Dynamic connectivity and response to change: what can be learned for managing River basins?

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Panta Rhei: Change in Hydrology and Society
EGU, Vienna, April 2014

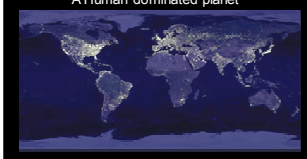
Panta Rhei
"Ever-present change in the universe"

Heraclitus of Ephesus (535 – 475 BCE)

" The "*weeping philosopher*" wringing his hands over the world

"Ever-present change in the universe"

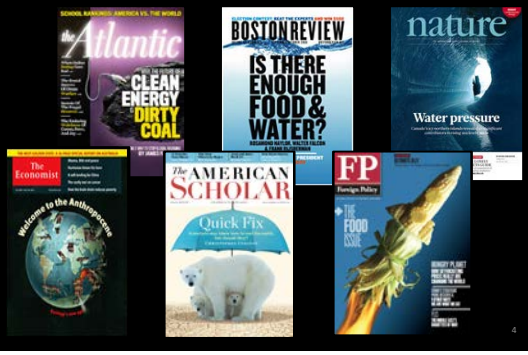
A Human dominated planet



Arctic sea ice

1979 2003

"Ever-present change in the universe"



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Today, I will talk about …

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

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Intensively managed landscapes

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

http://www.nasa.gov/press/goddard/2014/march/satellite-shows-high-productivity-from-us-corn-belt/#.U0AkG1cqgad

Put things into perspective: Economy, Food security, Environment

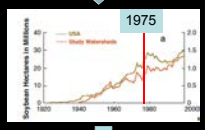
2013 approximate statistics for mid-western US (USDA)

Corn
Acres harvested: ~ 87 million acres = 4.2 Austrias
Average yield: 160 bushels/acre => 14 billion bushels
On farm grain price: $7.6/bushel

Soybean
Acres harvested: ~ 35 million acres = 1.7 Austrias
Average yield: 43 bushels/acre => 3.4 billion bushels
On farm grain price: $15/bushel

(1 acre = 63 by 63 meters; 1 Austria=83,871 km2)

Economy



Environment?

http://cornandsoybeandigest.com/blog/usda-increases-expected-crop-production

Intensively managed landscapes

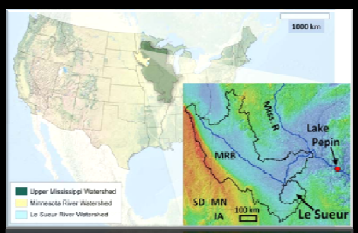
Artificial Drainage (ditches, tiles, wetland drainage) affects hydrology:

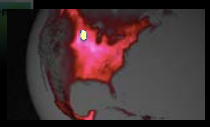
(1) Permanently decreases residence time of water on landscape
(2) Decreases evaporative losses
(3) Reduces soil-profile storage

(A) Increases water yield
(B) Redistributes hydrologic response at all scales
(C) Increases river erosion, sediment loads, turbidity
(D) Affects river biotic life

Minnesota River Basin (MRB)

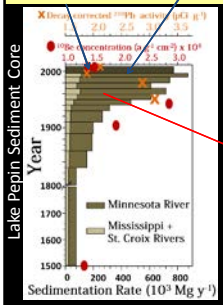
Convergence of geologic history and human actions





MRB: A system of excessive sedimentation

A recent shift in sediment sources
From **top soil** to near **bank eros**



Belmont et al. 2011 ES&T

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

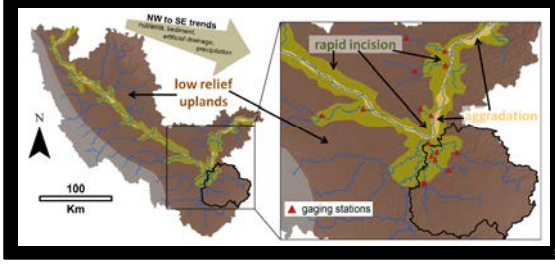
MRB is primary source of sediment and nutrients for Lake Pepin (37% area, 90% sediment)

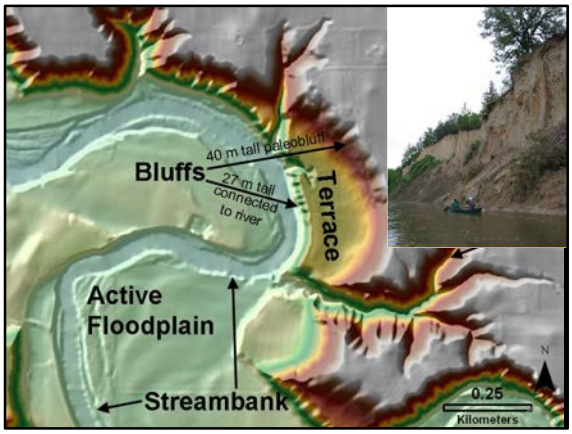
Why this regime shift in sediment sources

2 main reasons …

(1) Landscape structure (established 13.4 kyr ago)

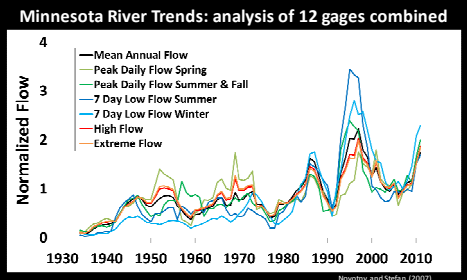
Uplands: flat land, passive rivers





(2) Changing Streamflows

Caused by combination of climate, artificial drainage, and land/crop management

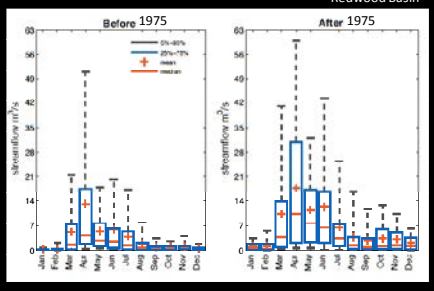


Five year running averages and normalized by the 1950-2002 mean values

Novotny and Stefan (2007)
Additional data from Sara Kelly

Monthly streamflow change

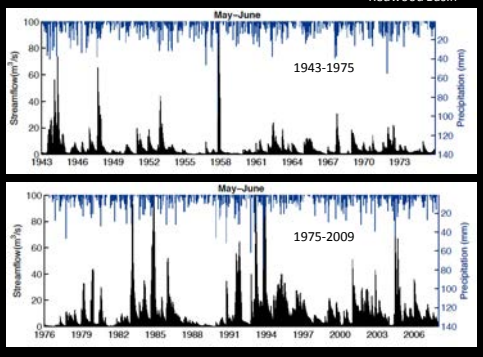
Redwood Basin



Planting season: Corn: April - June
Soybeans: end of April – June

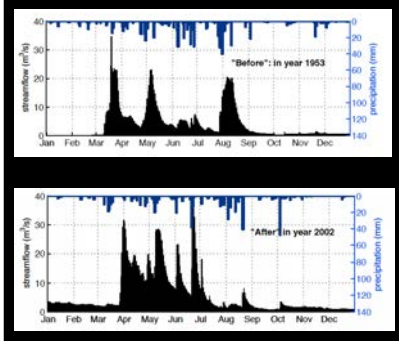
Daily streamflow change: May-June

Redwood Basin



Hydrologic response change

Redwood Basin

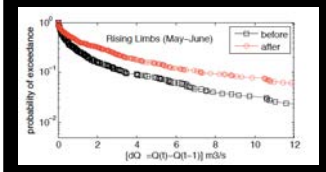


Year 1953
Total Rain: 700 mm
Total Q: 1,472 m3/sec

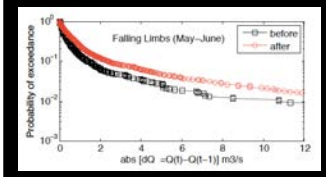
Year 2002
Total Rain: 635 mm
Total Q: 2,183 m3/sec

Hydrograph shape has changed

Redwood Basin



Rising Limbs at daily scale



Falling Limbs at daily scale

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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. What is the cascade of changes from hydrology to sediment production and transport, to stream geomorphologic change, to water stream biotic life?
3. How to identify "hot spots" of vulnerability to change to inform mitigation and/or management decisions?
4. In the absence of detailed physical models (challenged with scale and non-stationarity) what simpler models can capture essential elements of vulnerability to change?

FRAMEWORK: Sustainability through Vulnerability Science

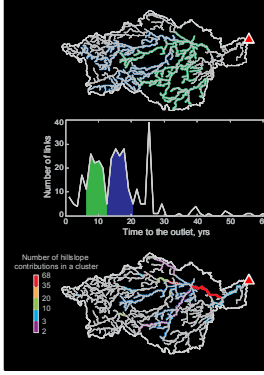
1. Space-time signatures of vulnerability
-- many key processes in complex systems are highly space-time localized (hot spots and moments for denitrification, river avulsion, localized sources of erosion, human-sensitive areas to flooding, etc.)
-- precursor signatures of accelerated change lead to abrupt system shifts
-- create "vulnerability maps" that overlay potential disturbances, measures of adoptive capacity, and effect of critical coupled interactions

2. Scale dependence of vulnerability
-- Heterogeneity is a fundamental governing variable itself
-- governance actions are also scale dependent
-- at what scale to evaluate a system for sustainability?

3. Process chains and vulnerability
-- Nonlinear amplifications and thresholds determine system evolution
-- identify chains of processes – natural and human – linked by strong interactions

4. Modeling
-- Reduced complexity models (RCMs), account for emergence and process hierarchy in which only a subset of the dynamics at one scale strongly affects those at other scales

RCMs for river basin sustainability



Response at outlet of basin
- Source contributions to peak response
- Synchronization and amplification of fluxes at outlet

Organization within the basin
- Identify emergence of persistent mass clusters
- Source contributions to clusters

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Sand transport process

Decompose the volumetric sand flux into a bulk velocity and two length scales:

$$Q_{s,i} = u_{s,i}(\theta_i H_i) B_i$$

At Q2:

Uniform flow

$$\tau_{b,i} = \rho g H_i S_i = \rho C_{f,i} u_{w,i}^2$$
$$Q_{w,i} = u_{w,i} H_i B_i$$

Sand transport

$$q_{s-i} = \frac{0.05}{C_{f,i}} (\tau_{-i})^{5/2}$$

Engelund & Hansen, 1967

Hydraulic geometry

$$u_{w,i} = (0.2) A_i^{0.07}$$
$$H_i = (0.003) A_i^{0.29}$$

Sand transport velocity at Q2: $u_{s,i} = (0.32) A_i^{0.285} S_i^{3/2}$

$$v'_{s,i} = \frac{\ell_i}{u_{s,i}}$$

Intermittency of Q2: $i'_{s,i} = i_{f,s} i_{s,i}$

Sand travel time: $t_{s,i} = (18) \ell_i A_i^{-0.285} S_i^{-3/2}$

ℓ_i link length
A_i upstream drainage area
S_i slope

see Czuba & Foufoula-Georgiou, 2014, WRR

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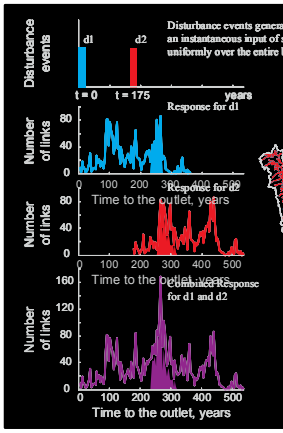
Synchronization of sediment delivery



Minnesota River Basin

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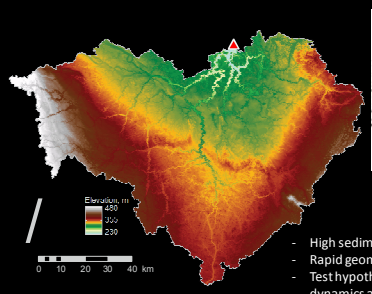
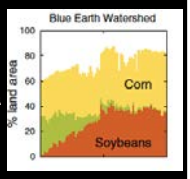
Blue Earth Basin





- High sediment loads
- Rapid geomorphic change
- Test hypothesis that climate and human dynamics are amplifying natural change

$A = 9{,}200\ km^2$

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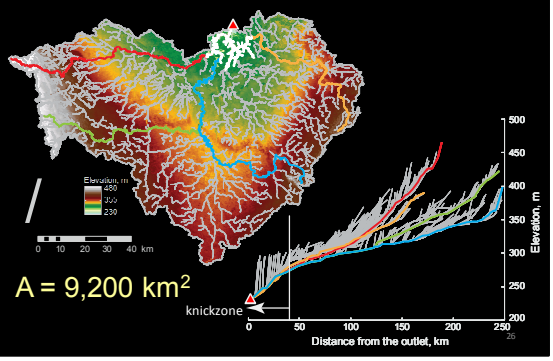
Blue Earth Basin



$A = 9{,}200\ km^2$

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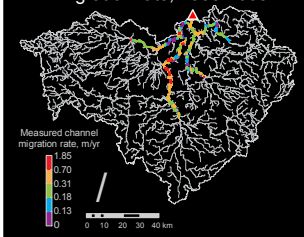
Geomorphic change in the Blue Earth Basin

Measured channel migration rate, 1938-2005



Data from K. Gran, M. Bevis, & P. Belmont

High rates of channel migration

- deliver large quantities of sediment to the river network,
- indirectly affect water quality and biotic functioning, and
- increase the risk to public and private property.

Challenges:

(1) Can we predict where/how these geomorphic changes arise?

(2) where/how to manage the system to limit future change?

Hypothesis: *vulnerable areas can be predicted by the location of emergent connectivity clusters within the basin.*

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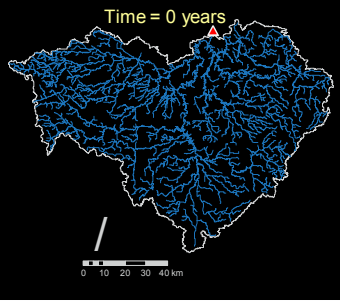
Space-time organization of uniform inputs

Introduce uniform input throughout the basin.

Follow inputs as they transport on the river network.

Time = 0 years



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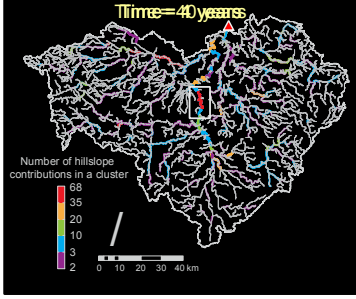
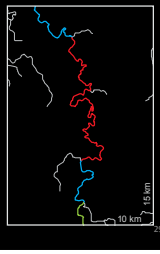
Space-time organization of uniform inputs

Define "cluster": as a group of inputs in close proximity"
(1) Spatial extent of a cluster: Kms
(2) Magnitude: Hillslope equivalent mass

Time = 40 years



Cluster at time = 40 years:
Spatial extent = 14.4 km
Number of inputs = 51 HME



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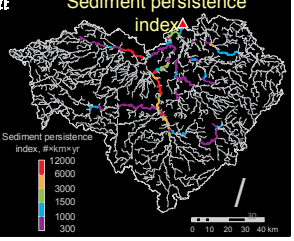
Persistence of organized sediment clusters

Characterize the persistence of sediment mass weighted by spatial cluster extent impacting each link

$$SPI_i = \int_{time} \left(\int_{\substack{all\ links\ j \in \\ cluster\ at\ i}} m_{j,t} \times \ell_j \right) dt$$

Sediment persistence index



SPI_i sediment persistence index of link i

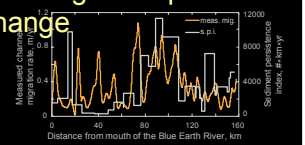
$m_{j,t}$ mass in link j at time t

ℓ_j length of link j

$SPI_i = [Mass \times Length \times Time]$

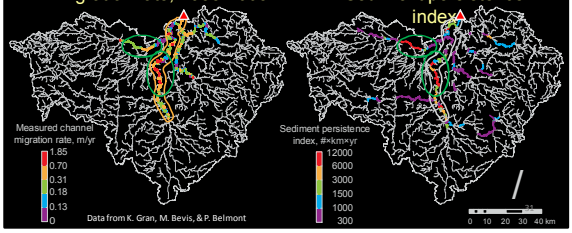
Identify hotspots of geomorphic change

Successfully identified hotspots considering uniform input.



Measured channel migration rate, 1938-2005

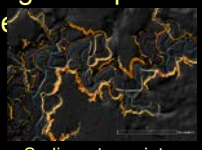
Sediment persistence index



Identify hotspots of geomorphic change

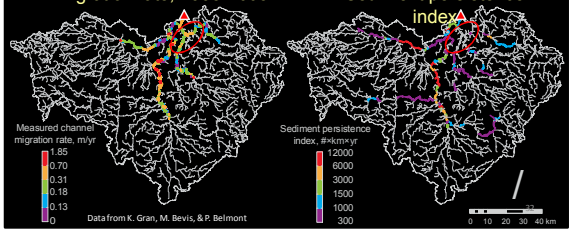
Missed important factors

Because of localized sources of sediment not considered here



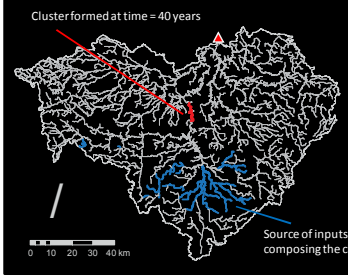
Measured channel migration rate, 1938-2005

Sediment persistence index



Unravel source of large persistent cluster

Locations with large persistent clusters correspond to areas vulnerable to geomorphic change.



Identify the source areas of the basin whose contributions synchronize into large clusters.

QU: What management options are available to break this synchronization?

- reduce sediment inputs
- slow the flow in a critical reach

Source of inputs at time = 0 years composing the cluster at time = 40 years

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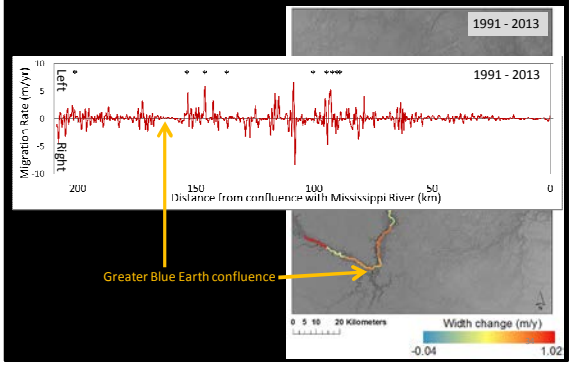
Changes propagate downstream …



"Ever-present change in the universe"

Heraclitus of Ephesus (535 – 475 BCE)

"No man steps on the same river twice "

"Ever-present change in the universe"

Heraclitus of Ephesus (535 – 475 BCE)

"The path up and down are one of the same"

("Unity in opposites")

Thank you!

NCED Summer Institute on Earth Surface Dynamics (SIESD), August 12-21, 2014

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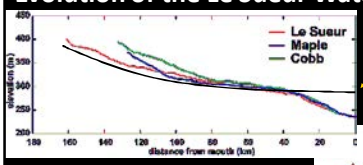
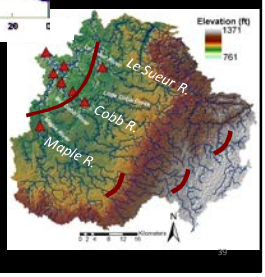
Evolution of the Le Sueur Watershed



Pre-13.5ka baselevel



NATURAL
- 13.4 ka: 60 m baselevel fall
- Rapid Holocene incision in lower 40 km

HUMAN
- Widespread agriculture began ~ 1830
- Extensive artificial drainage began ~ 1950

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