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
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
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.
“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

Horton (1931, p.192)
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 ...

– Established HS as a distinct Geoscience & NSF HS Program
A water cycle for all tastes!

Horton’s most seminal contributions in hydro-geomorphology

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 …

1. Hydro-meteorology decade
2. Hydro-geomorphology decade
3. Earth-Water-Life Integration decade

Involved in defining/performing interdisciplinary research …
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!

- transport
- scaling
- river
- rainfall
- model
- analysis
- temporal
- braided
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

Year 0
- 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
Research Integration: watch your covariances!

✓ Whole > Sum (parts)?

\[ X = X_1 + X_2 \quad X = \text{productivity of center} \]

\[ \text{Mean}(X) = \text{Mean}(X_1) + \text{Mean}(X_2); \]

\[ \text{Var}(X) = \text{Var}(X_1) + \text{Var}(X_2) + \text{COV}(X_1, X_2) \]

Whole > sum of its parts Iff COV (+)
A few Highlights from my Current Research
Precipitation estimation from space

Delta Sustainability

River meandering

Agricultural Landscapes
Precipitation estimation from space

Retrieval over land and complex terrain with emphasis on extremes

River meandering

Response to perturbations and meander train dynamics

Delta Sustainability

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

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
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 $\leftrightarrow$ Graph Representation $\leftrightarrow$ Algebraic Representation

2. Metrics for topologic and dynamic complexity

3. Framework for vulnerability maps

Tejedor et al., WRR, 2015a,b
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

\[
\frac{d\theta}{dt} = \frac{d\theta}{ds} \int_0^s U \frac{d\theta}{ds} ds = \frac{dU}{ds}
\]

Theta = centerline angle
U = local migration rate

Intrinsic geometric nonlinearity

Cutoff-imposed nonlinearity

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
Subsurface drainage tiles in MRB:
100 million ft/yr (30,500 Km/yr)
Streamflow: Minnesota River Basin

- Mean Annual Flow
- Peak Daily Flow Spring
- Peak Daily Flow Summer & Fall
- 7 Day Low Flow Summer
- 7 Day Low Flow Winter
- High Flow
- Extreme Flow

(S. Kelly, after Novotny and Stefan 2007)
-- a water issue
-- driven by economy
-- driven by food demand
-- driven by energy demand
-- affecting the environment …

… NEED SOLUTIONS
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

Economics

Channel Network
- Δ Q
- Δ Channel dynamics, Sediment transport & deposition
- Δ Channel Width and/or Depth
- Δ Aquatic Habitat
- Δ Nutrient Cycling

Δ Climate and/or Land use

Terrestrial Environment
- Δ Rainfall-Runoff Processes
- Δ Vegetation & Soils
- Δ Sediment and Nutrients

Floodplain
- Δ Flood Propagation, Floodplain inundation

Policy
“Make everything as simple as possible but not simpler”

Albert Einstein
“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 (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
Agriculture transitioned from hay and small grains to soybeans beginning in the southeast MRB.
Streamflow change during growing season

Foufoula-Georgiou et al., 2015, WRR
MRB: Streamflow change


Precipitation

P

Streamflow

Q

Foufoulà-Georgiou et al., 2015, WRR
A strengthened dependence of a daily streamflow increase \((dQ^+/dt)\) in response to previous day precipitation. This is especially so in mid-quantiles.
Reduction of inherent NL in daily $Q$ dynamics!
(signature of a more “regulated” system due to tile drainage)

Phase space reconstruction

Original Q Series  Linearized versions  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

Can we shift more flows below the threshold?

And thus reduce near-channel erosion in the incised zone

Water-Sediment FCs
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 Fofoula-Georgiou, 2015, WRR
Hydro-geo-ecologic cascade of change?

Hansen et al., 2015, Freshwater Science
Hansen et al., 2015, Freshwater Science

**Hydro-geo-ecologic cascade of change?**

Mussel population density (mussels/m²), $M_t$

\[
\frac{dM_t}{dt} = f_5(S_t) \times M_t \left(1 - \frac{M_t}{f_6(C_t)}\right)
\]

- $f_5(S_t)$: sediment modulated mussel pop. growth rate
- $f_6(C_t)$: logistic growth with food modified effective carrying capacity

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**Q_t**

- Streamflow
  - (-) light reduction
  - (-) dilution
  - (+/-) density dependent population growth

**C_t**

- Phytoplankton population density

**M_t**

- Mussel population density
  - (-) consumption
  - (+/-) density dependent population growth
  - (+) food availability

Measured mussel population density (mussels/m²):
- 0.4 - 0.6
- 0.7 - 1.0
- 1.1 - 3.9
- 4 - 12
Hydro-geo-ecologic cascade of change?

- $S_t$: Suspended sediment concentration
  - (+) sediment generation
  - (-) light reduction
  - (-) reduced recruitment
  - (-) filtration

- $C_t$: Phytoplankton population density
  - (+/-) density dependent population growth
  - (+) food availability

- $M_t$: Mussel population density
  - (-) consumption
  - (+) food availability
  - (+/-) density dependent population growth

Map: Measured mussel population density (mussels/m²)
- 0.4 - 0.6
- 0.7 - 1.0
- 1.1 - 3.9
- 4 - 12
Hydro-geo-ecologic cascade of change?

Effective carrying capacity

Sediment-biota FCs

St. Croix (12)
Chippewa (3)
Watonwan (8)
Baseline
±10% change in $a_{QS}$

$Q_t$ Streamflow

$M_{sim}(t_{calc})$ (mussels/m²)

$S_{t,avg}$ (mg/L)

Sensitive to change

Extirpation

Transitional

Measured mussel population density (mussels/m²)
- 0.4 - 0.6
- 0.7 - 1.0
- 1.1 - 3.9
- 4 - 12

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?

![Graph showing reduction in downstream sediment loading vs. mean wetland residence time. The graph includes lines for different wetland percentages: 0.5%, 2%, 4%, and 7.5% wetlands. The x-axis represents mean wetland residence time in days, ranging from 0.1 to 100. The y-axis represents the reduction in downstream sediment loading in percentage.]

WRS-Q reduction FCs
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 km²
- All sites with controlled % cropland (85% cropland +/- 2.5%)

J. Finlay, A. Hansen
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
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   -- at what scales to evaluate a system for sustainability?

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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 scientists
Sustained Interdisciplinary Collaboration

INTENSIVELY MANAGED LANDSCAPES
Critical Zone Observatory (IML-CZO)

NSF

A Water Sustainability and Climate Project

Resilience under Accelerated Change

Upper Mississippi River Basin

Minnesota

Minnesota River Basin, MN

Iowa

Clear Creek Watershed, IA

Illinois

Upper Sangamon Basin, IL

Critical Zone Observatory Site
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

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 Carsteaun (1997)
-- Venu Venugopal (1998)
-- Deborah Nykanen (2000)
-- Boyko Dodov (2003)
-- 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