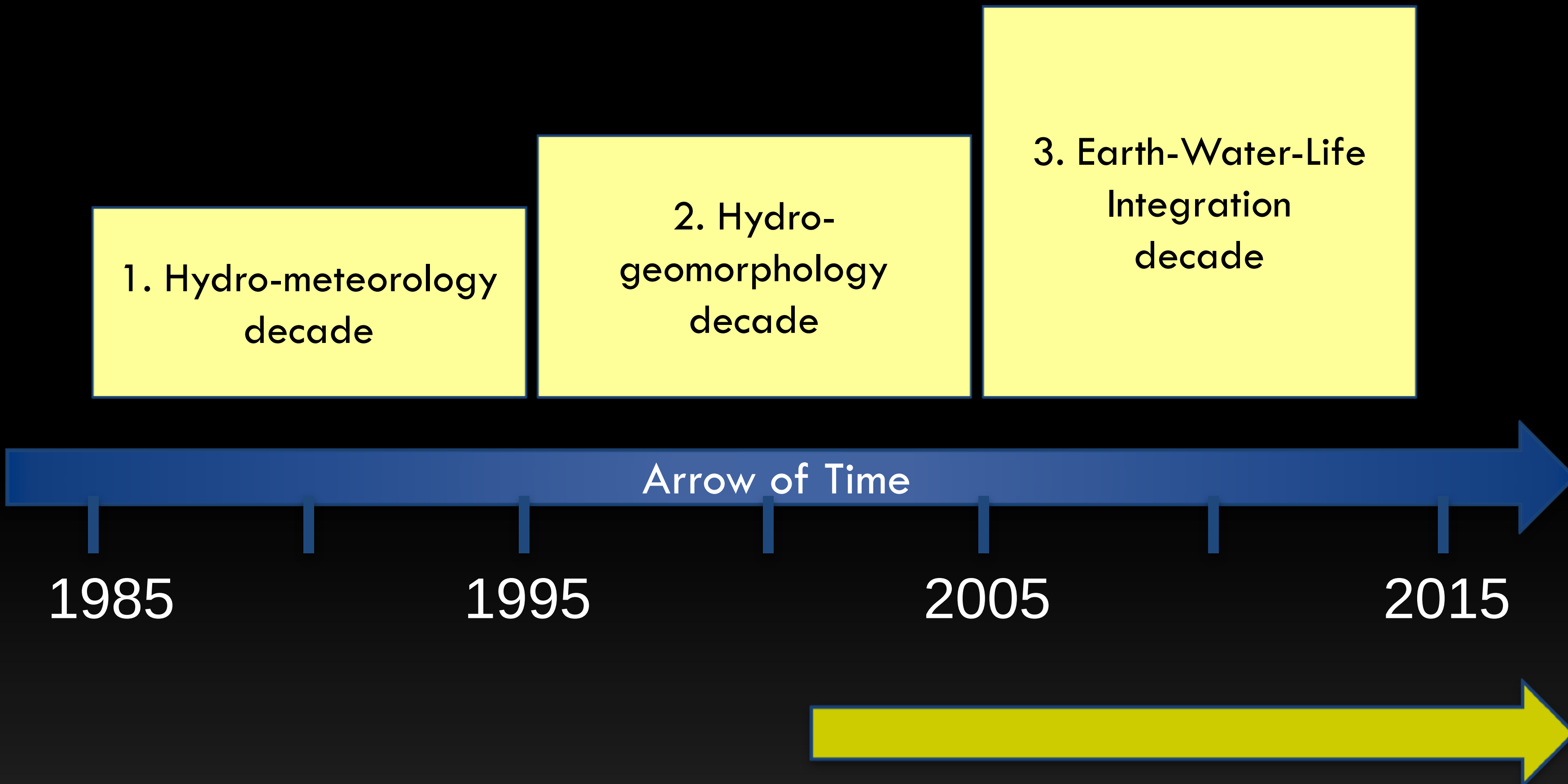
AGU Horton Medal
AGU Horton Research Grants

AMS Horton Lecture

GSA ?

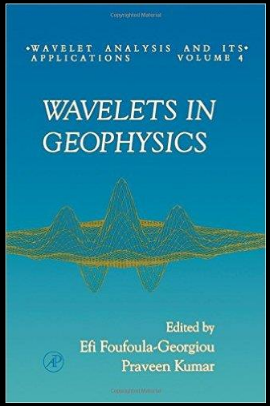
(A hint to GSA!)

Looking back at my own career …



Involved in defining/performing interdisciplinary research …

Problems that captured me …



Arrow of Knowledge

Arrow of Knowledge

1. What is the space-time structure of rainfall?

- Min complexity (scaling) models across space-time scales?
- Relation of "structure" to thermodynamic parameters?
- How to use for downscaling/estimation/retrieval?

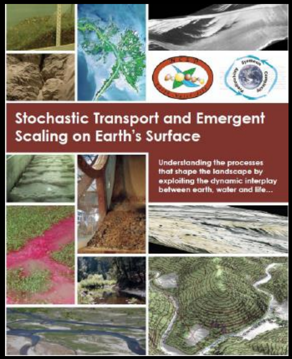
2. Can geomorphic patterns reveal processes?

- What is the climate signature on river network structures?
- Can we constrain sediment transport laws from landscape form?
- Do distributary patterns reveal their shaping processes?

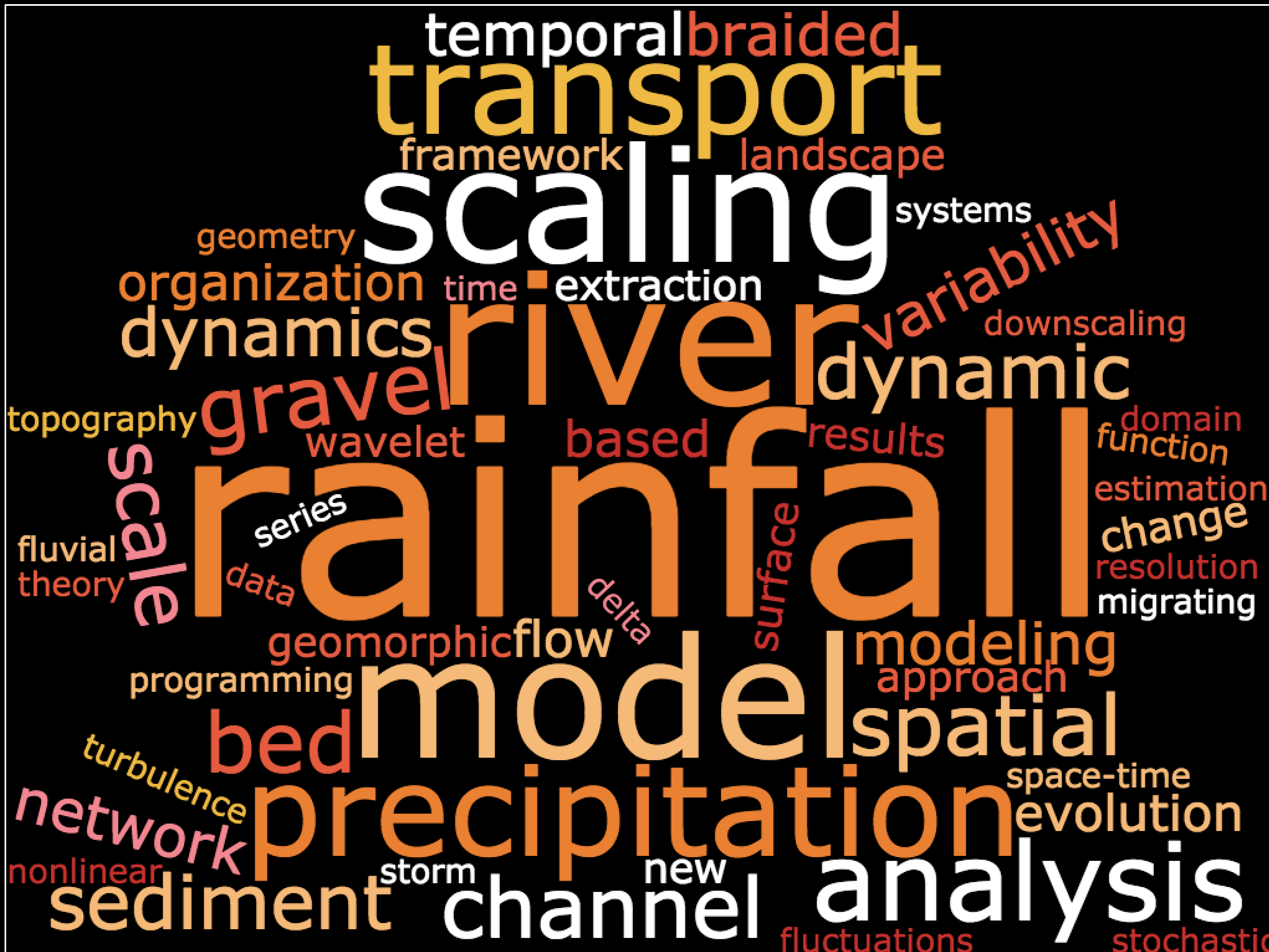
3. How to quantify Earth-Water-Life interactions?

- Reduced complexity models for the cascade of changes?
- Discovery of emergent process "hot spots"?
- Climate vs. human amplifications?

Theory, Observations, Experiments

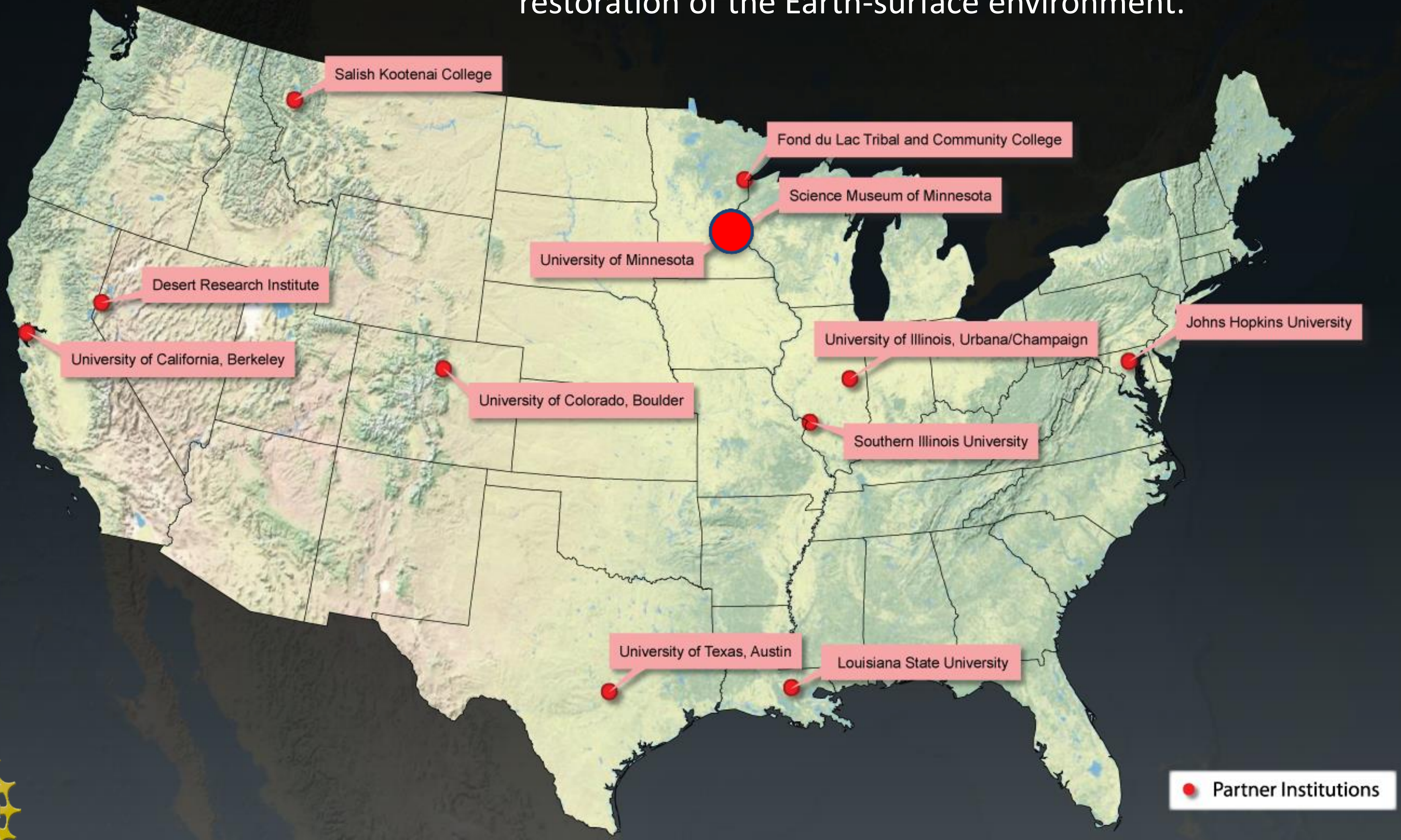


Word Cloud: 30yrs-worth of my publications!

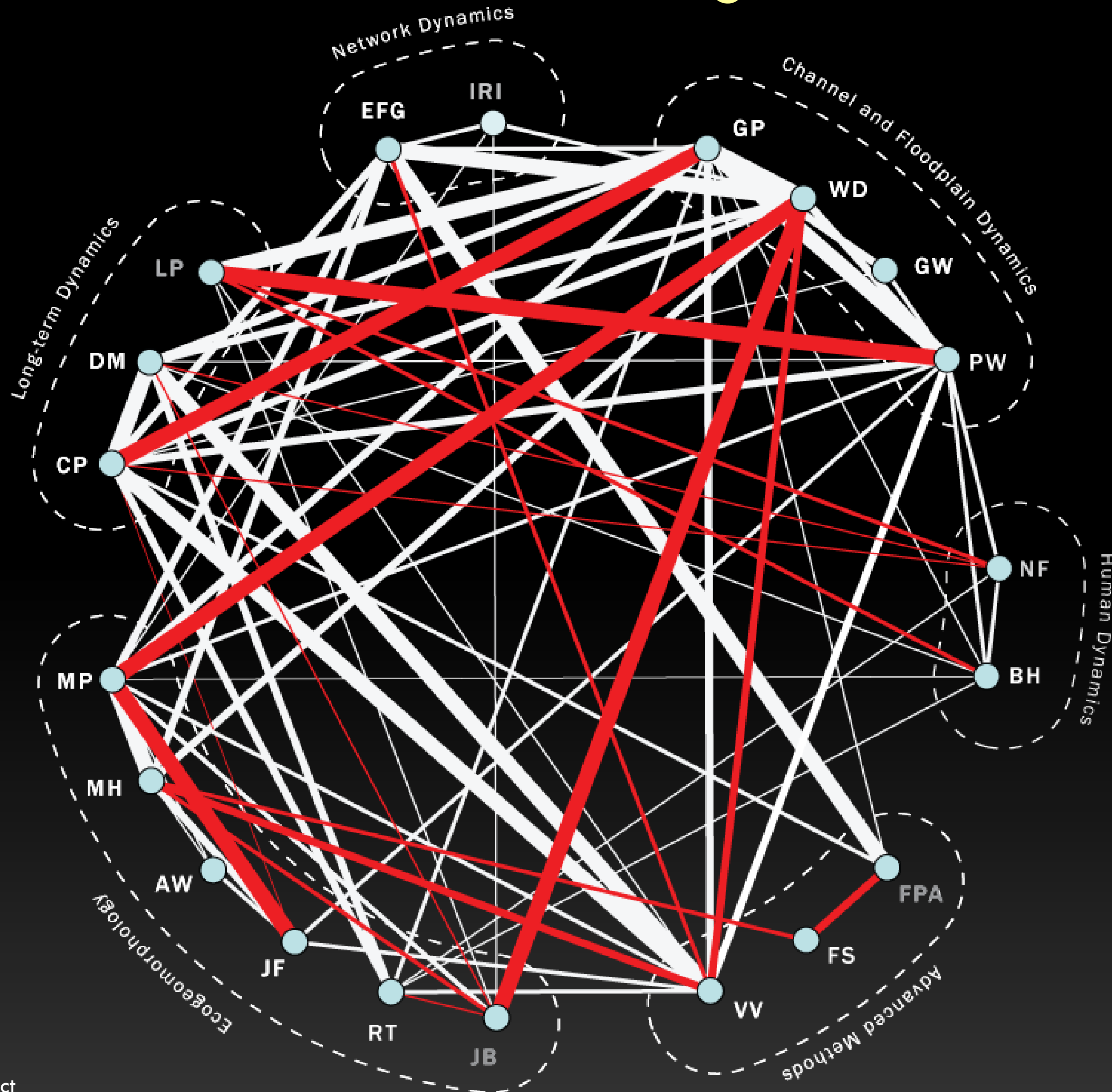


National Center for Earth surface Dynamics
NCED: 2002-2012+

To predict the coupled dynamics and co-evolution of landscapes and their ecosystems, in order to transform management and restoration of the Earth-surface environment.



NCED: the Power of Integrative Research



0.5px: initial development
2.0px: on-going defined project
4.0px: project produced synthesis paper
8.0px: well-established project with shared students or multiple papers

Year 8

Research Integration: watch your covariances!

✓ **Whole > Sum (parts)?**

X1 = productivity of PI 1

X2 = productivity of PI 2

X = X1 + X2 X = productivity of center

Mean(X) = Mean(X1) +Mean(X2);

Var(X) = Var(X1) + Var(X2) + **COV(X1,X2)**

Whole > sum of its parts Iff *COV* (+)

A few Highlights from my Current Research

NSF

BELMONT FORUM

UNIVERSITY OF MINNESOTA

NASA


Precipitation
estimation from
space

Delta Sustainability

River meandering

Agricultural
Landscapes

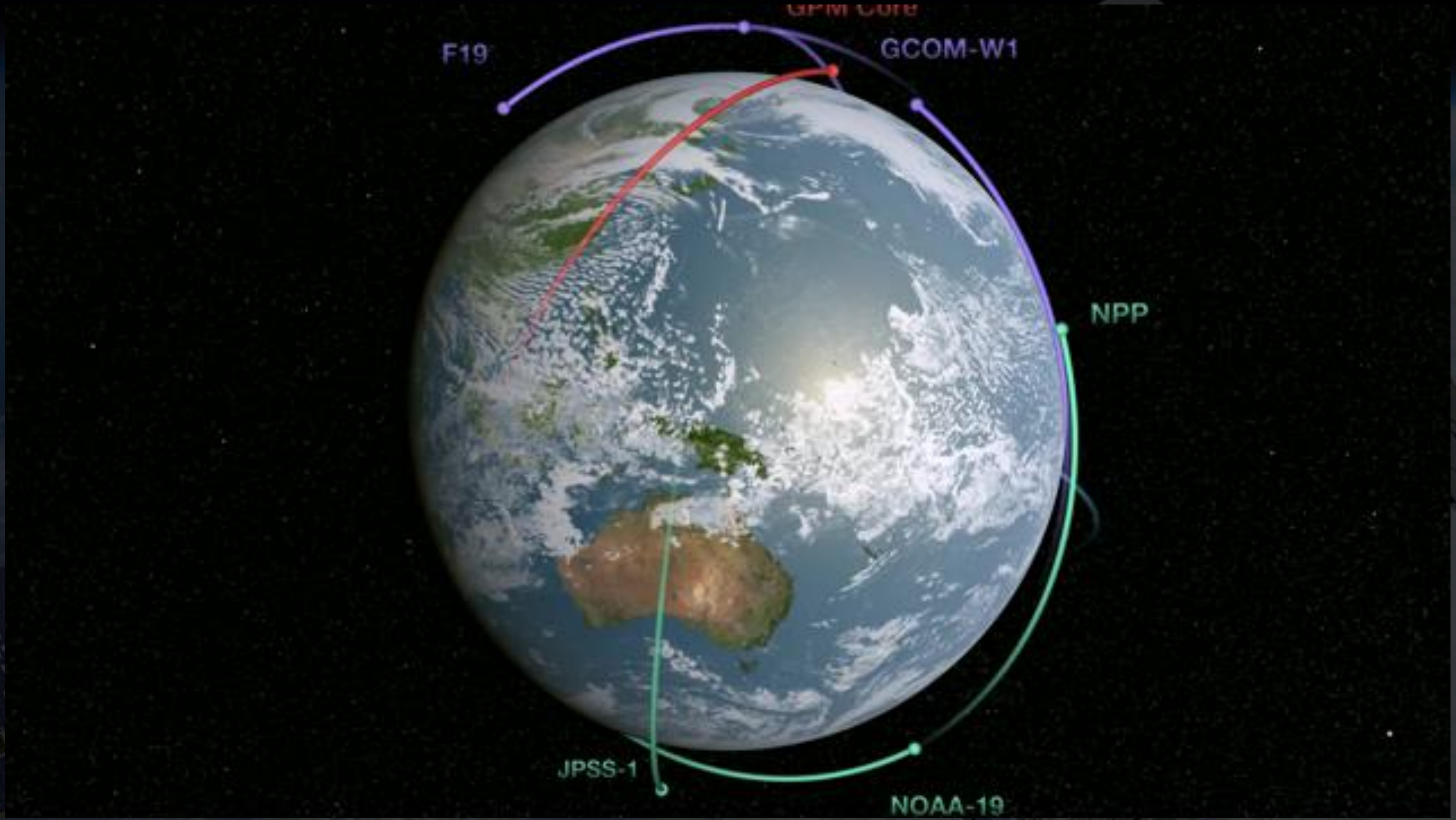

Precipitation estimation from space
Retrieval over land and complex terrain with emphasis on extremes


Delta Sustainability
Characterize delta topology and dynamics for classification, process inference, and vulnerability assessment


River meandering
Response to perturbations and meander train dynamics


Agricultural Landscapes
Human impacts on hydrology and river ecology

Precipitation Estimation from Space

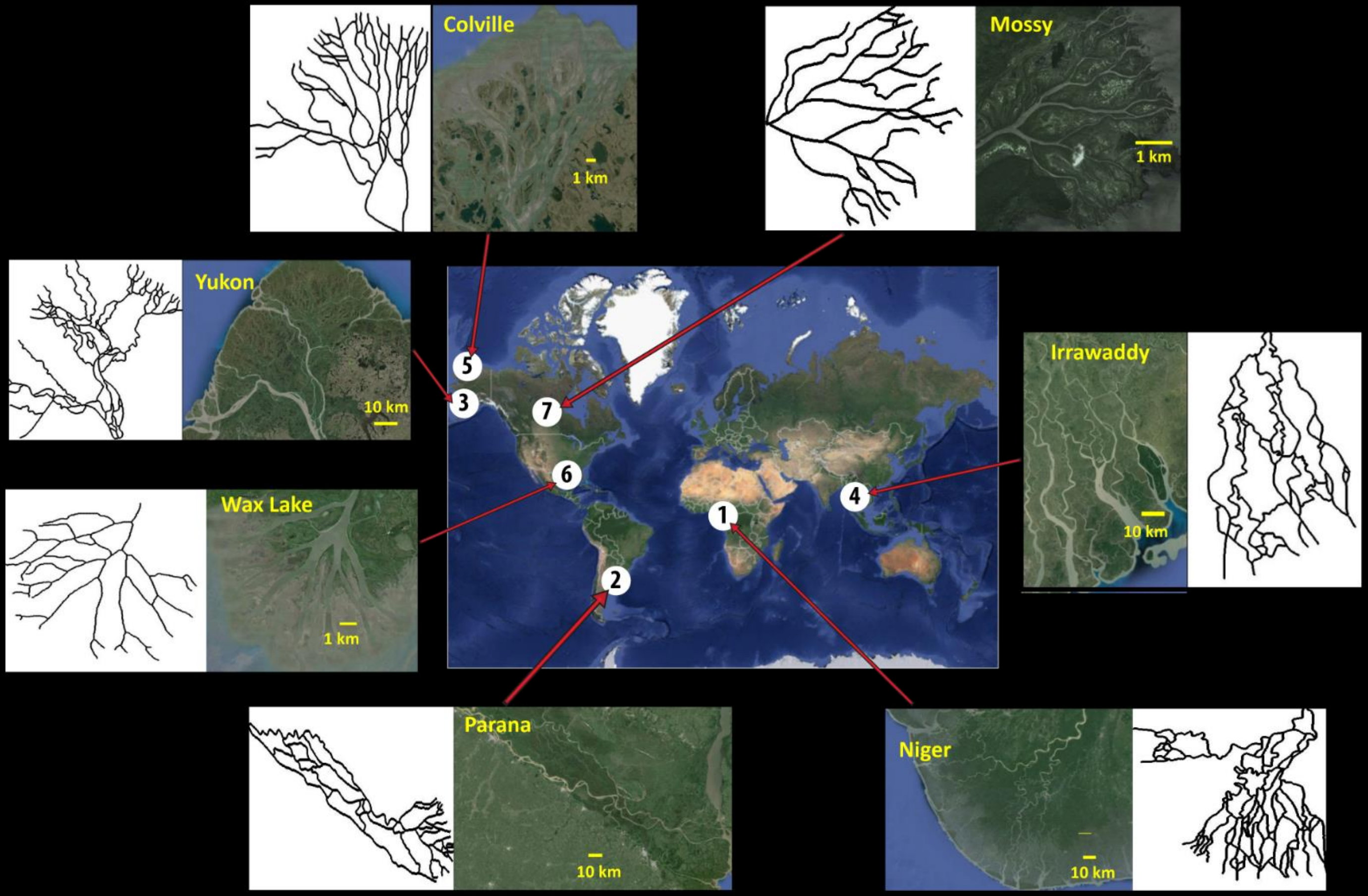


GPM core satellite launched in 2014 following success of TRMM (beyond the tropics)

- How to retrieve rainfall over radiometrically complex terrain?
- How to estimate, fuse, and downscale simultaneously?

Ebtehaj et al., 2014, 2015a,b,c
Foufoula-Georgiou et al., 2014

Delta Sustainability



Deltas around the world are threatened by sea level rise and upstream human actions

- Do network geometry and dynamics reveal processes? => delta classification
- Can we build a network-based approach to vulnerability assessment?

Tejedor et al., WRR, 2015a,b

Delta Sustainability

1. Graph theoretic Approach

Deltaic Surface

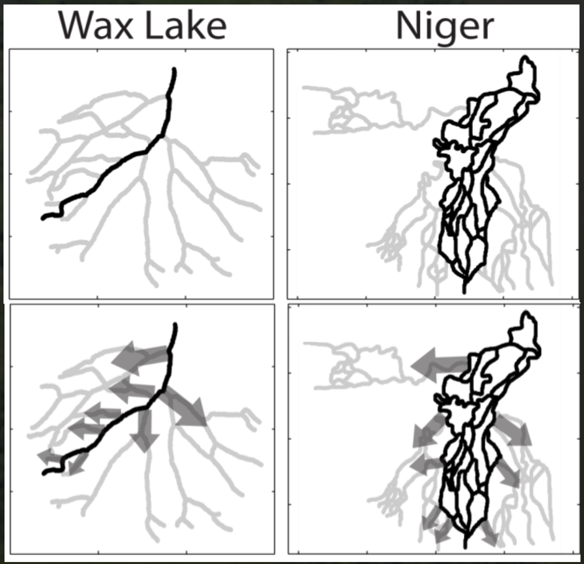
Graph Representation

$$\begin{pmatrix} 0&0&0&0&0&0&0&0\\ 1&0&0&0&0&0&0&0\\ 0&1&0&0&0&0&0&0\\ 0&1&0&0&0&0&1&0\\ 0&0&0&1&0&0&0&0\\ 0&0&0&1&0&0&0&0\\ 1&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&1&0 \end{pmatrix}$$

Adjacency Matrix

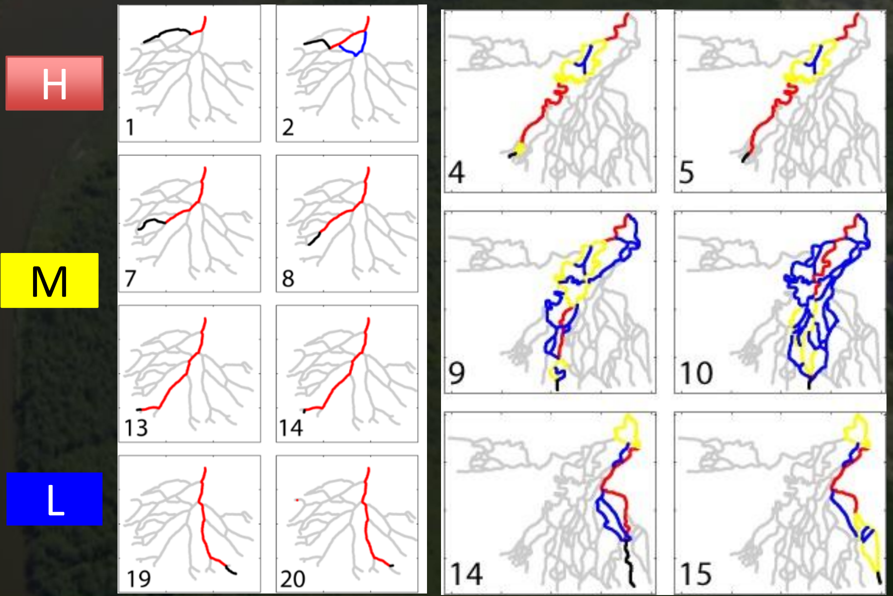
Algebraic Representation

2. Metrics for topologic and dynamic complexity



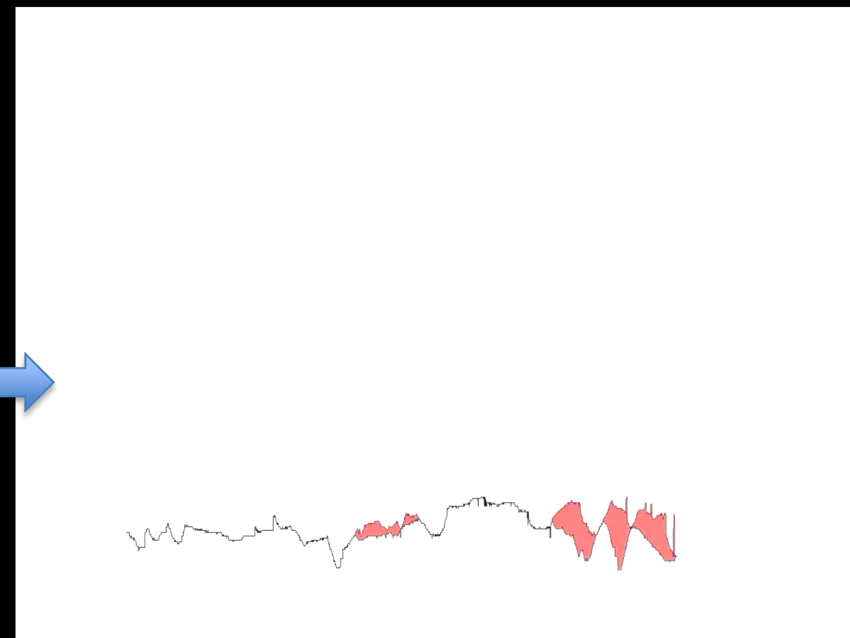
Tejedor et al., WRR, 2015a,b

3. Framework for vulnerability maps

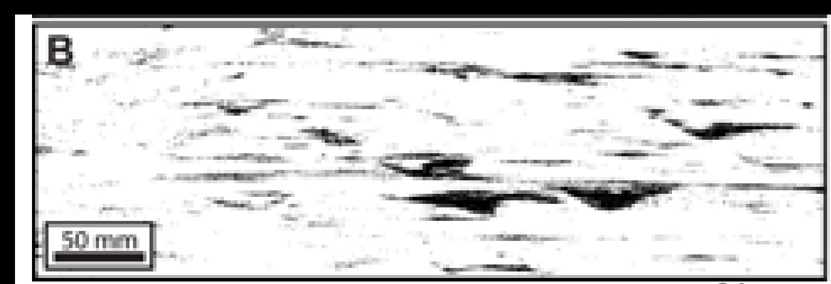


Delta Sustainability

Controlled Laboratory experiments: Form Deltaic Surface Evolution & Stratigraphy



St. Anthony Falls Laboratory
University of Minnesota



Experiment DB03, SAFL – see Sheets et al., 2007
Ganti et al., JGR-ES, 2011, 2013

River Meandering

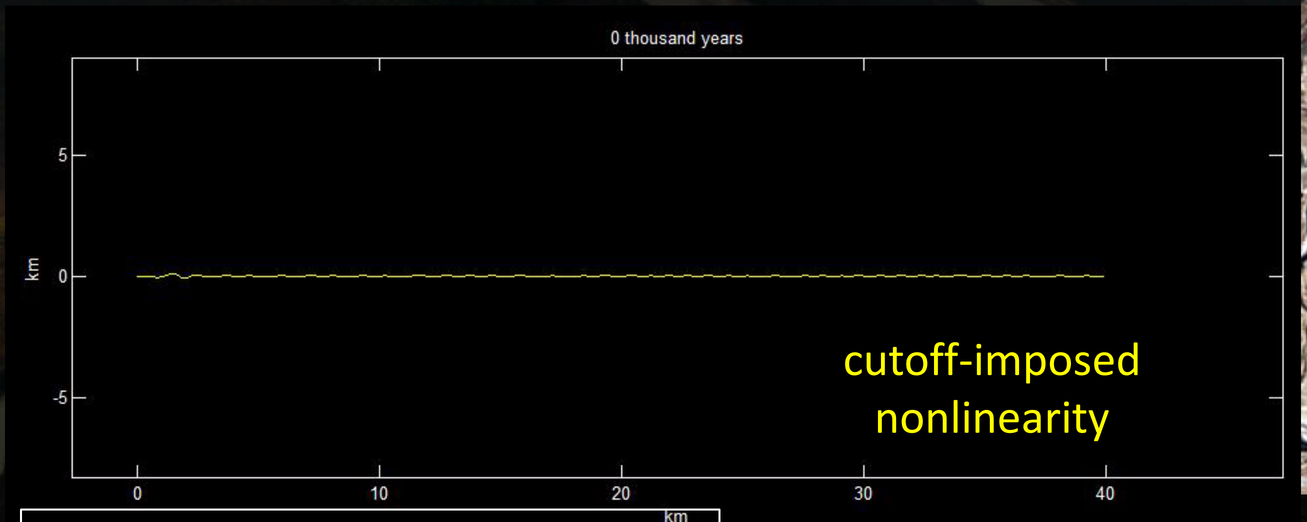
Does static planform geometry record meander dynamics?
How sensitive are dynamics to local perturbations?

channel alignment evolution

theta = centerline angle
U = local migration rate

$$\frac{d\theta}{dt} - \frac{d\theta}{ds}\int_0^s U \frac{d\theta}{ds}\, ds = \frac{dU}{ds}$$

intrinsic geometric nonlinearity

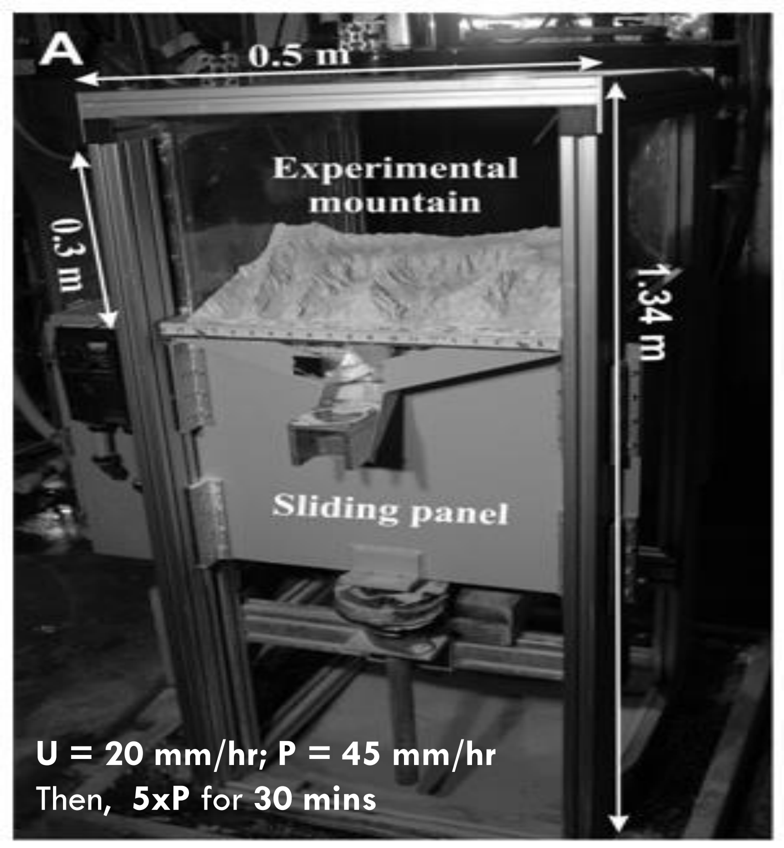


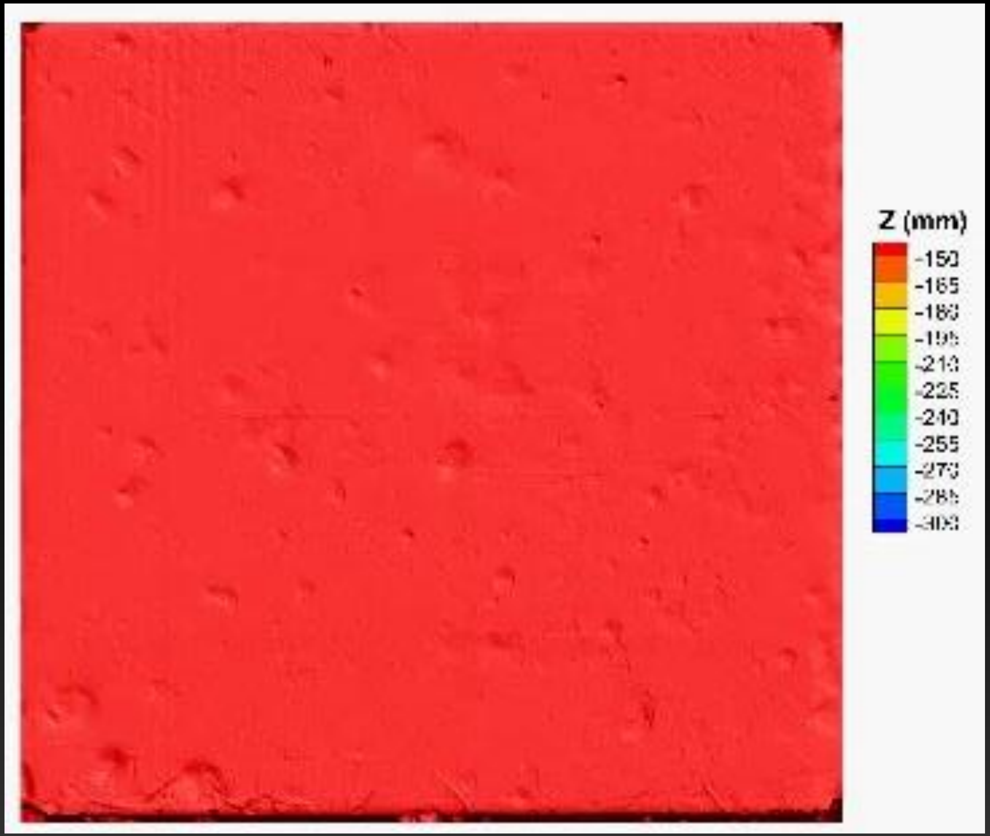
cutoff-imposed nonlinearity

Schwenk, Lanzoni, EFG, The life of a meader bend, JGR-ES, 2014

Landscape response to climate change

- What scales/processes are involved in landscape re-organization?
- What new equilibrium states do landscapes reach after perturbations?





Singh et al., WRR, 2015

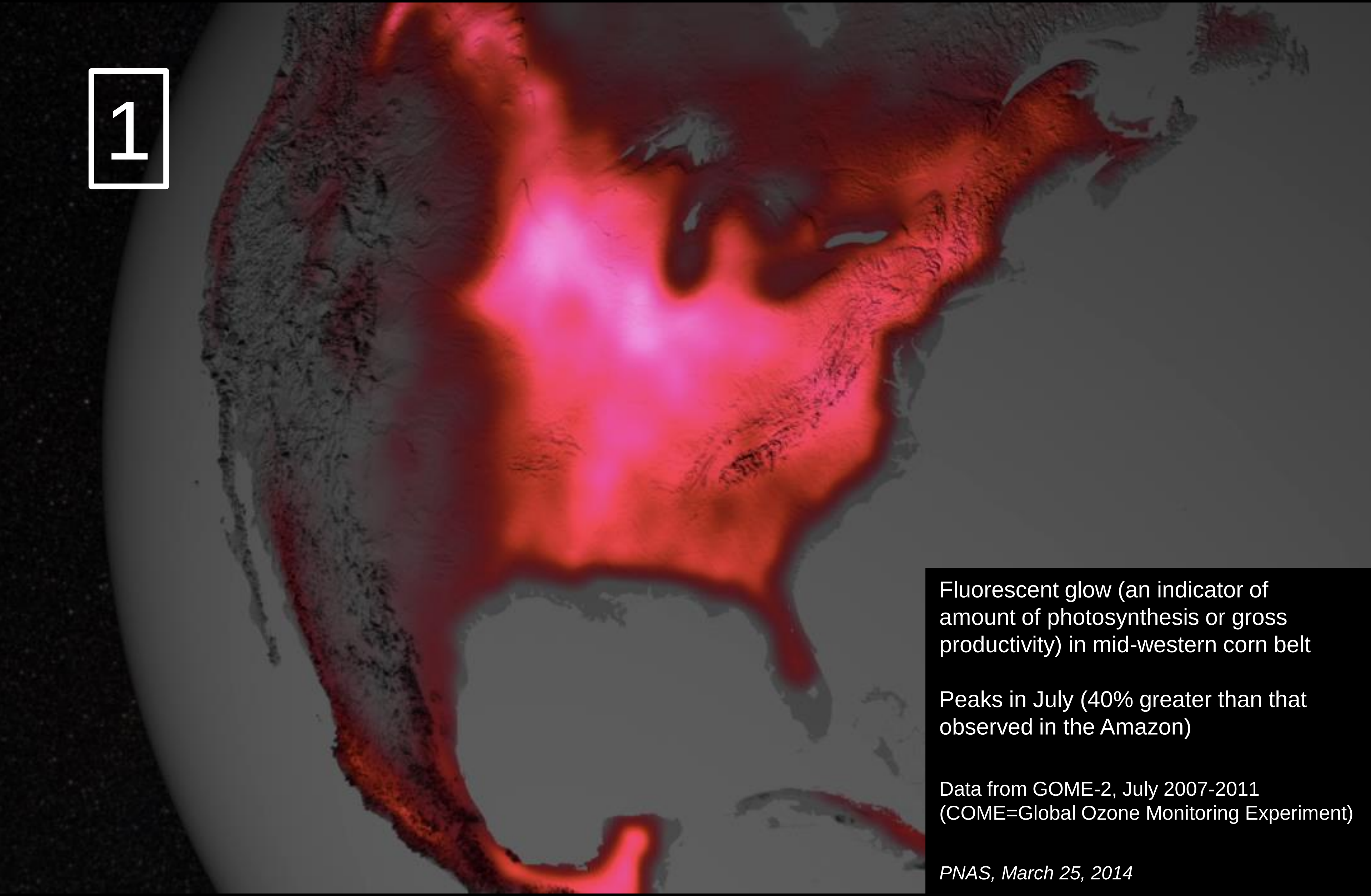
Agricultural Landscapes: Economy, Water, Food, Environment

A global problem …

"If we fail on food, we fail on everything."
-Godfray, 2011 PNAS

How to ensure sustainability of agriculture in addition to all other environmental goods and services, which agriculture inevitably alters?

The Story…



Fluorescent glow (an indicator of amount of photosynthesis or gross productivity) in mid-western corn belt

Peaks in July (40% greater than that observed in the Amazon)

Data from GOME-2, July 2007-2011
(COME=Global Ozone Monitoring Experiment)

PNAS, March 25, 2014

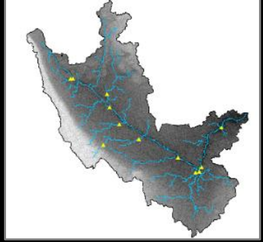

2

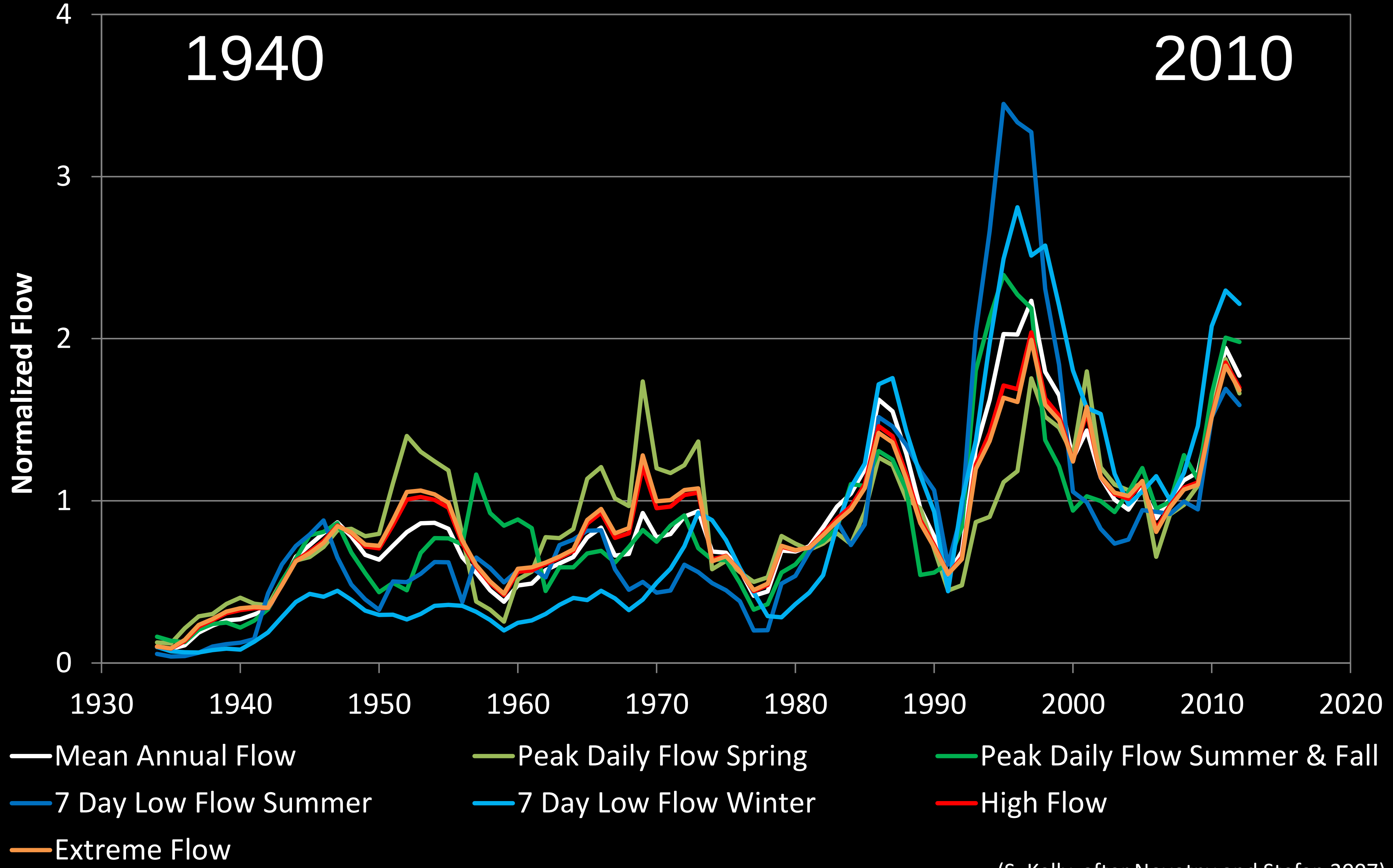

3


4

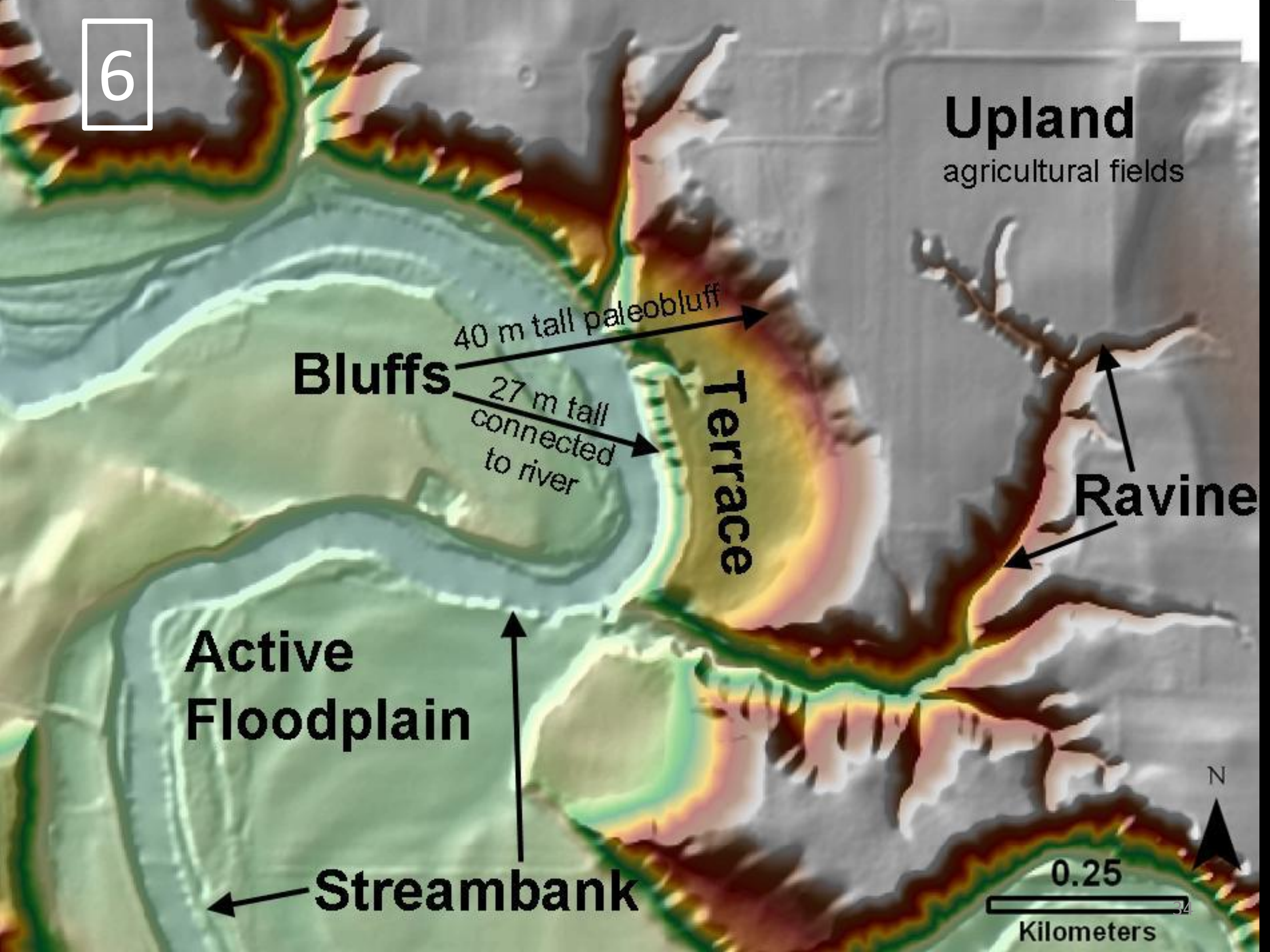
5

Streamflow: Minnesota River Basin





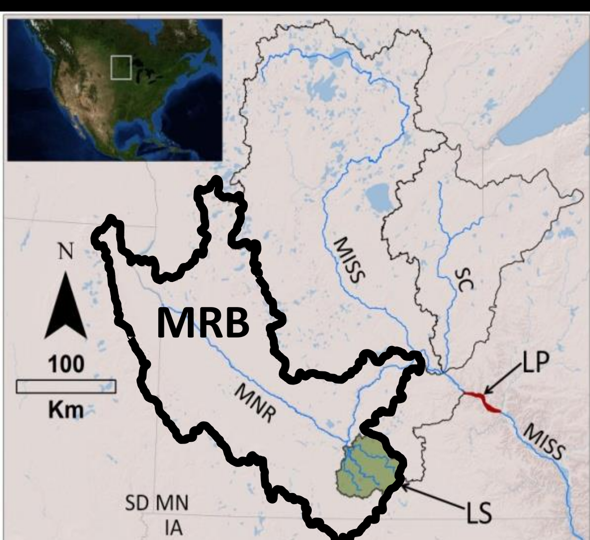
(S. Kelly, after Novotny and Stefan 2007)

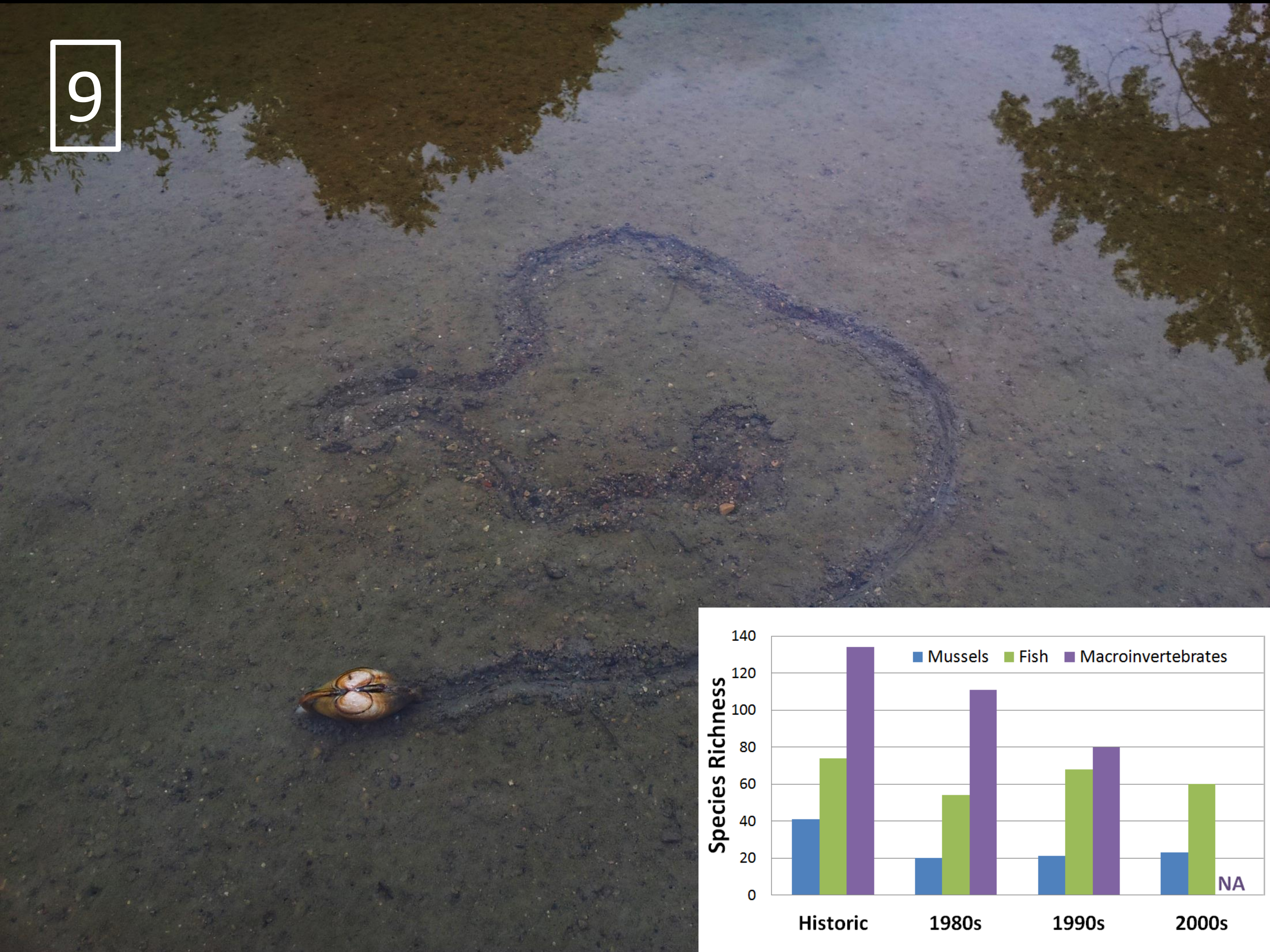

6
Upland
agricultural fields
40 m tall paleobluff
Bluffs
27 m tall
connected
to river
Terrace
Ravine
Active
Floodplain
Streambank
N
0.25
Kilometers

(S. Levine, B. Call, P. Belmont)

8

(Photo: Star-Tribune)




9
Mussels
Fish
Macroinvertebrates
Species Richness
140
120
100
80
60
40
20
0
NA
Historic
1980s
1990s
2000s

-- a water issue
-- driven by economy
-- driven by food demand
-- driven by energy demand
-- affecting the environment …

… NEED SOLUTIONS

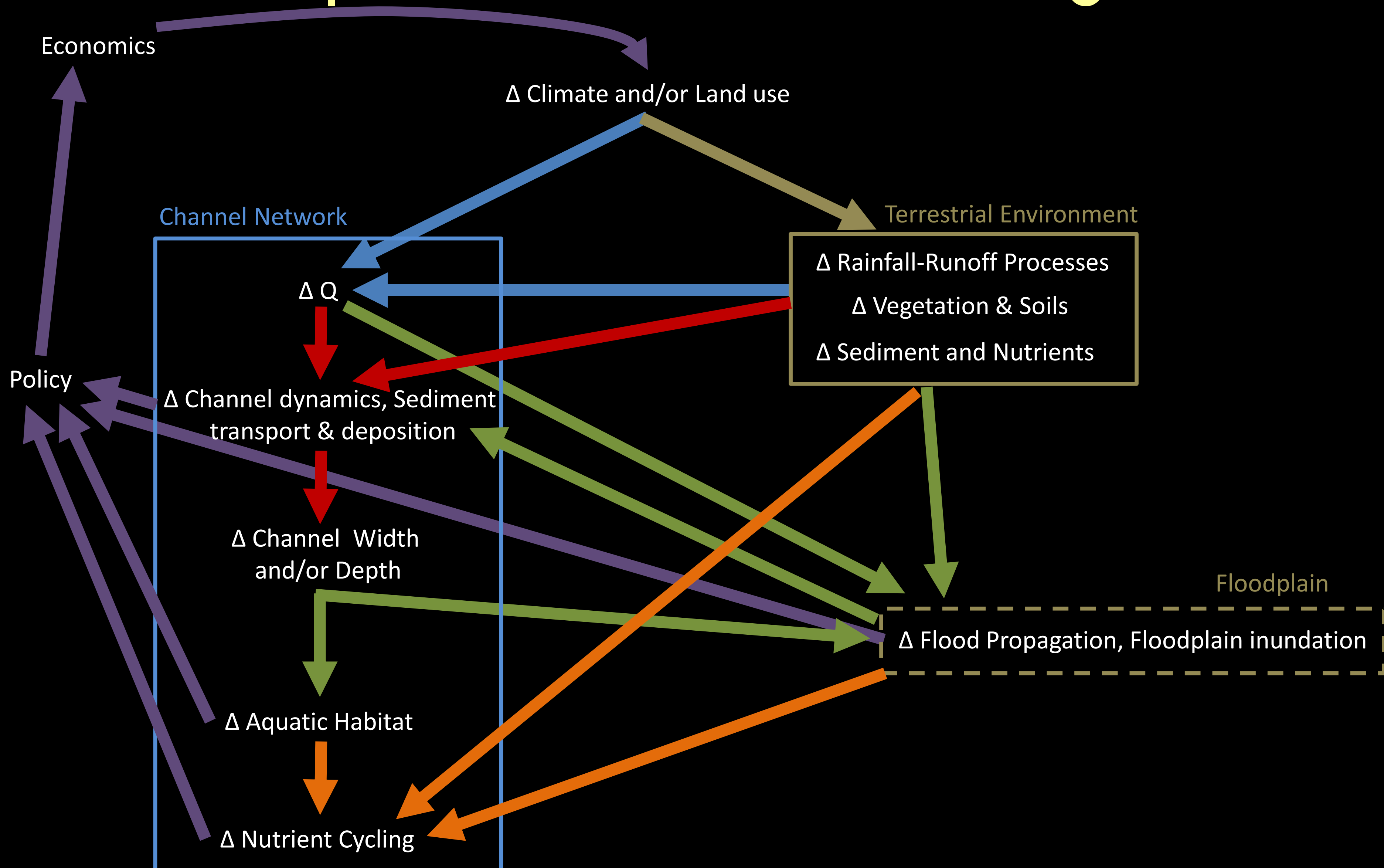
Challenging questions for integrated hydrologic sciences and sustainability

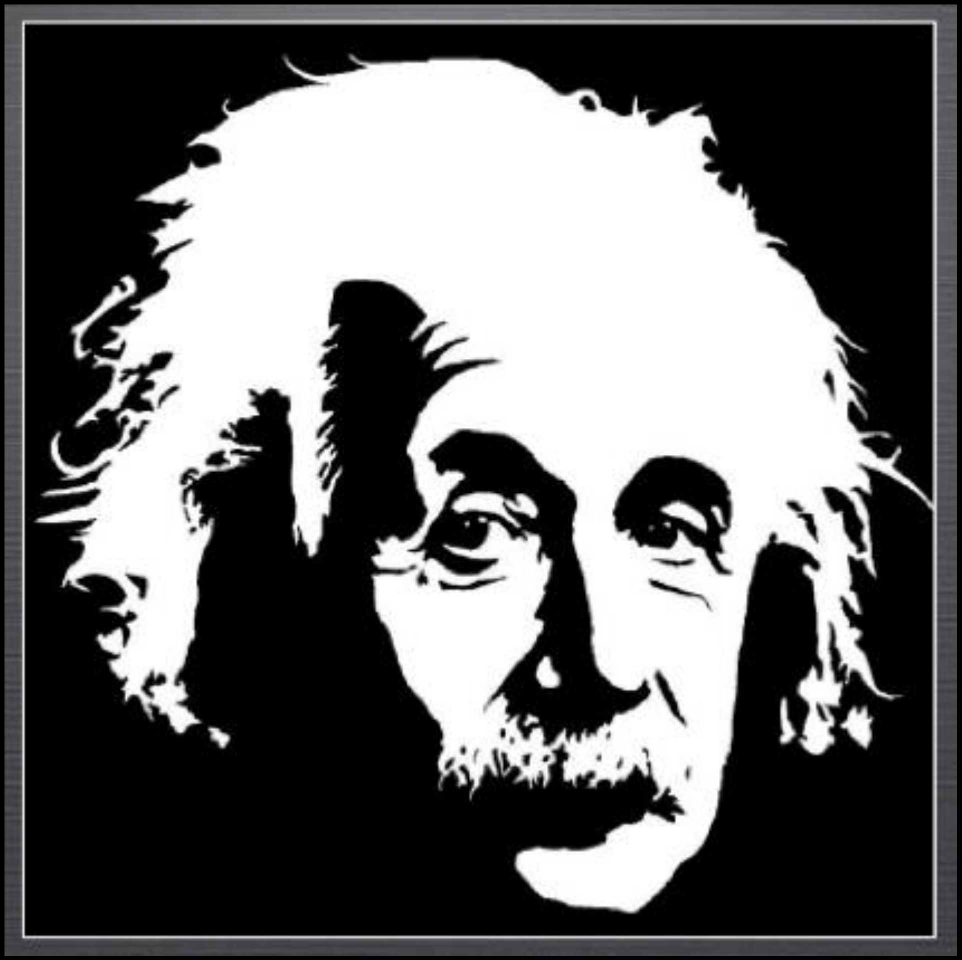
1. What is the interplay of climate and human-induced changes on hydrology at multiple scales: from storm-event to annual/decadal trends?

2. How do changes cascade from hydrology to sediment production and transport, to stream geomorphologic change, to aquatic and riparian ecology?

3. How to identify "hot spots" of vulnerability to inform mitigation and/or management decisions?

Complex cascade of changes





“Make everything as simple as possible but not simpler”

Albert Einstein

Proposed Framework

"Sustainability through Vulnerability Science"

FRAMEWORK: Sustainability through Vulnerability Science

1. Space-time signatures of vulnerability

-- critical space-time localization, leading indicators of abrupt system shifts, vulnerability maps, coupled interactions

2. Scale dependence of vulnerability

-- heterogeneity is a fundamental governing variable
-- natural processes, human management actions and policies are scale dependent
-- at what scales to evaluate a system for sustainability?

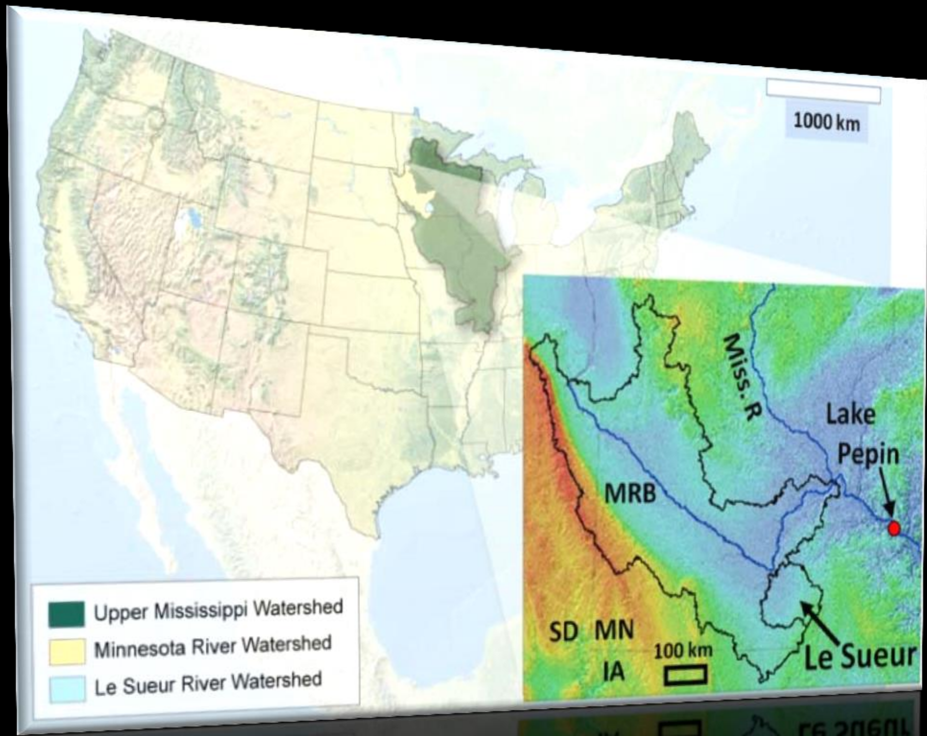
3. Process chains and vulnerability

-- Nonlinear amplifications and thresholds govern evolution of human-natural system

4. Hierarchical reduced-complexity modeling for emergent processes

-- Only a subset of dynamics at one scale strongly affects those at other scales

Minnesota River Basin: our prototype



CLEAN WATER LAND & LEGACY AMENDMENT

Minnesota River Basin (MRB) = 44,000 km^2 basin draining to the Mississippi River

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

Minnesota plans to spend > $3.5 billion over next 20 years improving health of the state's terrestrial and aquatic ecosystems. Where to concentrate efforts to be most effective?

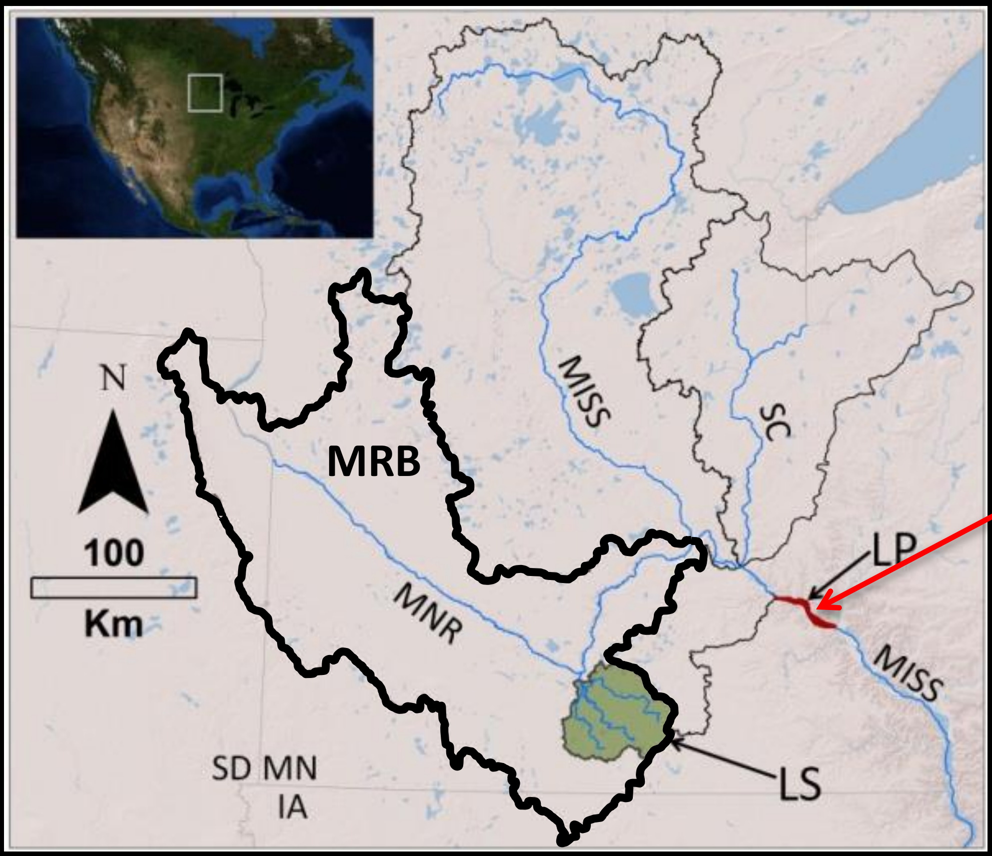
The cause of the problem is obvious, right?

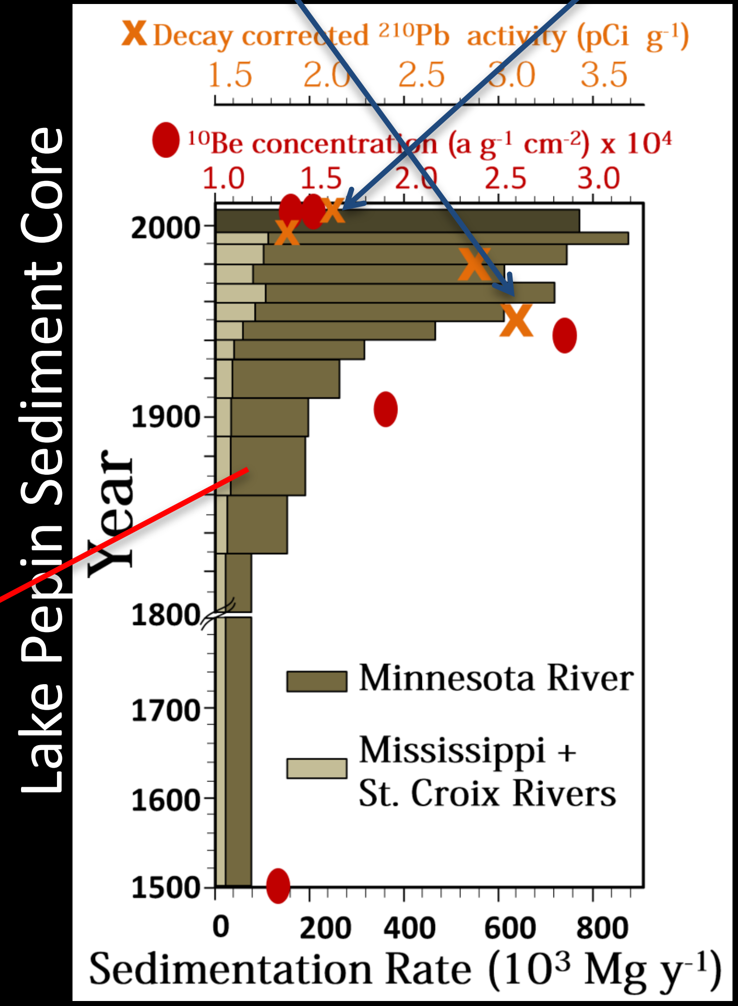
MRB: A system of excessive sedimentation…

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

MRB is primary source of sediment and nutrients for Lake Pepin (37% area, 90% sediment)

Recent shift in sediment sources: From **top soil** to **bank erosion**



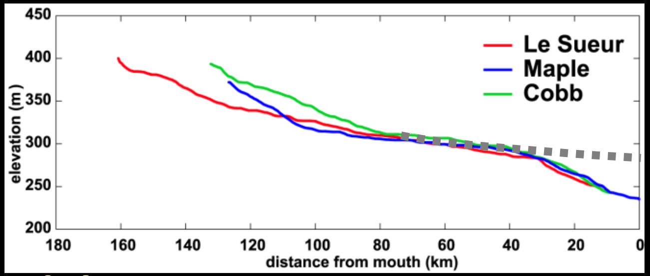


Belmont et al. 2011 ES&T

Landscape structure established 13.4 kyr ago

Uplands: flat land, passive rivers

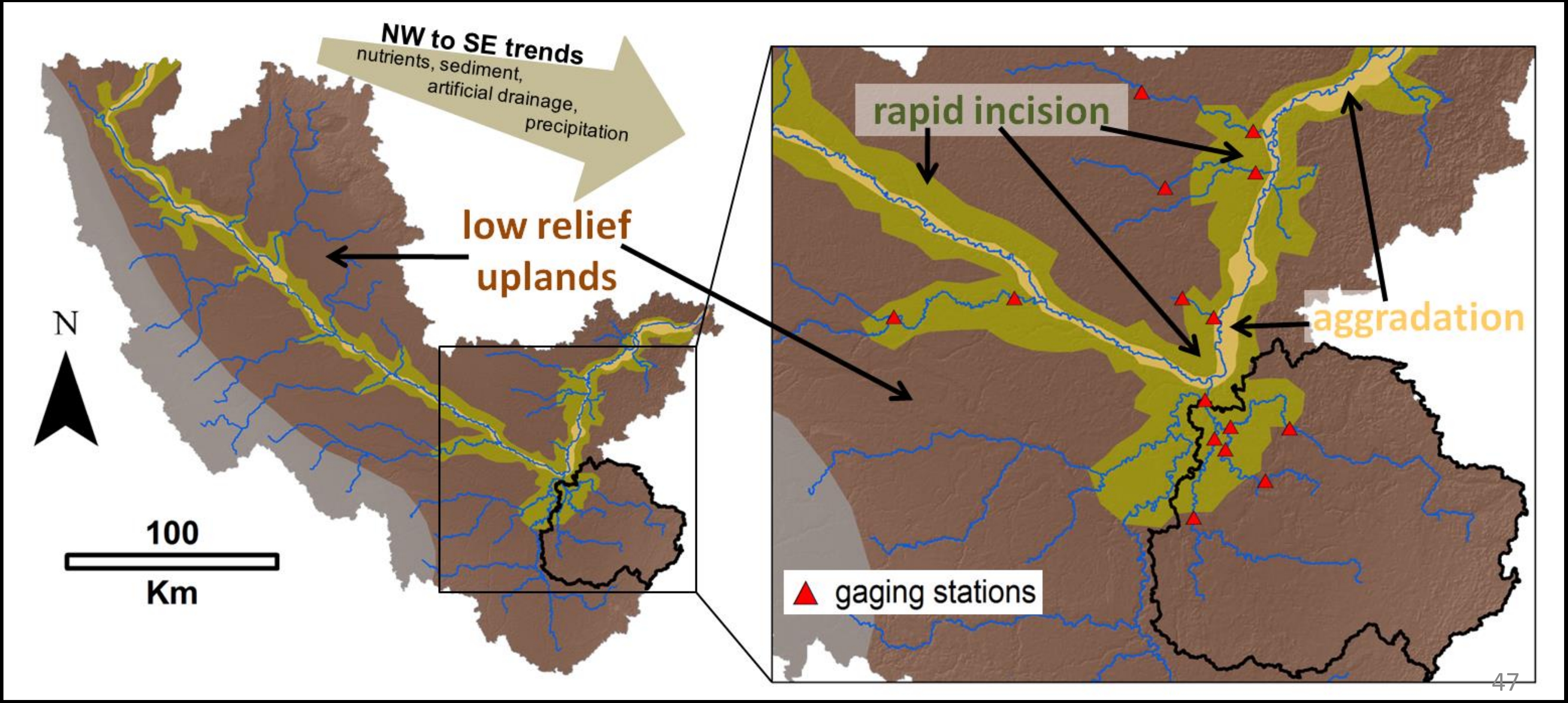
Knick zone: steep, highly dynamic, incising rivers



Minnesota River Valley: rapidly aggrading channel and floodplain

System structure → implications for routing of water, sediment and nutrients

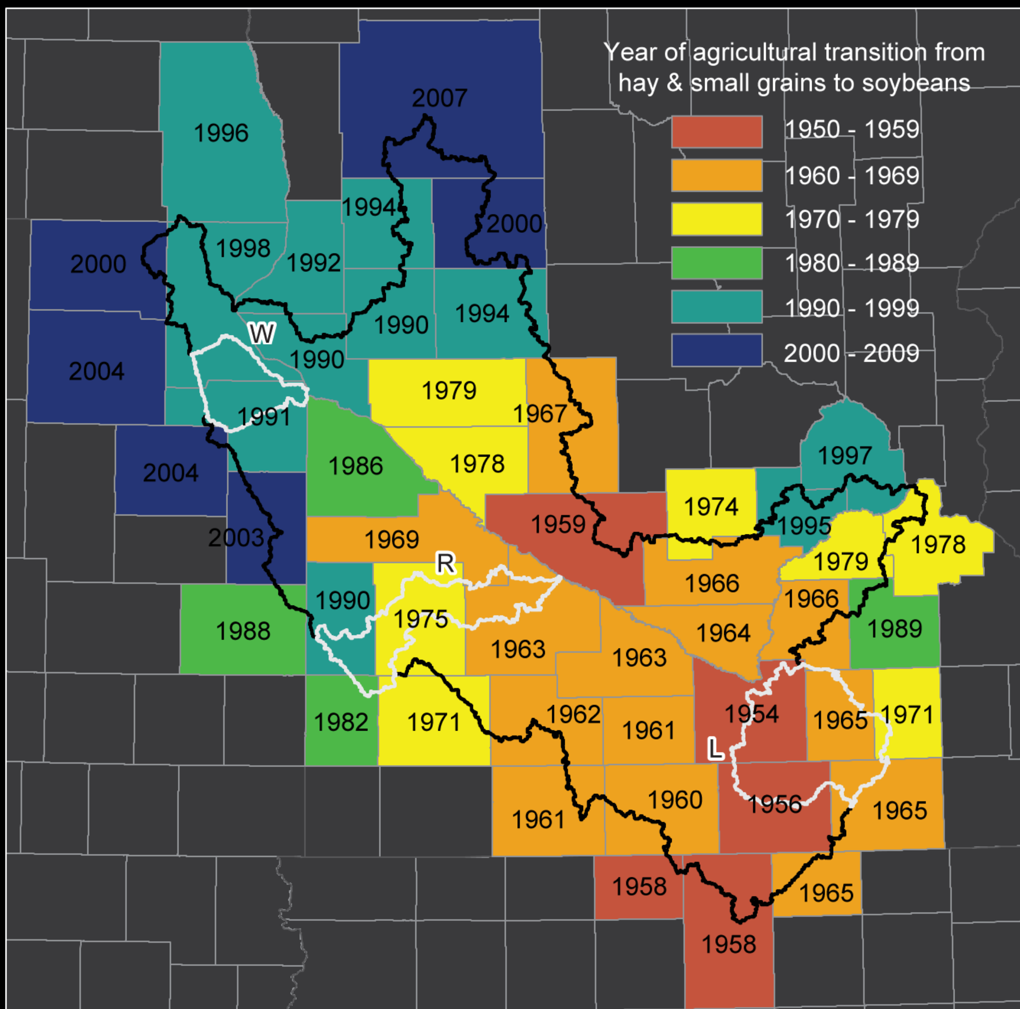
Each region responds differently to external changes

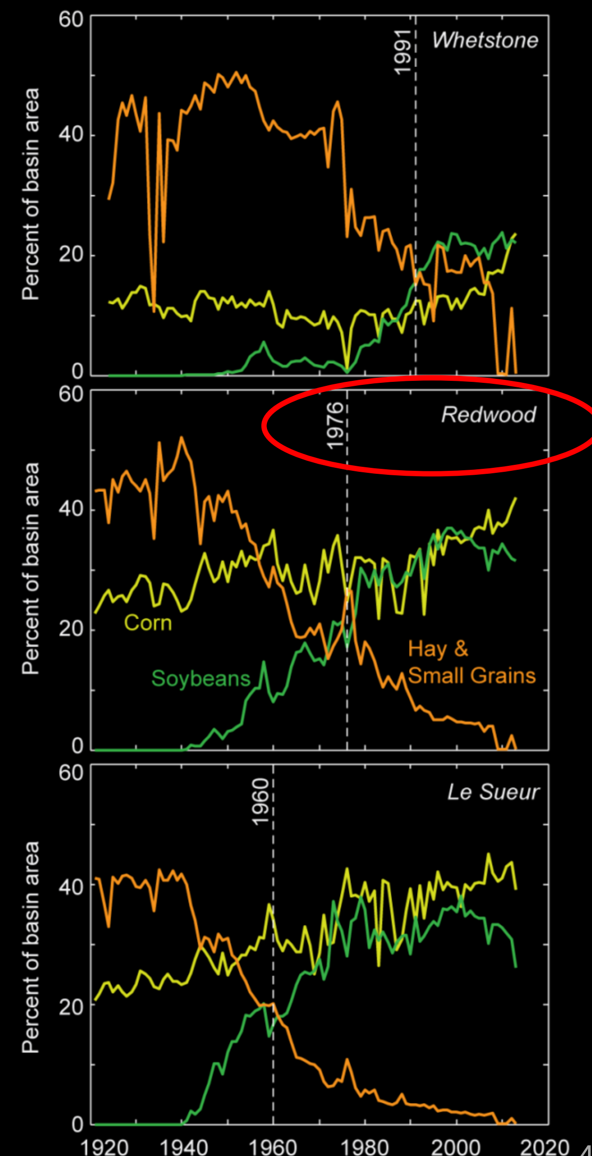


Belmont et al. 2011 GSA

MRB: Land use/Land Cover Change

Agriculture transitioned from hay and small grains to soybeans beginning in the southeast MRB

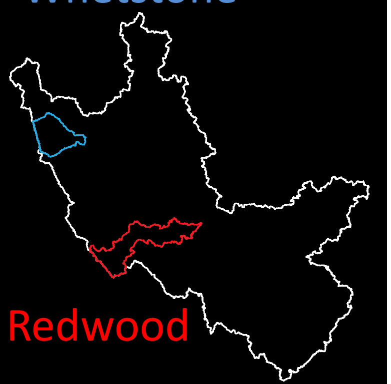




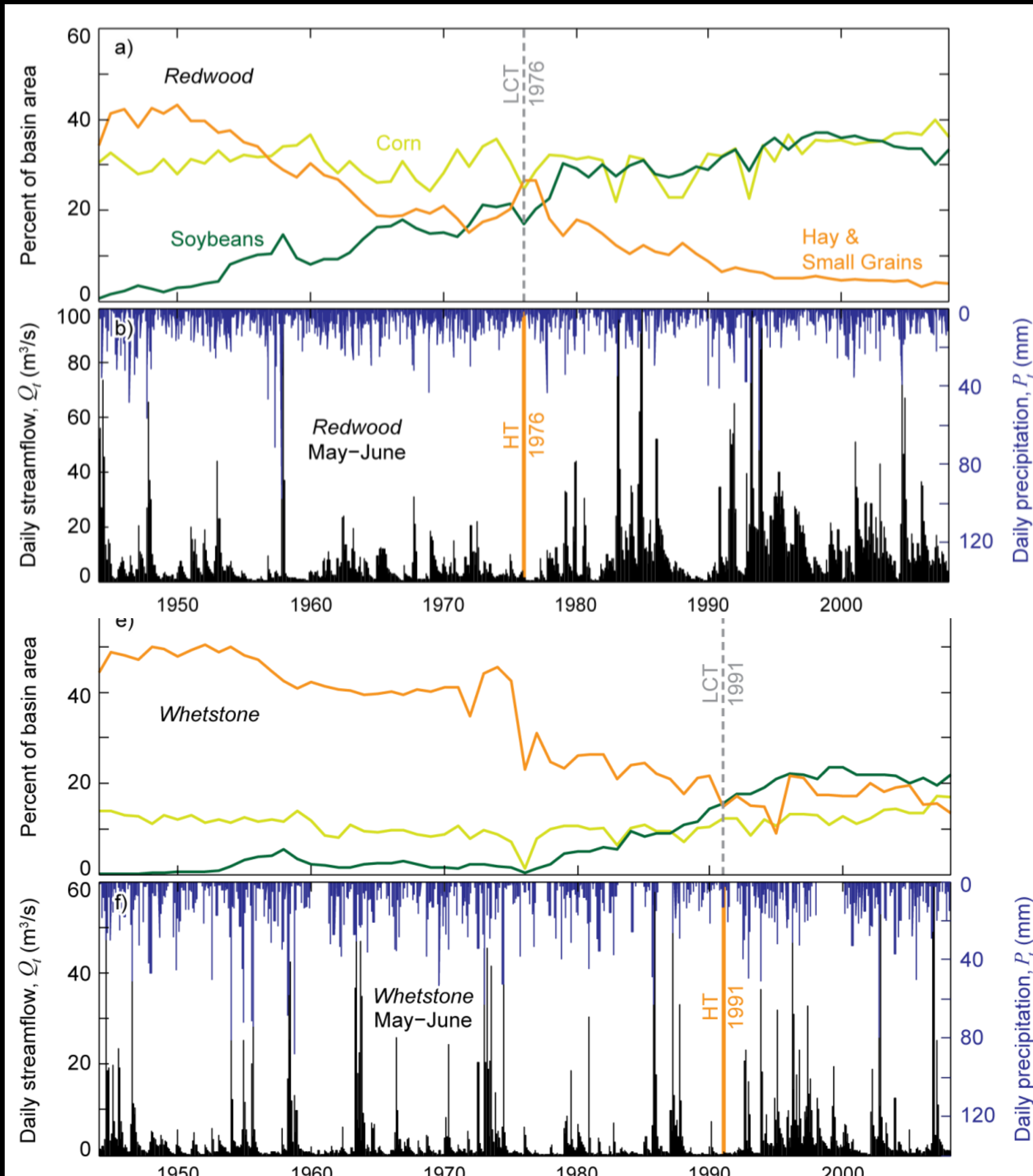
Foufoula-Georgiou et al., 2015, WRR

Streamflow change during growing season

Whetstone

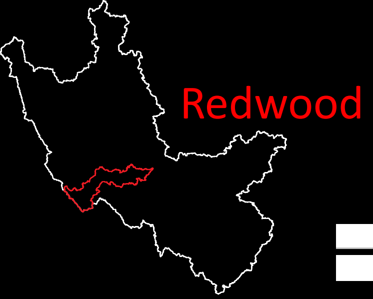


Redwood

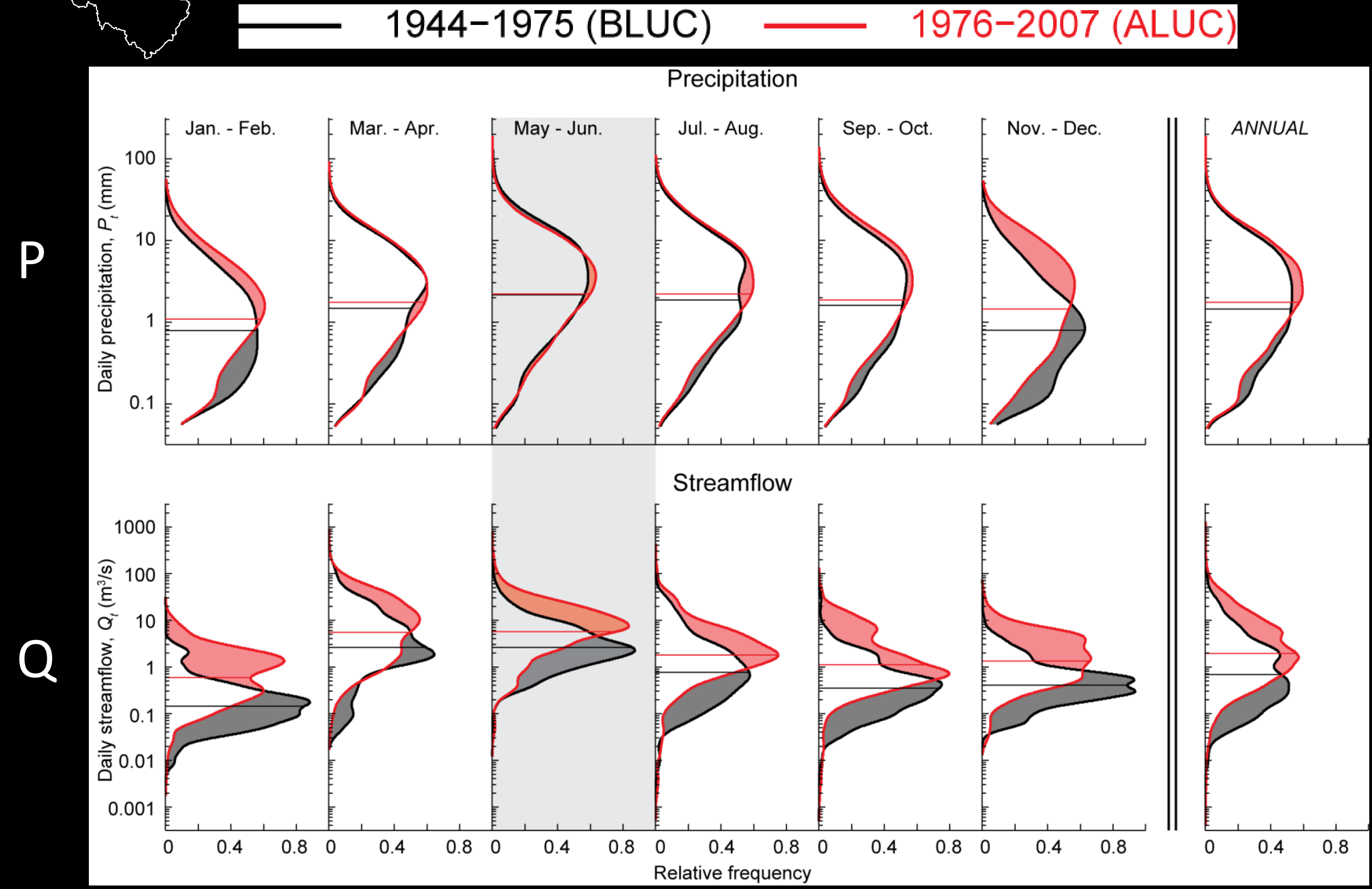


Whetstone Redwood

Foufoula-Georgiou et al., 2015, WRR



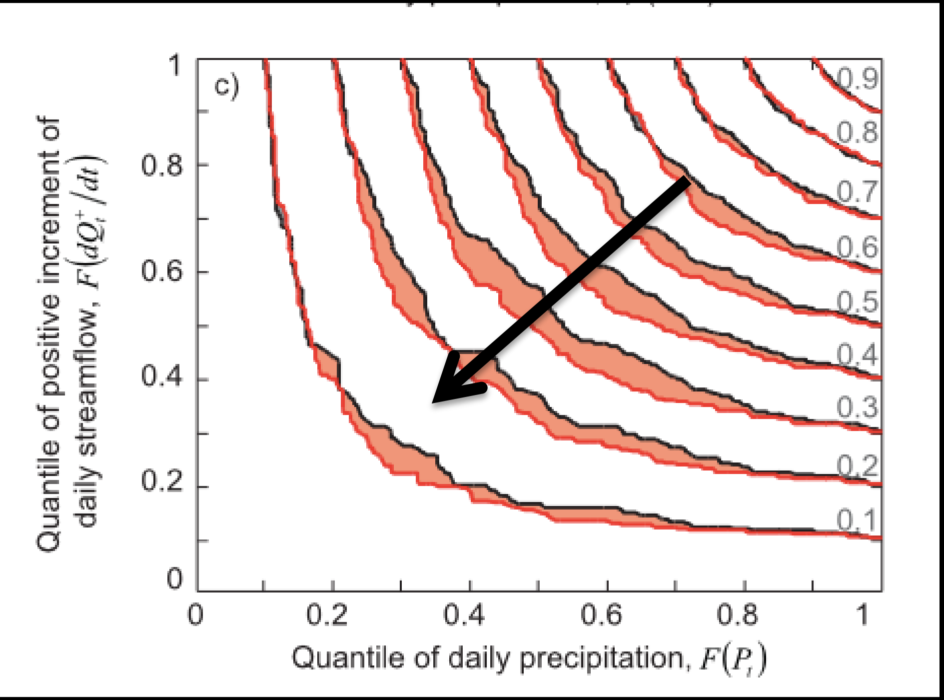
MRB: Streamflow change



Foufoula-Georgiou et al., 2015, WRR

Strengthened dependence of daily dQ^+/dt on P

Copula analysis



A strengthened dependence of a daily streamflow increase (dQ+/dt) in response to previous day precipitation

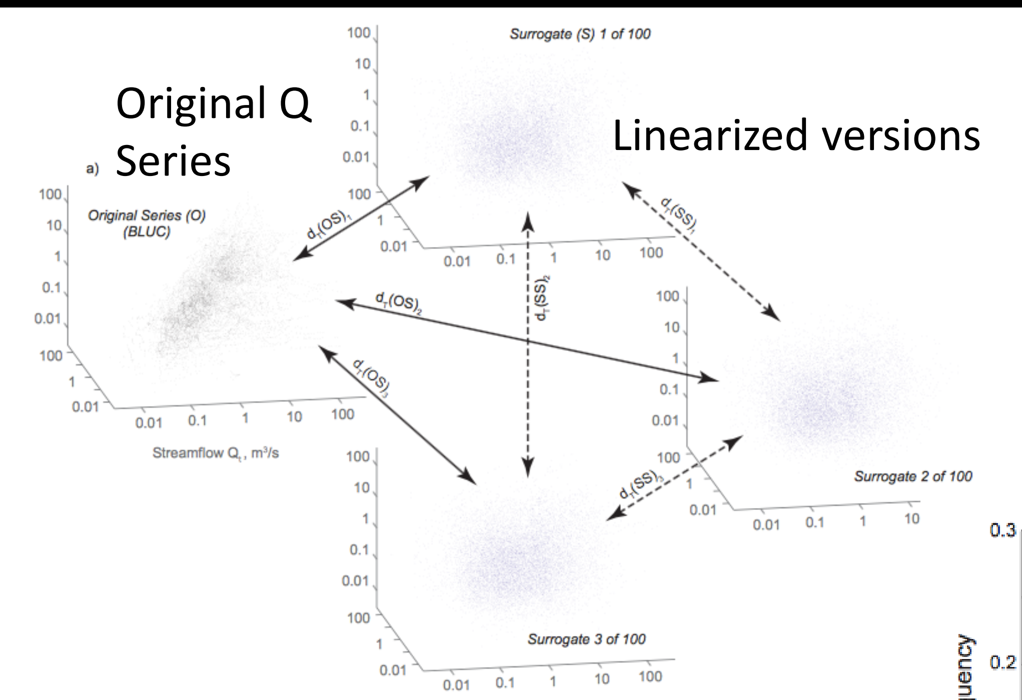
This is especially so in mid-quantiles

Foufoula-Georgiou et al., 2015, WRR

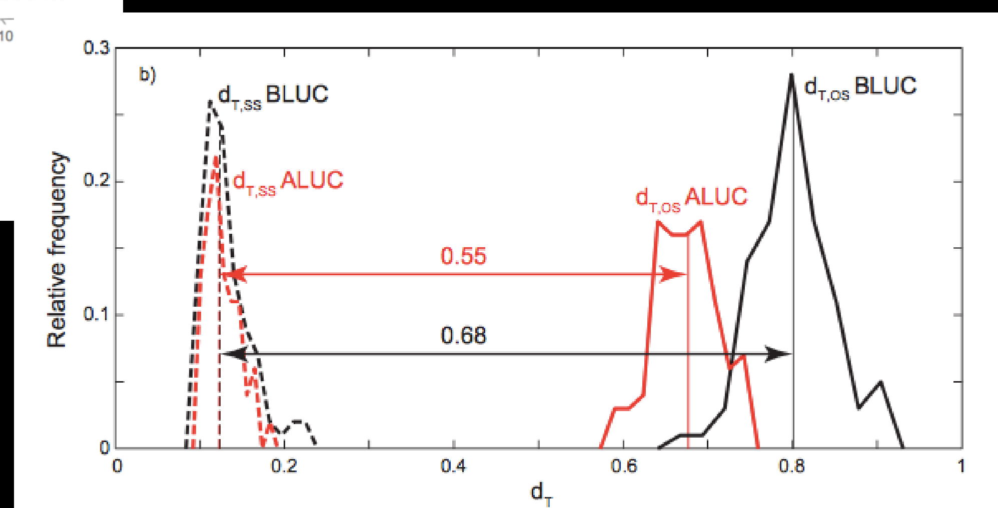
Reduction of inherent NL in daily Q dynamics!

(signature of a more “regulated” system due to tile drainage)

Phase space reconstruction



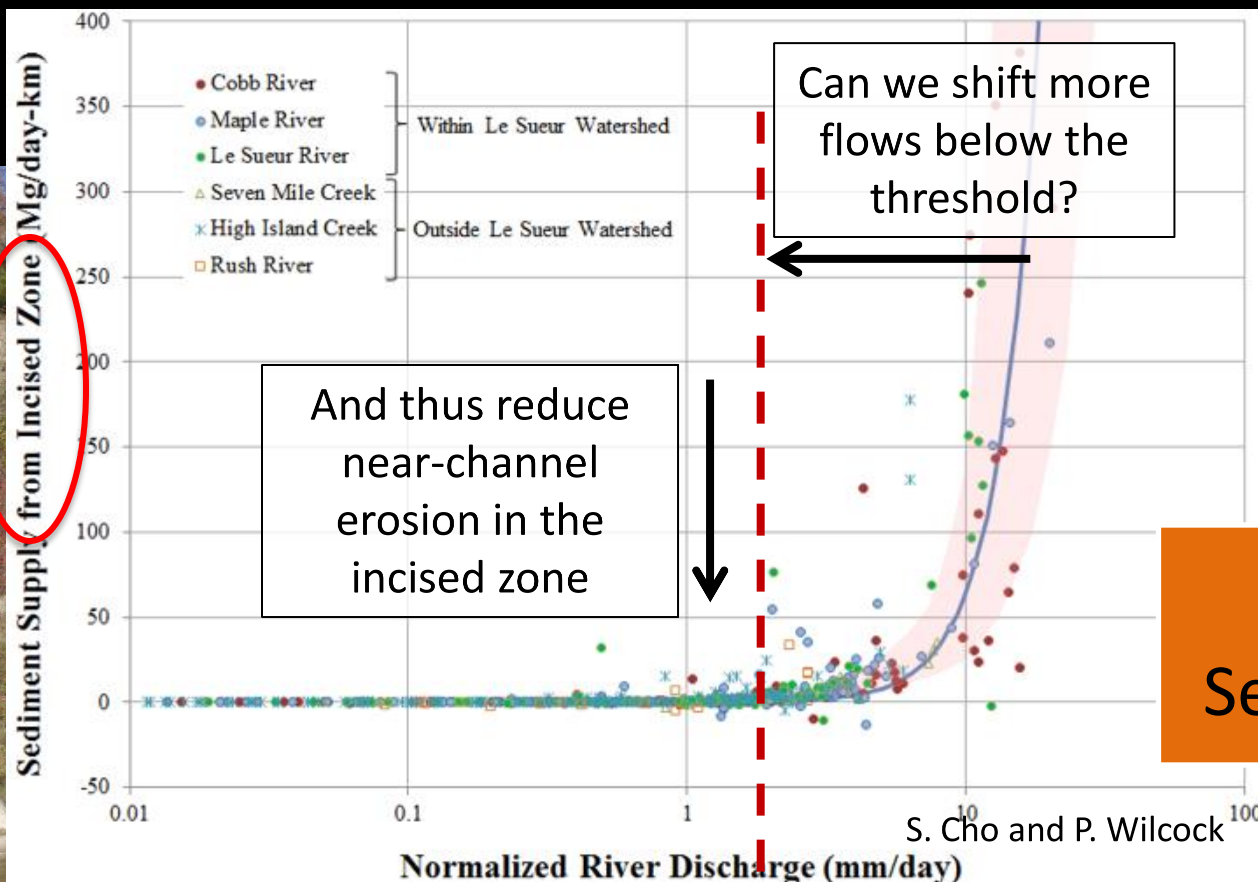
Reduced NL after LUC



Foufoula-Georgiou et al., 2015, WRR

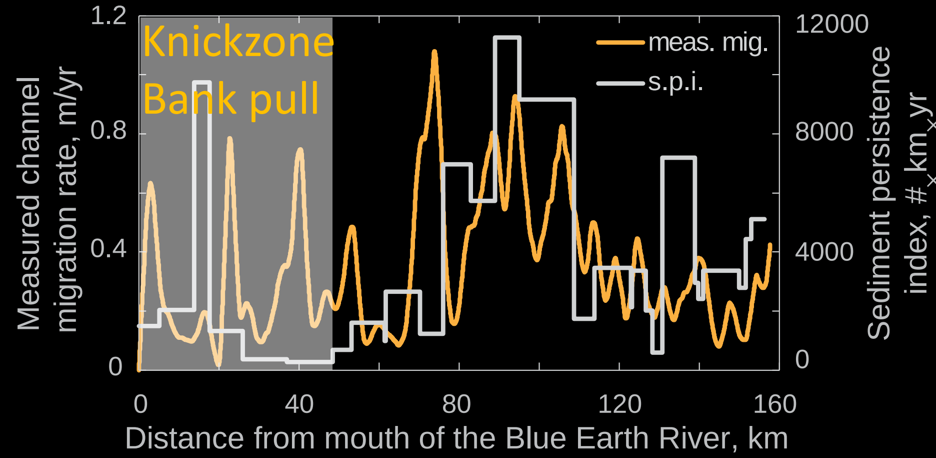
Streamflow to Sediment Cascade?

- Amplified Q increases sediment generation
- Hydrology determines effectiveness of sediment reduction management options

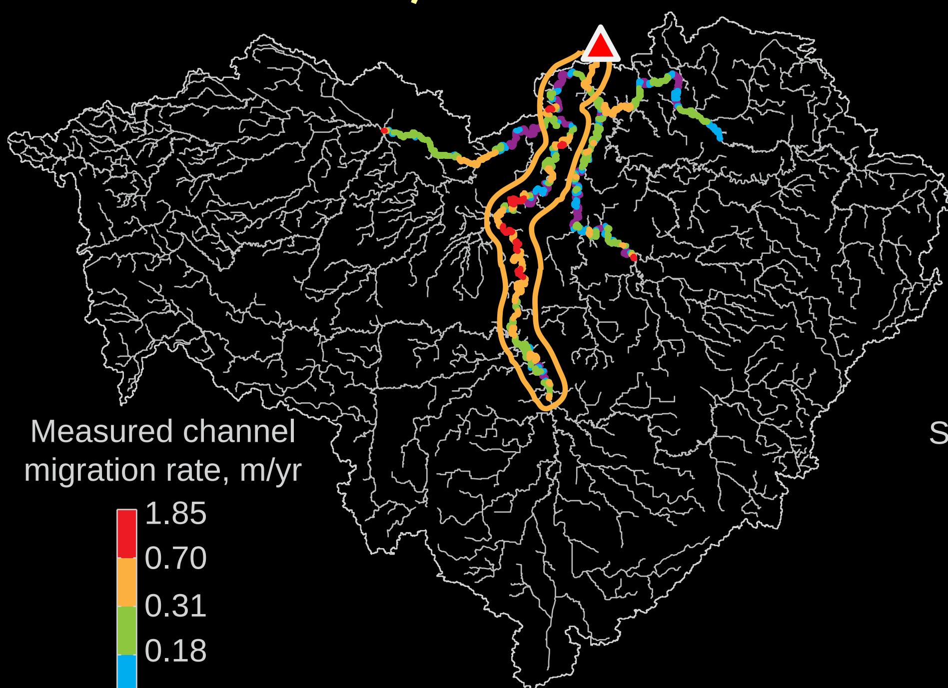


Hotspots of geomorphic change?

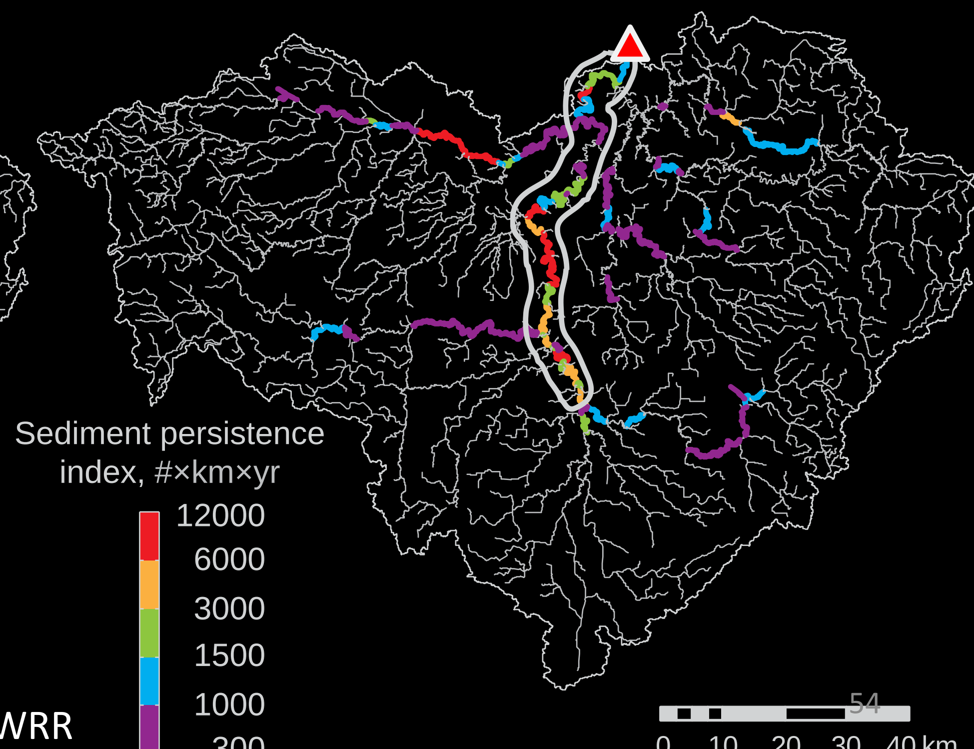
Above knickzone, a simple network-based model predicts persistence of sediment & identifies hotspots of channel migration suggesting bar push may be a driving mechanism.



Measured channel migration rate, 1938-2005

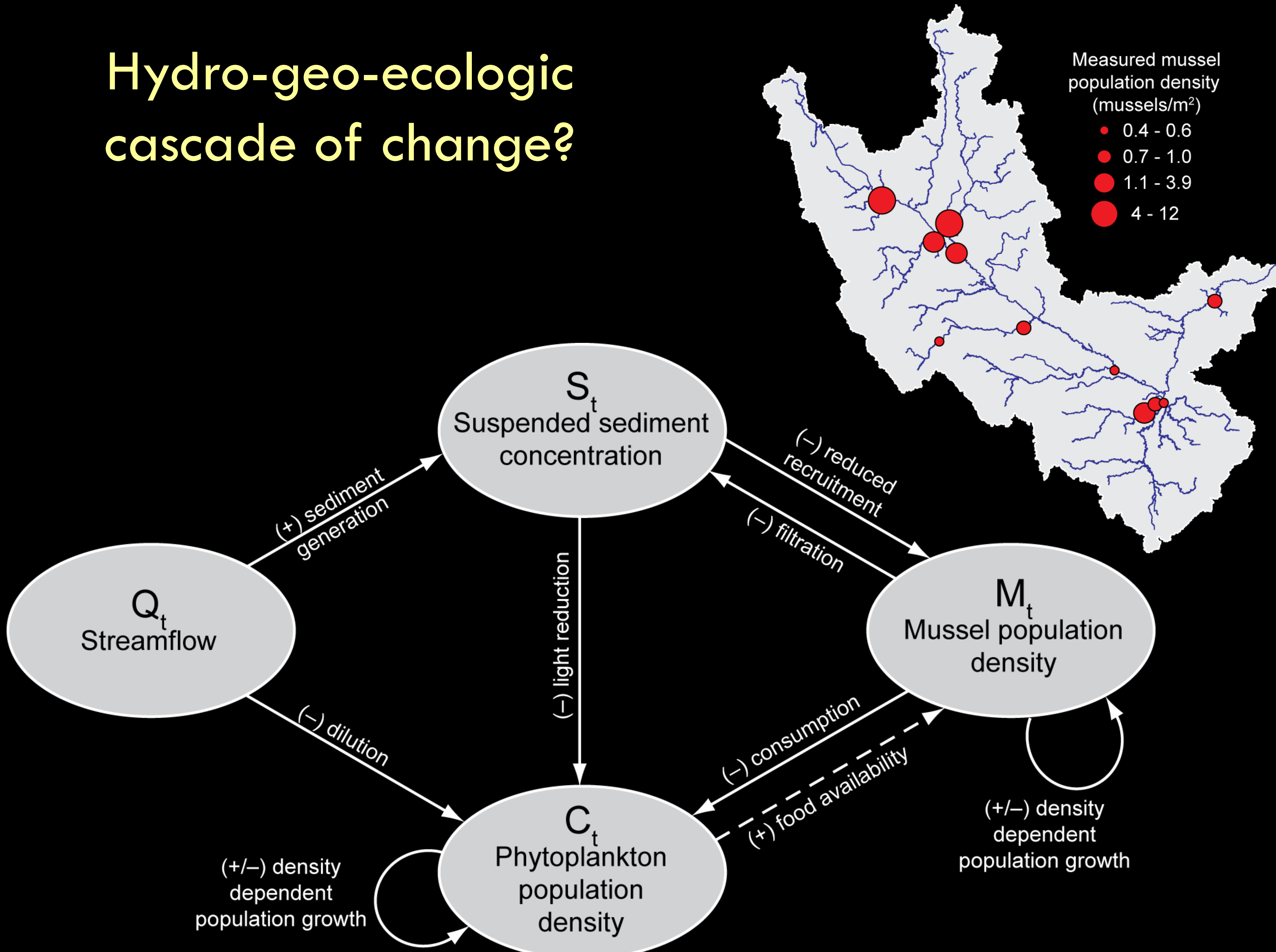


Modeled Sediment persistence index



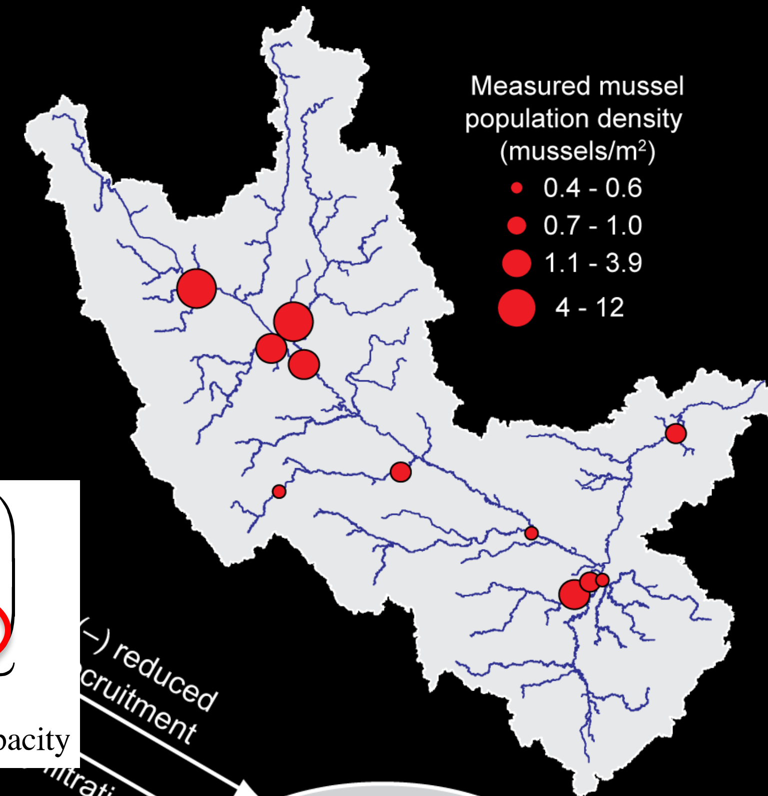
Czuba and Foufoula-Georgiou, 2015, WRR

Hydro-geo-ecologic cascade of change?



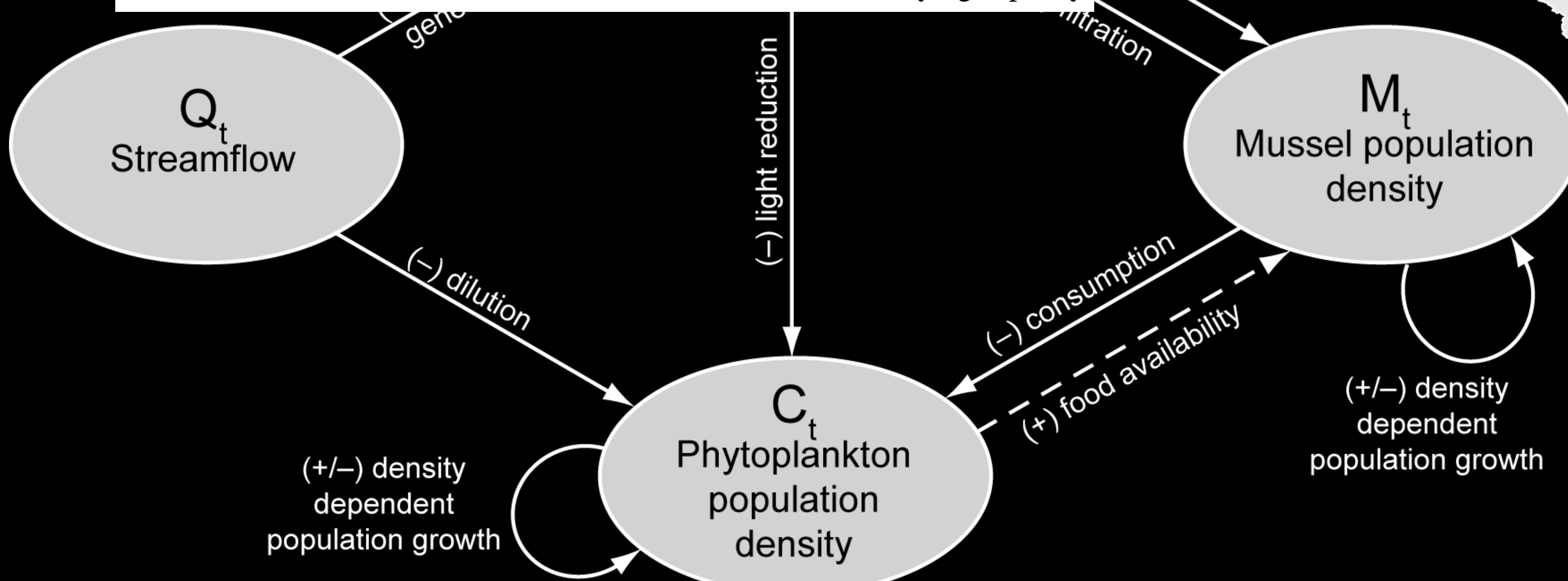
Hansen et al., 2015, Freshwater Science

Hydro-geo-ecologic cascade of change?



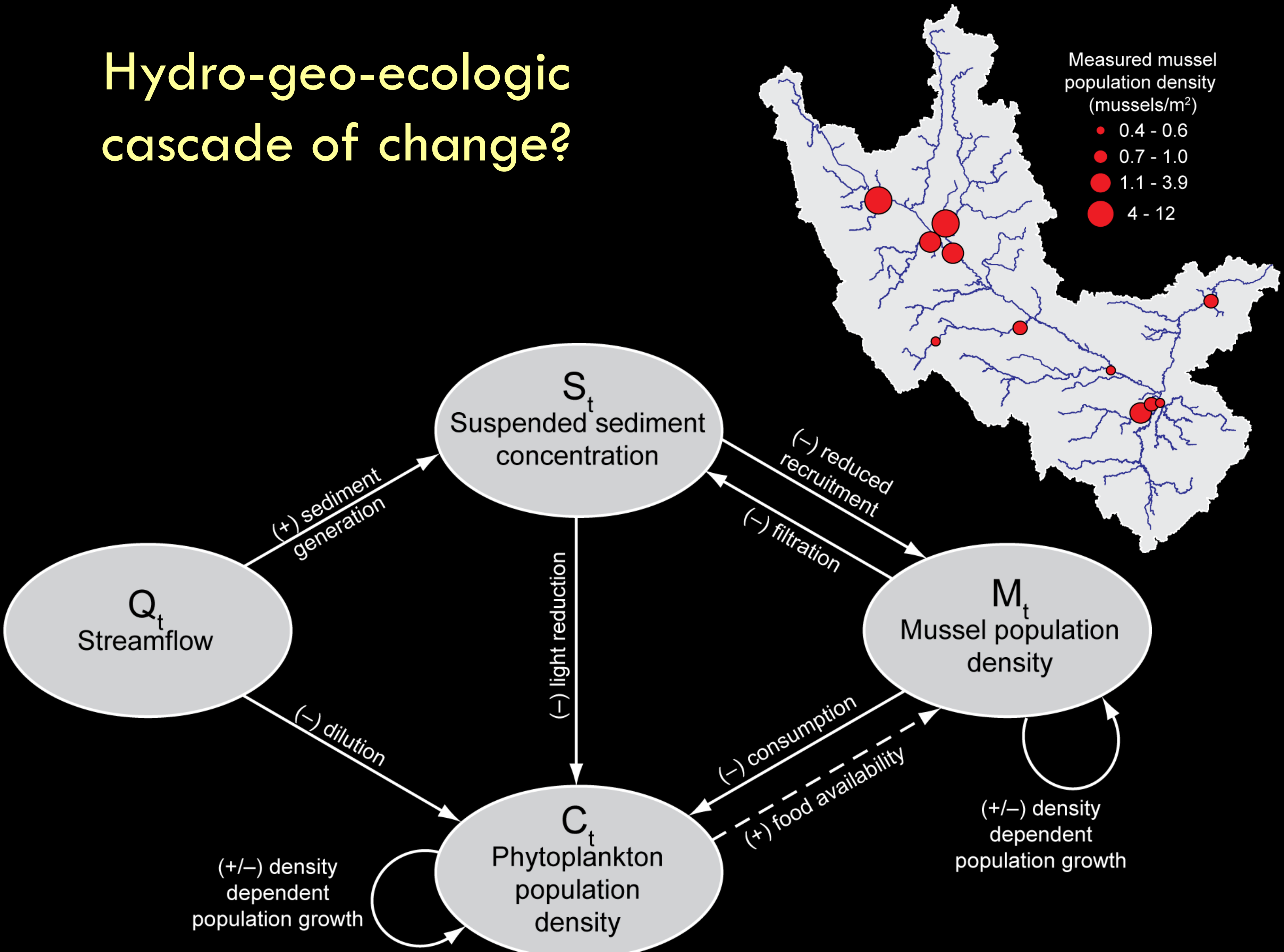
Mussel population density (mussels/m^2), M_t

$$\frac{dM_t}{dt} = \underbrace{f_5(S_t)}_{\text{sediment modulated mussel pop. growth rate}} \; \underbrace{M_t\left(1-\frac{M_t}{f_6(C_t)}\right)}_{\text{logistic growth with food modified effective carrying capacity}}$$



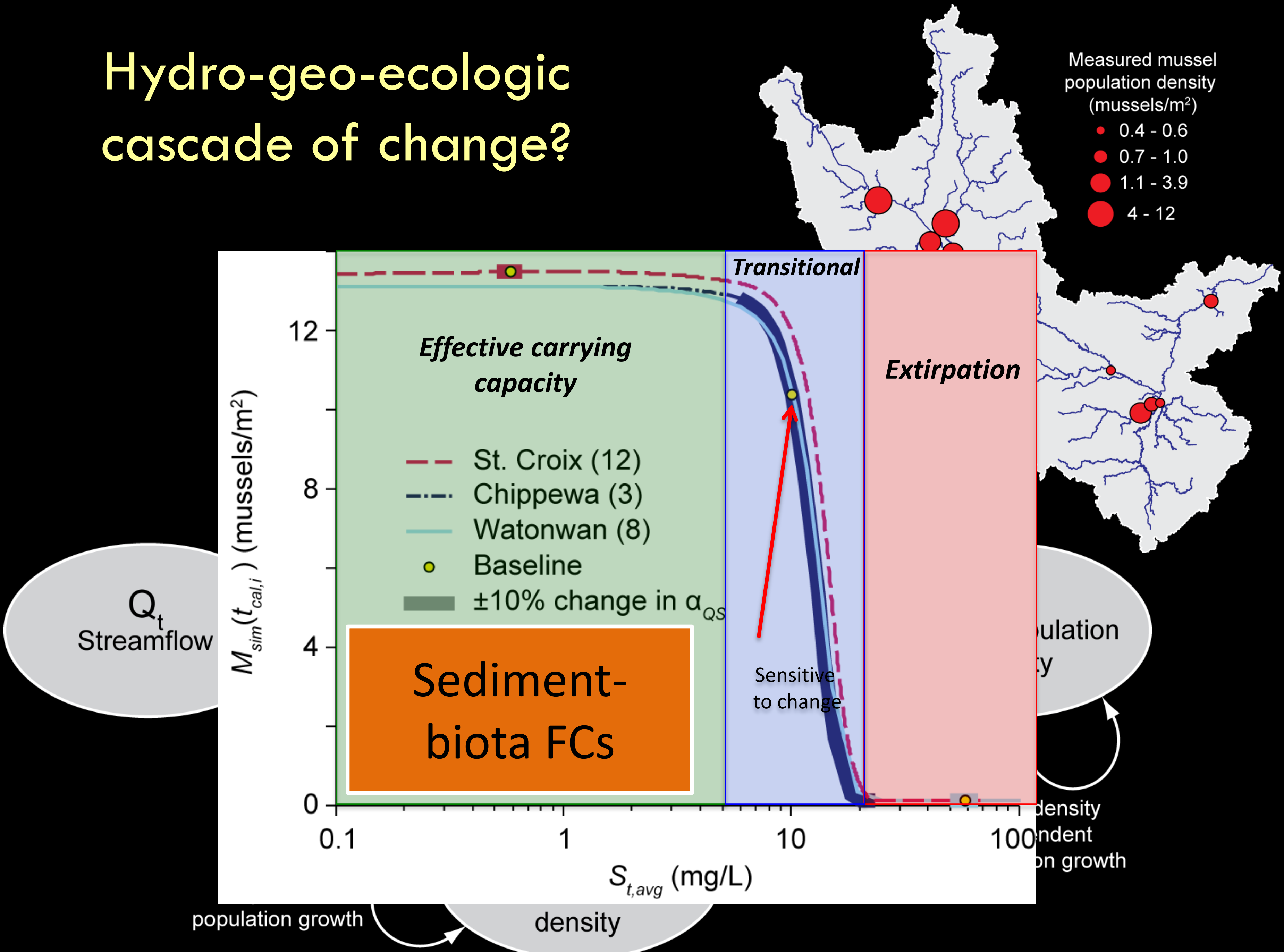
Hansen et al., 2015, Freshwater Science

Hydro-geo-ecologic cascade of change?



Hansen et al., 2015, Freshwater Science

Hydro-geo-ecologic cascade of change?



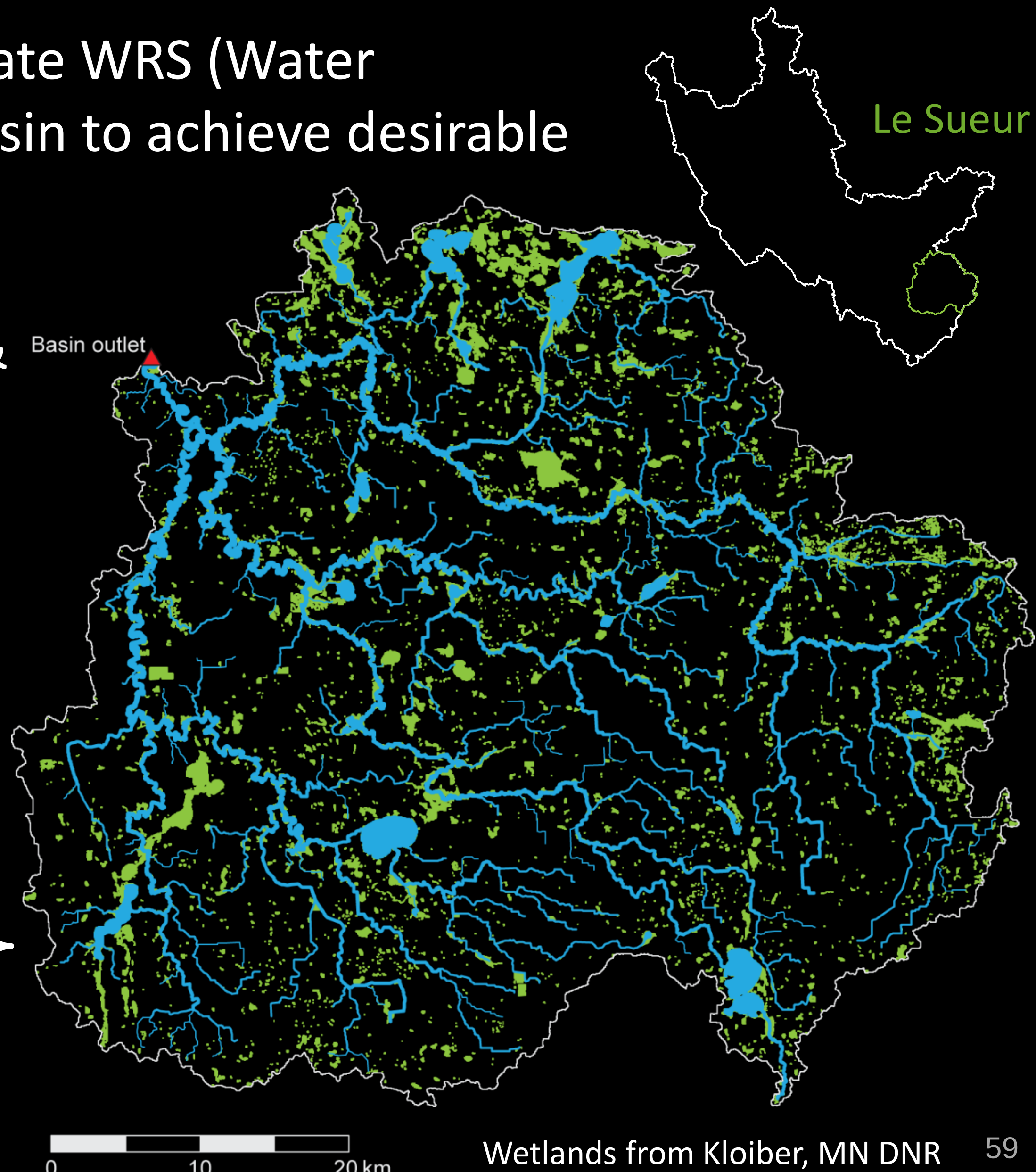
Hansen et al., 2015, Freshwater Science

Distributed Water Management Strategy

- Design and strategically locate WRS (Water Retention Sites) within a basin to achieve desirable goals
- WRS: functional wetlands & Temporary H2O Impoundment sites

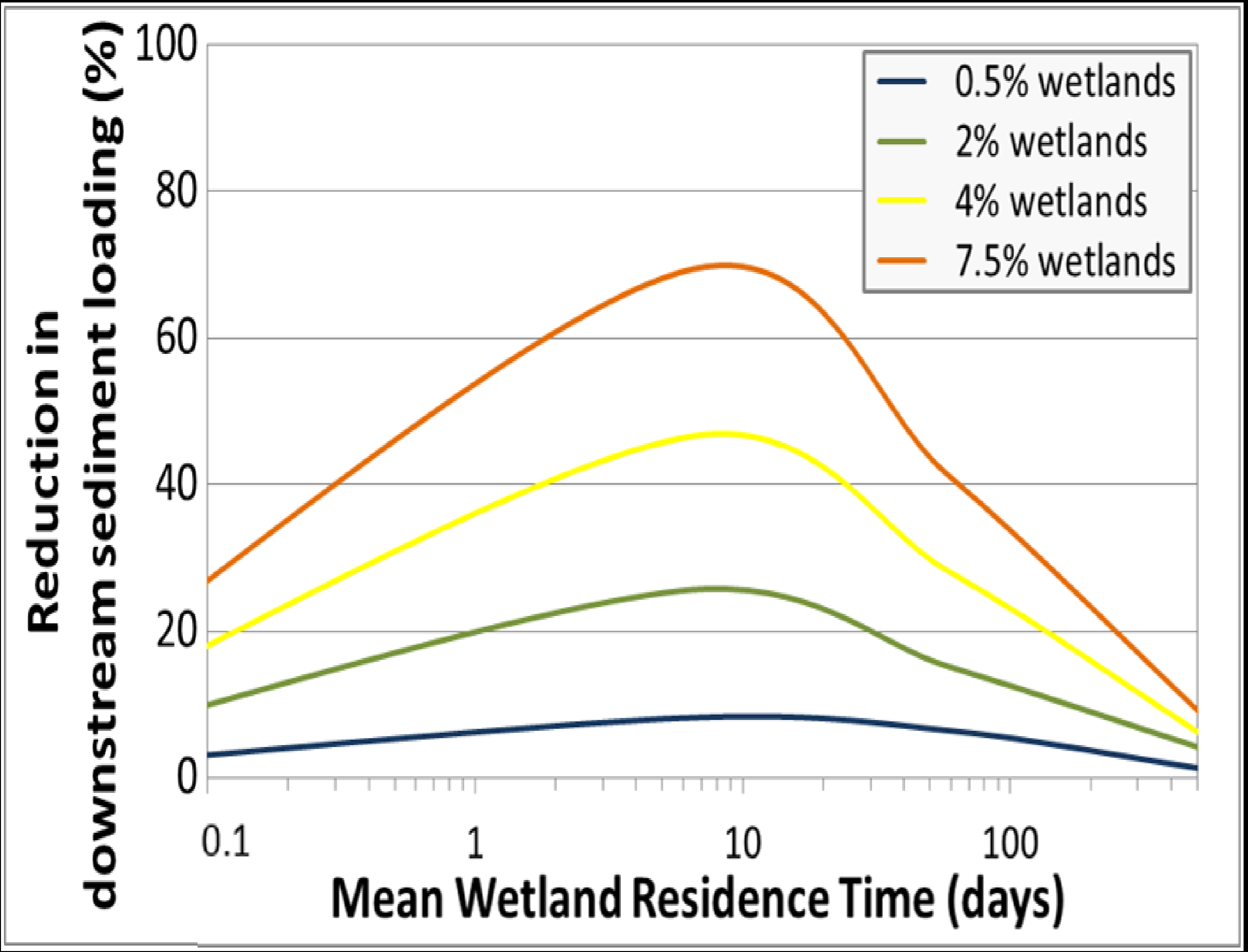
⇩

Hydraulic conductivity
Extent
Depth
Location



Wetlands from Kloiber, MN DNR

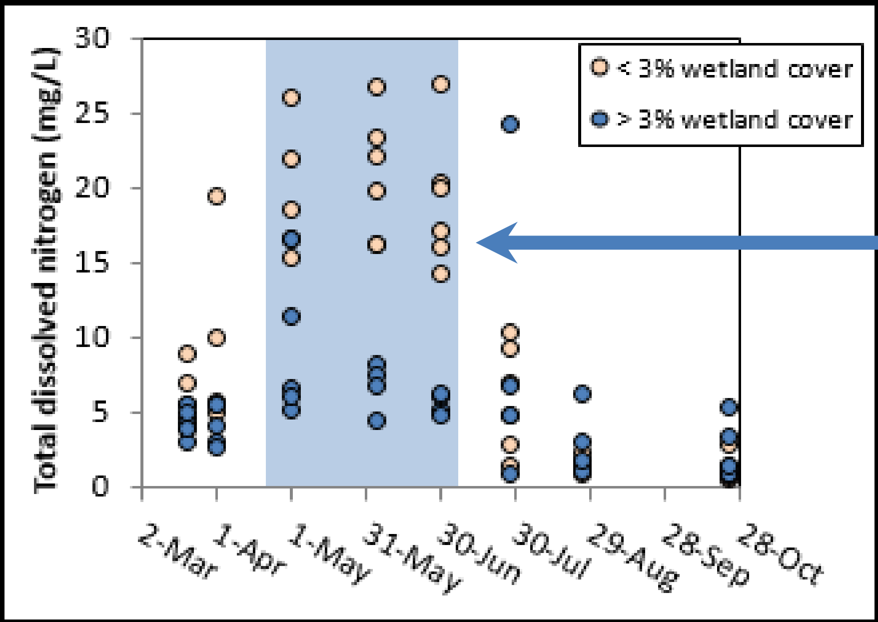
Water Retention Structure (WRS) to sediment reduction?



WRS-Q reduction FCs

Karen Gran, Patrick Belmont

Wetlands also decrease nitrogen concentrations in ditches during most critical season

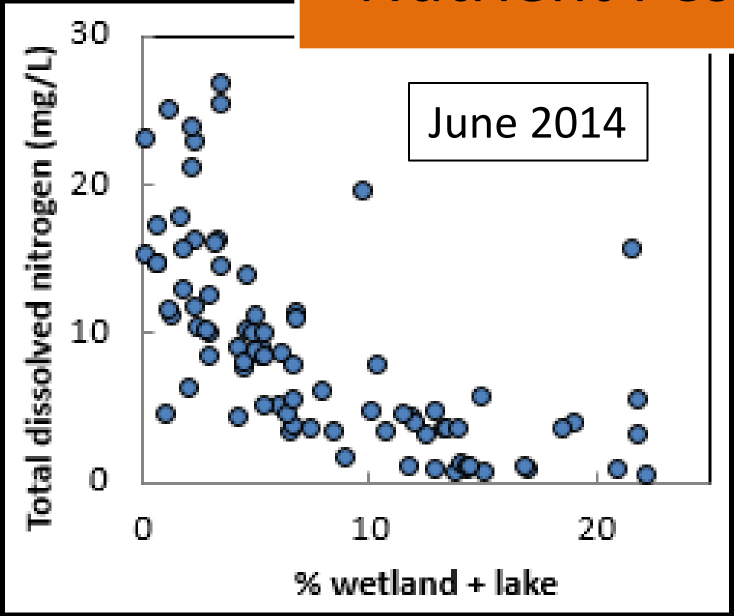


A small wetland can go a long way…

- Typically highest flows (large impact on loads)
- Apr-June flux sets size of Gulf Hypoxic Zone (Turner et al. 2012)

Water-Nutrient FCs

Wetland coverage is a 1st order control of TDN reduction in June w/ important thresholds of diminishing returns



- 94 sites in 3 HUC-8 basins, sampled same week in June 2014
- Drainage areas: 3 to 5800 km^2
- All sites with controlled % cropland (85% cropland +/- 2.5%)

J. Finlay, A. Hansen

FRAMEWORK: Sustainability through Vulnerability Science

1. Space-time signatures of vulnerability

-- critical *space-time localization*, leading *indicators of abrupt system shifts*, vulnerability maps, *coupled interactions*

2. Scale dependence of vulnerability

-- *heterogeneity* is a fundamental governing variable
-- natural processes, human management actions and policies are *scale dependent*
-- at what scales to evaluate a system for sustainability?

3. Process chains and vulnerability

-- *Nonlinear amplifications* and *thresholds* govern evolution of human-natural system

4. Hierarchical reduced-complexity modeling for emergent processes

-- Only a *subset of dynamics* at one scale strongly affects those at other scales

We are at an important junction …

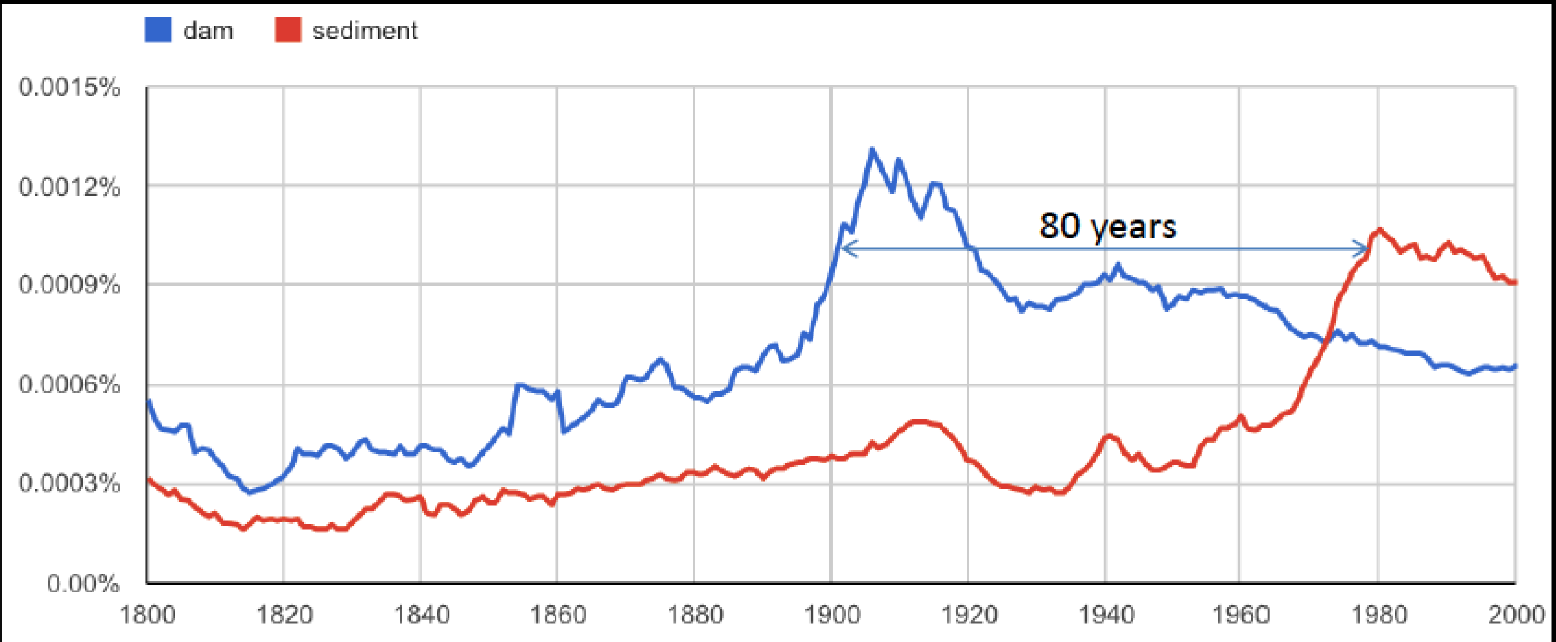
Humans have made profound changes to water, sediment and nutrient regimes

"Humans have simultaneously increased the sediment transport by global rivers through soil erosion (by 2.3 billion Mg/yr), yet reduced the flux of sediment reaching the world's coasts (by 1.4 billion Mg/yr) because of retention within reservoirs."

~Syvitski et al., 2007

… We chocked rivers and starved deltas ….

Unintended Consequences realized yrs later



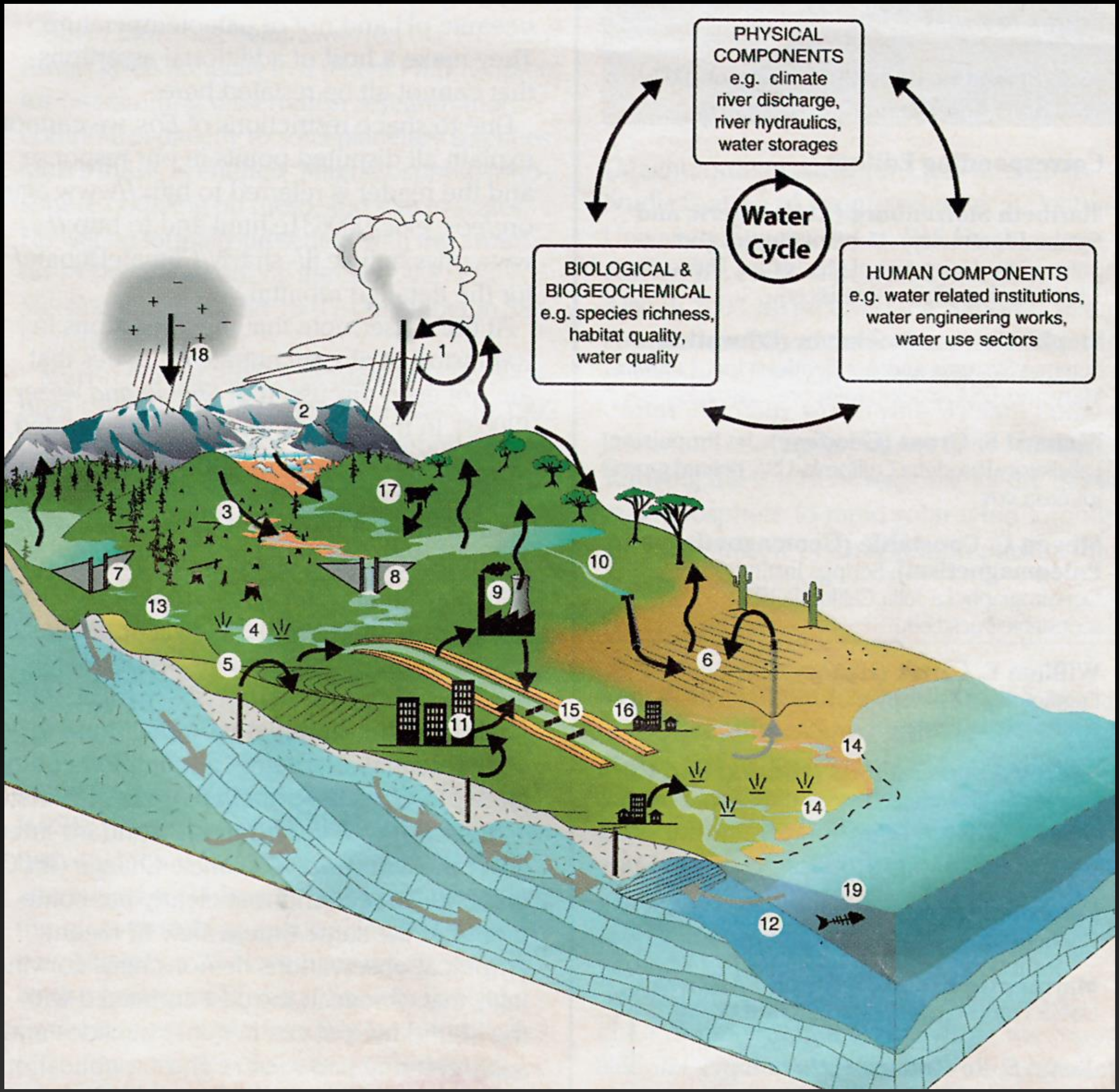
Google n-gram: Measures relative occurrence of words in books over the past 200 years

Courtesy of S. Gibson and P. Boyd, USACE

We treated the Hydrologic Cycle alone …

And climate change comes on top of everything else …

The "Earth-Water-Life Cycle"



Vorosmarty et al., EOS, 2014

The Needs/The Vision

1. We need to understand the Earth-Water-Life cycle better (including the effects of human "replumbing"): quantitatively, process-based, from weather to climate scales and from the basin to continental scale

1. We need integrated wide-ranged observations (hydro-meteorological, geophysical, geochemical, geochronological, HR topography, biological, …) to discover critical interactions and constrain models

1. We need to pursue model development (from reduced complexity to fully coupled) with an eye towards making testable predictions

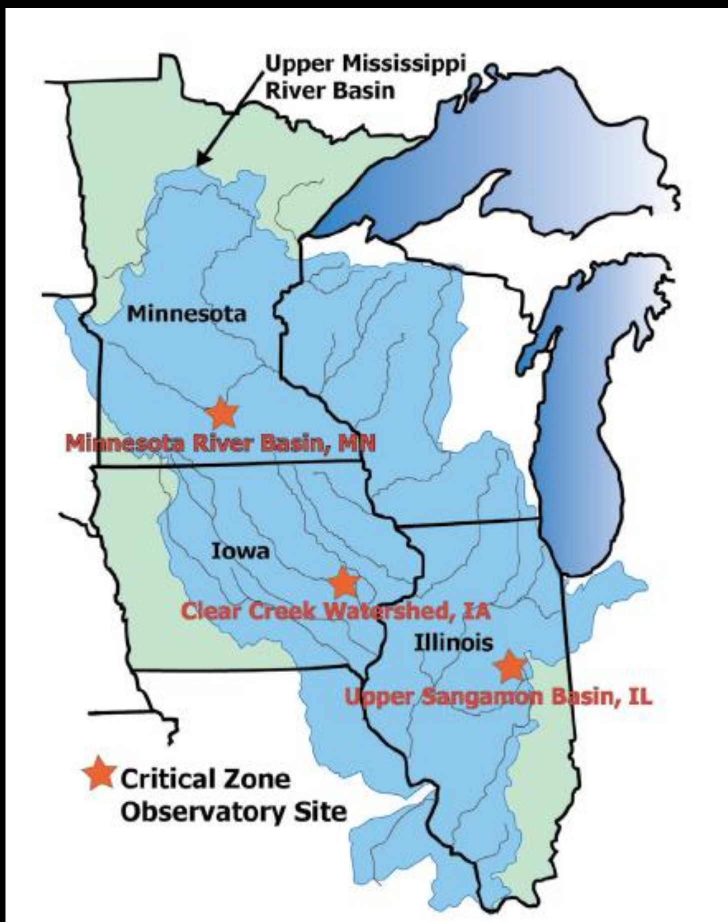
1. We need to engage decision makers, policy makers and the public

2. We need to educate the next generation of T scientists

Sustained Interdisciplinary Collaboration

INTENSIVELY MANAGED LANDSCAPES
Critical Zone Observatory (IML-CZO)

NSF



REACH
Resilience under
Accelerated
Change

A Water Sustainability and Climate Project

Engaging the public: "SIP of Science"

Engaging the public to science-based solutions on pressing problems

"The Sip of Science series features *discussions that bridge the gap between science and culture in a setting that bridges the gap between brain and belly.* "

The series takes place the second Wednesday of every month.

SMM: Future Earth Exhibit

Summer Institute on Earth-surface Dynamics

Mentoring the Next Generation of Earth-surface Scientists

SIesd

2009: Complexity and predictability in earth systems
2010: Rivers and Vegetation
2011: Coastal processes and dynamics of deltaic systems
2012: Future Earth: Prediction under environmental change
2013: From sub-surface to surface
2014: Complexity and predictability in earth's surface
2015: Earth-casting under human and climate pressures
2016: Intensively Managed Landscapes

The AMS community has a vital role to play…

A career’s worth of people to thank!

Past PhD students

-- Praveen Kumar (1993)
-- Sanja Perica (1995)
-- Alin Carsteanu (1997)
-- Venu Venugopal (1998)
-- Deborah Nykanen (2000)
-- Boyko Dodov (2003)
-- Sukanta Basu (2004)
-- Chandana Gangodagamage (2009)
-- Paola Passalacqua (2009)
-- Arvind Singh (2011)
-- Vamsi Ganti (2012)
-- Ardeshir Mo Ebtehaj (2013)

Past post-doctoral fellows

-- Victor Sapozhnikov
-- Daniel Harris
-- Bruno Lashermes

Collaborators (a few of many)

-- Kevin Droegemeier
-- Chris Paola
-- Vaughan Voller
-- Bill Dietrich
-- Patrick Belmont
-- Peter Wilcock
-- Ilya Zaliapin
-- Stefano Lanzoni
-- Michele Guala
-- Chris Keylock
-- Tryphon Georgiou
-- …

Special thanks to my research group


Jon Schwenk


Jon Czuba


M. Danesh


Z. Takbiri


A. Hansen


A. Longjas


A. Tejedor


Mahesh


Zi Wu


Mulu

… and my kids


Katerina


Thomas

Thank you!

1:30 PM-2:30 PM: Wednesday, 13 January 2016

Lecture 3
Horton Lecture
Location: Room 240/241 (New Orleans Ernest N. Morial Convention Center)
Hosts: (Joint between the **32nd Conference on Environmental Information Processing Technologies**; the 23rd Conference on Probability and Statistics in the Atmospheric Sciences; the Fourth Symposium on the Weather, Water, and Climate Enterprise; the Fifth Aviation, Range, and Aerospace Meteorology Special Symposium; the Seventh Conference on Environment and Health; the 22nd Conference on Applied Climatology; the 13th Conference on Space Weather; the 19th Joint Conference on the Applications of Air Pollution Meteorology with the A&WMA; the 30th Conference on Hydrology; the Special Sessions on US-International Partnerships; the 25th Symposium on Education; the 14th Symposium on the Coastal Environment; the 12th Annual Symposium on New Generation Operational Environmental Satellite Systems; the Fourth Symposium on Building a Weather-Ready Nation: Enhancing Our Nation's Readiness, Responsiveness, and Resilience to High Impact Weather Events; the Fourth AMS Symposium on the Joint Center for Satellite Data Assimilation (JCSDA); the Peter Lamb Symposium; the 20th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS); the 18th Symposium on Meteorological Observation and Instrumentation; the 14th Conference on Artificial and Computational Intelligence and its Applications to the Environmental Sciences; the 11th Symposium on Societal Applications: Policy, Research and Practice; the Seventh Conference on Weather, Climate, Water and the New Energy Economy; the Sixth Conference on Transition of Research to Operations; the Fourth Symposium on Prediction of the Madden-Julian Oscillation: Processes, Prediction and Impact; the 28th Conference on Climate Variability and Change; the Events; the 18th Conference on Atmospheric Chemistry; the 14th History Symposium; the Eighth Symposium on Aerosol–Cloud–Climate Interactions; and the Special Symposium on Seamless Weather and Climate Prediction—Expectations and Limits of Multi-scale Predictability)

1:30 PM L3.1
Climate and Humans as Amplifiers of Hydro-ecologic Change: Science and Policy Implications for Intensively Managed Landscapes (Invited Presentation)
Efi Foufoula-Georgiou Sr., Univ. of Minnesota/National Center for Earth Surface Dynamics, Minneapolis, MN