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

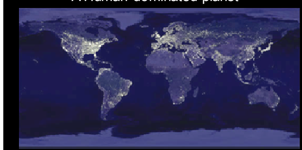
Panta Rhei
"Ever-present change in the universe"

Heraclitus of Ephesus (535 – 475 BCE)

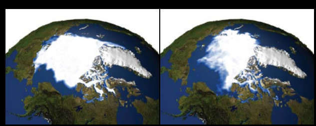
" The "*weeping philosopher*" wringing his hands over the world

"Ever-present change in the universe"

A Human dominated planet

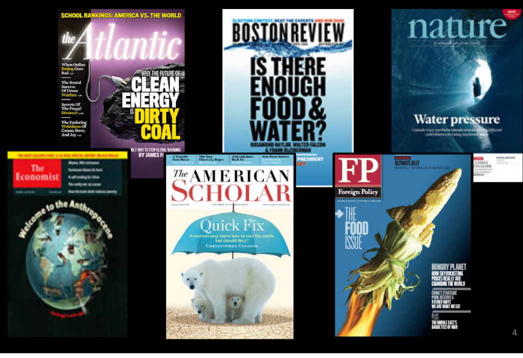


Arctic sea ice



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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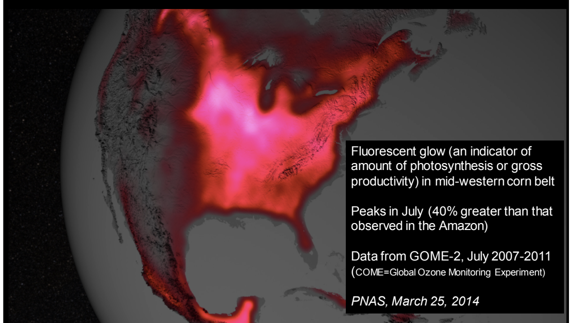
Intensively managed landscapes



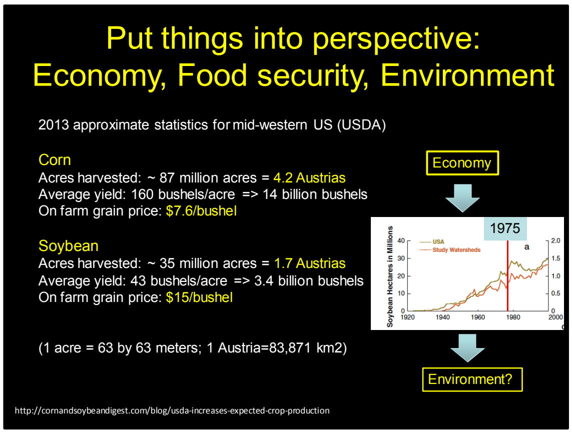
Fluorescent glow (an indicator of amount of photosynthesis or gross productivity) in mid-western corn belt

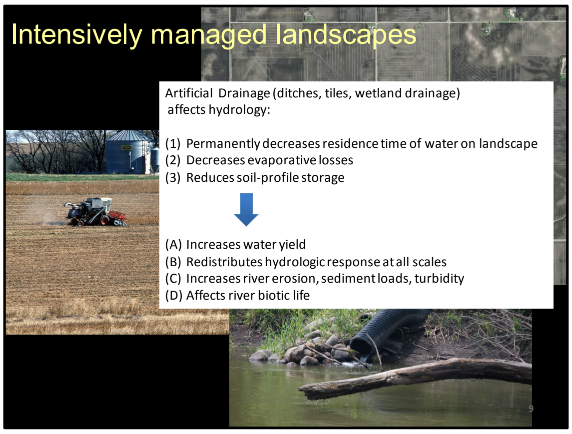
Peaks in July (40% greater than that observed in the Amazon)

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

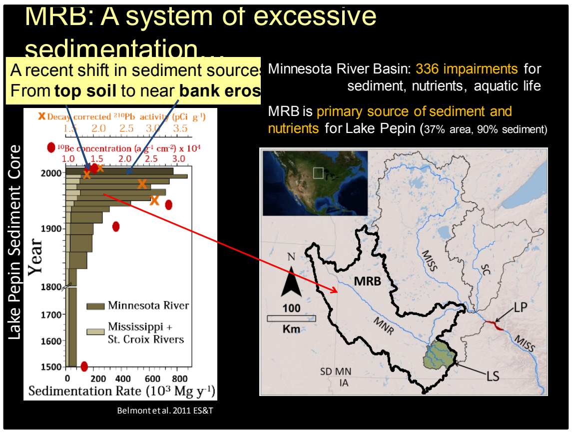
PNAS, March 25, 2014

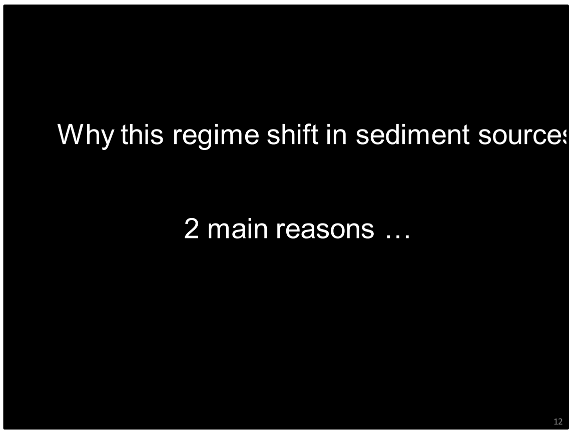
http://www.nasa.gov/press/goddard/2014/march/satellite-shows-high-productivity-from-us-corn-belt/#.U0AkG1cqgad


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
1975
Soybean Hectares in Millions
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

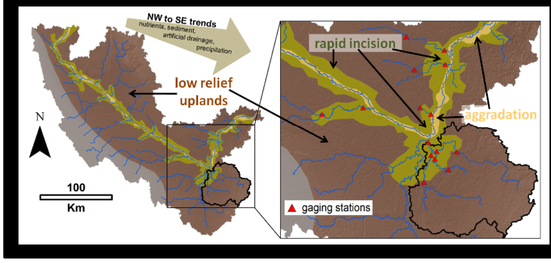

Minnesota River Basin (MRB)
Convergence of geologic history and human actions
REACH
Lake Pepin
MRB
Le Sueur
NSF


MRB: A system of excessive sedimentation...
A recent shift in sediment source
From top soil to near bank eros
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)
Lake Pepin Sediment Core
Year
Minnesota River
Mississippi + St. Croix Rivers
Sedimentation Rate
MRB
MNR
LP
LS
SD MN IA
100 Km
Belmont et al. 2011 ES&T


Why this regime shift in sediment sources
2 main reasons …

(1) Landscape structure (established 13.4 kyr ago)

Uplands: flat land, passive rivers



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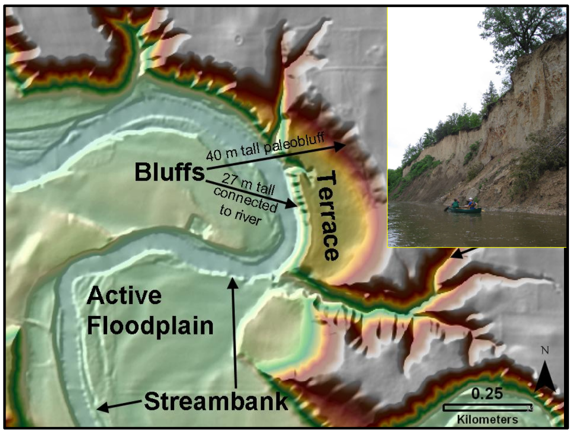
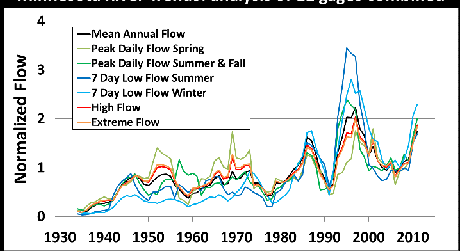


(2) Changing Streamflows

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

Minnesota River Trends: analysis of 12 gages combined



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

Novotny and Stefan (2007)
Additional data from Sara Kelly

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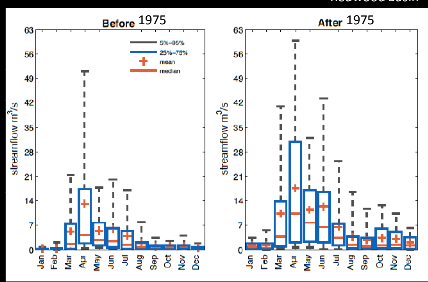
Monthly streamflow change

Redwood Basin



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

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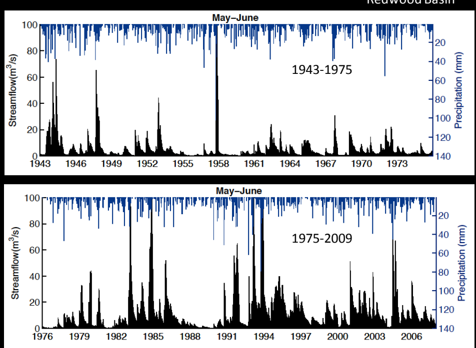
Daily streamflow change: May-June

Redwood Basin



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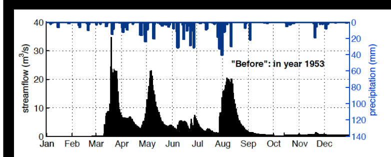
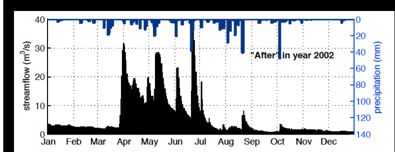
Hydrologic response change

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

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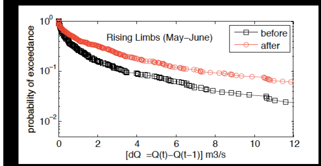
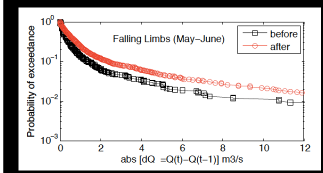
Hydrograph shape has changed

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

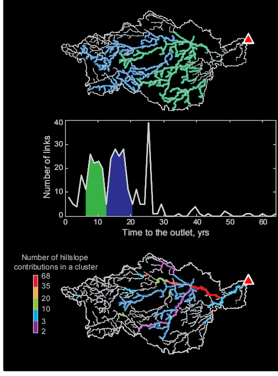
1. Space-time signatures of vulnerability
-- many key processes in complex systems are highly space-time localized
(hot spots and moments for denitrification, river avulsion, localized sources of erosion, human-sensitive areas to flooding, etc.)
-- precursor signatures of accelerated change lead to abrupt 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: $u_{s,i} = (0.32)A_i^{0.285} S_i^{3/2}$

$t'_{s,i} = \frac{\ell_i}{u_{s,i}}$

Intermittency of Q2: $t'_{s,i} = I_{f,s} t_{s,i}$

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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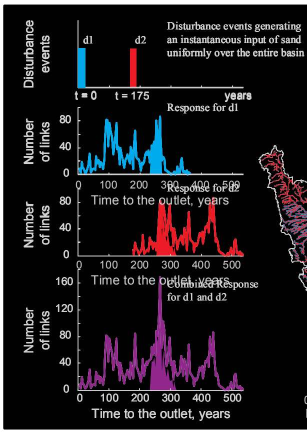
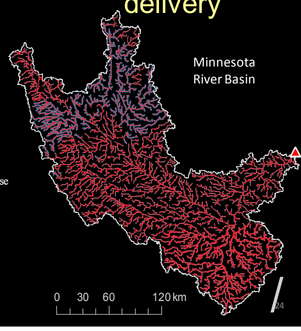
Synchronization of sediment delivery



Minnesota River Basin



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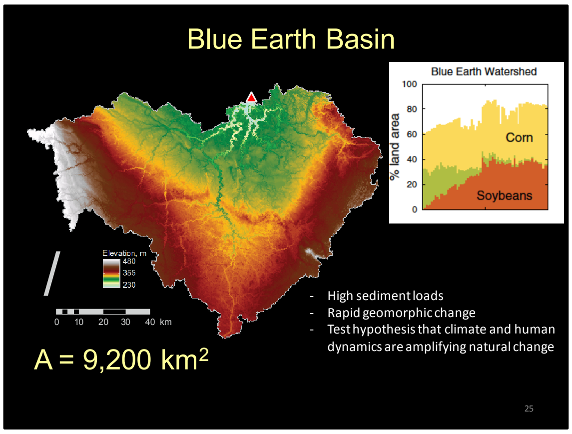
Blue Earth Basin
Blue Earth Watershed
% land area
100
80
60
40
20
0
Corn
Soybeans
Elevation, m
480
355
230
0 10 20 30 40 km
A = 9,200 km2
- High sediment loads
- Rapid geomorphic change
- Test hypothesis that climate and human dynamics are amplifying natural change
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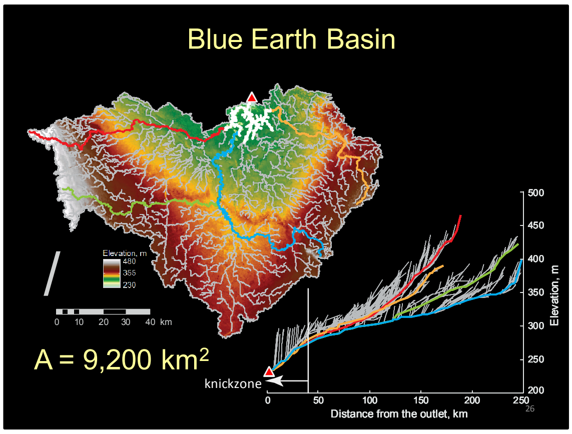
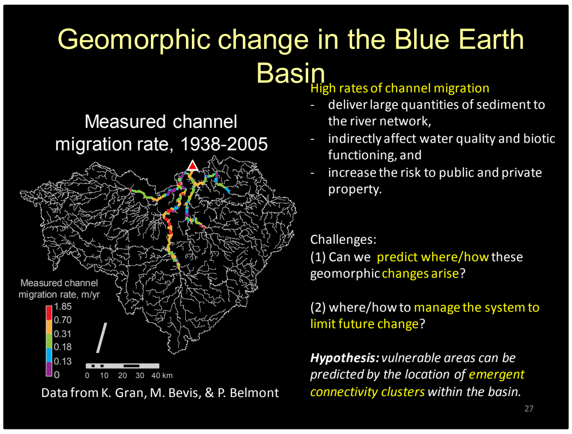

Blue Earth Basin
Elevation, m
480
355
230
0 10 20 30 40 km
A = 9,200 km2
knickzone
Elevation, m
500
450
400
350
300
250
200
0 50 100 150 200 250
Distance from the outlet, km
26


Geomorphic change in the Blue Earth Basin
Measured channel migration rate, 1938-2005
Measured channel migration rate, m/yr
1.85
0.70
0.31
0.18
0.13
0
0 10 20 30 40 km
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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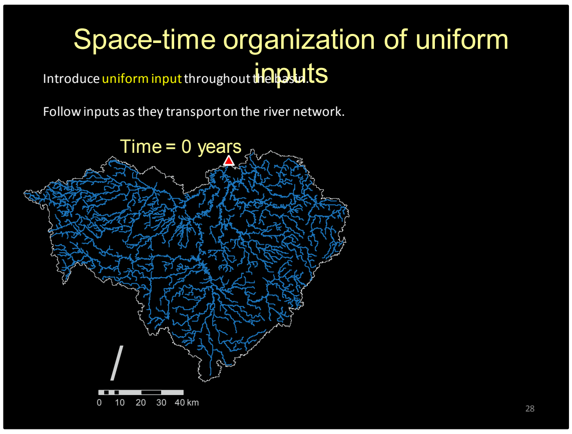
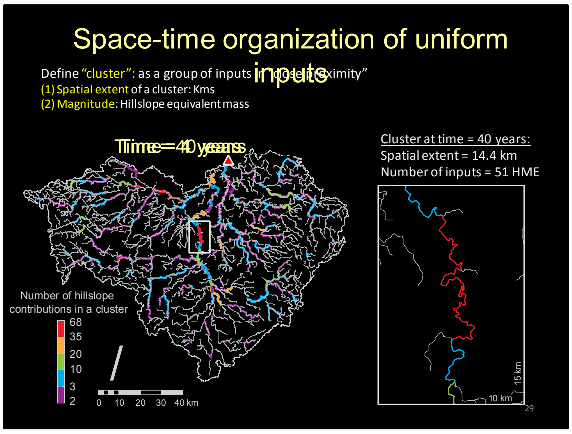
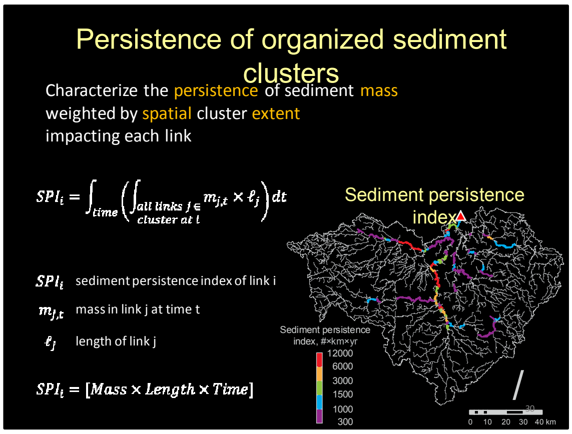
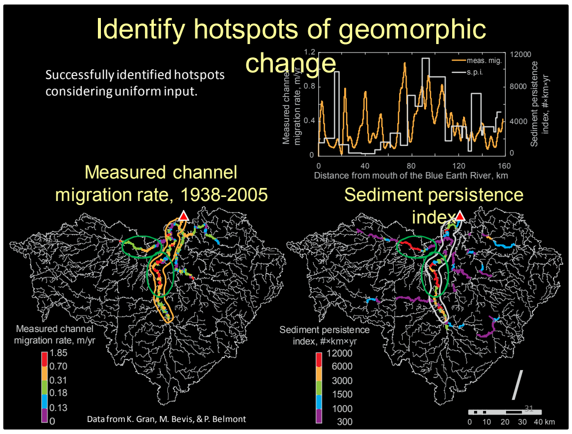
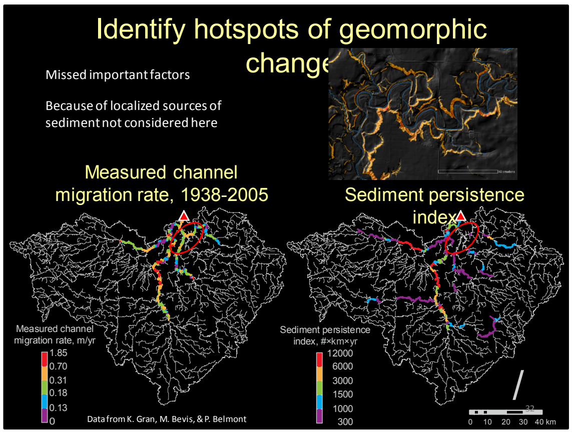
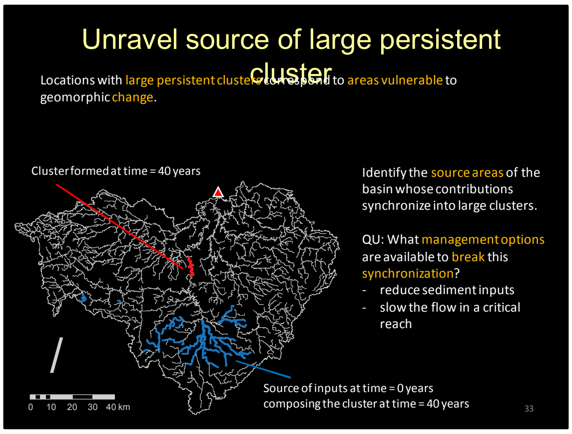

Space-time organization of uniform inputs
Introduce uniform input throughout the basin.
Follow inputs as they transport on the river network.
Time = 0 years
0 10 20 30 40 km
28

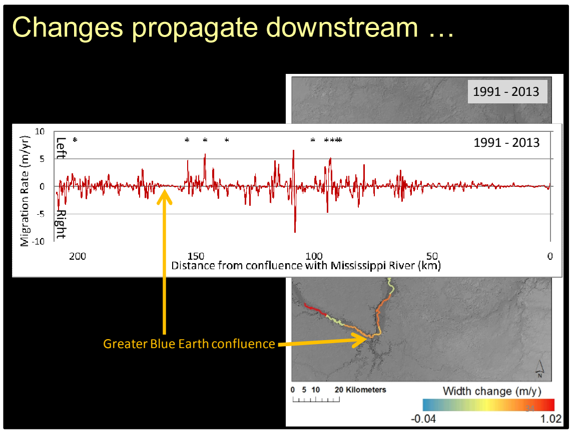

Space-time organization of uniform inputs
Define "cluster": as a group of inputs in close proximity"
(1) Spatial extent of a cluster: Kms
(2) Magnitude: Hillslope equivalent mass
Time = 40 years
Cluster at time = 40 years:
Spatial extent = 14.4 km
Number of inputs = 51 HME
Number of hillslope contributions in a cluster
68
35
20
10
3
2
0 10 20 30 40 km
15 km
10 km
29


Persistence of organized sediment clusters
Characterize the persistence of sediment mass weighted by spatial cluster extent impacting each link
$SPI_i = \int_{time} \left(\int_{all\ links\ j \in cluster\ at\ t} m_{j,t} \times \ell_j \right) dt$
SPI_i sediment persistence index of link i
$m_{j,t}$ mass in link j at time t
ℓ_j length of link j
$SPI_i = [Mass \times Length \times Time]$
Sediment persistence index
Sediment persistence index, #×km×yr
12000
6000
3000
1500
1000
300
0 10 20 30 40 km
30

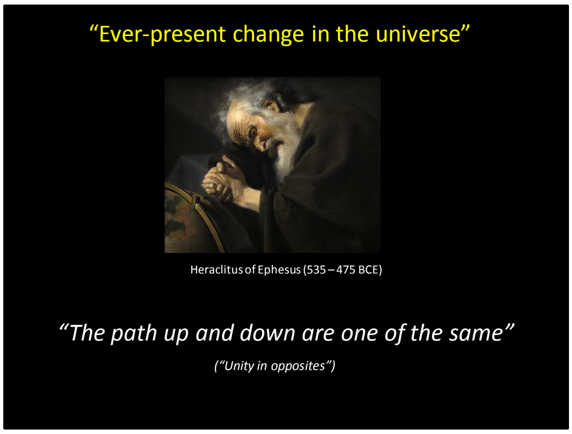

Identify hotspots of geomorphic change
Successfully identified hotspots considering uniform input.
Measured channel migration rate, 1938-2005
Sediment persistence index
Distance from mouth of the Blue Earth River, km
Measured channel migration rate, m/yr
1.85
0.70
0.31
0.18
0.13
0
Sediment persistence index, #×km×yr
12000
6000
3000
1500
1000
300
Data from K. Gran, M. Bevis, & P. Belmont
0 10 20 30 40 km


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
Measured channel migration rate, m/yr
1.85
0.70
0.31
0.18
0.13
0
Sediment persistence index, #×km×yr
12000
6000
3000
1500
1000
300
Data from K. Gran, M. Bevis, & P. Belmont
0 10 20 30 40 km


Unravel source of large persistent cluster
Locations with large persistent clusters correspond to areas vulnerable to geomorphic change.
Cluster formed at time = 40 years
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
0 10 20 30 40 km
33


Changes propagate downstream …
1991 - 2013
1991 - 2013
Migration Rate (m/yr)
Left
Right
Distance from confluence with Mississippi River (km)
200
150
100
50
0
Greater Blue Earth confluence
0 5 10 20 Kilometers
Width change (m/y)
-0.04
1.02


"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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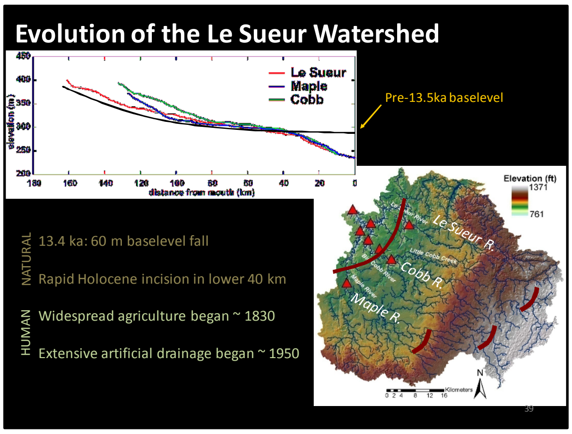
Evolution of the Le Sueur Watershed
Le Sueur
Maple
Cobb
elevation (m)
distance from mouth (km)
Pre-13.5ka baselevel
NATURAL
13.4 ka: 60 m baselevel fall
Rapid Holocene incision in lower 40 km
HUMAN
Widespread agriculture began ~ 1830
Extensive artificial drainage began ~ 1950
Elevation (ft)
1371
761
Le Sueur R.
Little Cobb Creek
Cobb R.
Maple R.
Kilometers
0 2 4 8 12 16
N
39