Water Cycle Dynamics in a Changing Environment: Advancing Hydrologic Science through Synthesis

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Coming to you from Urbana, Illinois

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To begin at 3:05 ET
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December Activities

- December 3rd CUAHSI Membership Meeting
- December 11th CUAHSI Reception @ AGU
Water Cycle Dynamics in a Changing Environment: Advancing Hydrologic Science through Synthesis

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Objective 1. Conduct synthesis activities that will produce transformational outcomes in hydrologic science towards improved predictability of water cycle dynamics in a changing environment
Limits to predictability

Prediction means making probabilistic statements about future system states given the current and past observed states and our understanding of how nature works.

The four classical limits of predictability are:

• System identification (correct boundary conditions, driving forces)
• Characterization of initial states based on all available information
• Translation of our understanding of how nature works into a perceptual model of the system (identification of relevant /dominant processes, how they are coupled
• Appropriate mathematical representation (i.e., numerical or predictive model) (parameters, model structure) to produce probabilistic statements
Behavior = Structure + Response

- Structures and responses are linked by *physical mechanisms* and *evolutionary probabilities*
What do we observe?
How do we predict?

- Matter and Forces
  - Mechanistic perspective

- Patterns and processes
  - Evolutionary perspective

Could there be a broadening of our perspectives?
Could there be a synthesis?
It’s a tangled WEB!
WEB=Water, Earth, Biota (Gupta, 2003)

Water, as the life blood of the planet, links many earth components. Many examples of interacting behavior across coupled systems:
- Some connections are obvious, others subtle and devious.
- C, N and P cycles are closely tied to the water cycle.
- Biological activity, habitat structure are all dependent on the spatial fragmentation and temporal stability of water.
- Space-time structure is often interesting as scale increases.
- Many of the key problems in science → scaling, nonlinearity, predictability, space-time oscillations emerge.
- Methods of deconvolution of effects limited ← statistical or mechanistic.

Upmanu Lall
Contextual Hierarchy for Water Cycle Studies

Physical Systems
(Oceans, atmosphere, rivers/lakes, aquifers)

Patterns
(e.g. Stream network organization)

Non-linear process dynamics
(human impact, engineering works, water use, management)

Units of representation

Units of conceptualization

Units of engagement

Stores
Water, Carbon, Nutrient, Sediment

Fluxes
Residence time/age

Flowpaths
Saling, self-organization, emergence

Ecological Systems
(habitats, disturbance regimes, life cycles)

Biogeochemical Systems
Nutrient cycles, carbon cycle, contaminant

Models, Assimilation & Prediction

Courtesy: P Kumar
Evidence of Self-organisation: Stream network

LANDSAT image over coastal Sarawak, Malaysia, 1996
Evidence of self-organisation: soil catena

Dietrich et al., 1995
Spotted pattern (creosotebush) in the Chihuahuan Desert of New Mexico (Wainwright et al., 2002)

Typical banded vegetation pattern in Niger (Valentin et al., 1999)

Northern Territory: Acacia woodlands
www.nt.gov.au/ipe/pwcnt

Saco et al., 2006
Patterns exist in time too ....
Human impacts:
Intersection $\rightarrow$ rivers, people, dams

yellow are lights, dams blue and streams dark-gray.

Integrated global dynamics of Water and People $\rightarrow$ settlement by rivers $\rightarrow$ modify local hydrologic cycle $\rightarrow$ cross local population threshold $\rightarrow$ increased exposure to drought and flood $\rightarrow$ add water infrastructure $\rightarrow$ threshold $\rightarrow$ growth at new settlement $\leftarrow$ emergent spatio-temporal patterns; collapse?
Working Hypotheses

• Goal: improved predictions of water cycle dynamics .. through increased understanding

• Water cycle dynamics is very complex, too difficult to predict using traditional (purely statistical or purely mechanistic) methods

• Patterns help us to reduce the complexity through reduced dimensionality, and thus help to improve predictions

• Patterns (both observed and so far unobserved) are emergent properties arising out of complex interactions and feedbacks between a multitude of processes.

• Study of patterns (how to describe them, why they emerge, their impact on the overall response) yields new insights and lead to increased understanding.

• Study of observed patterns (why they emerge) may give insights into unobservable or as yet unobserved patterns, and help to make improved predictions
Investigation of Emergent Patterns

- **Top-down questions**: pattern description, measurement and identification. What can we learn from existing datasets?

- **Theoretical questions**: ‘deep, why type questions’: Why does this pattern emerge? Under what circumstances do we expect it to occur? What are the underlying rules?

- **Bottom-up questions**: what are the consequences of these patterns (what are their effects on processes of interest)? How do they scale up? How does the understanding (e.g., their ecological function, organizing principles etc.) improve our capacity to make predictions?

- **Human interactions**: how do human activities interact with these patterns in time and space? How are the patterns affected by human activities?

- **Study of patterns needs a multitude of perspectives (concepts, data, methods etc. from different disciplines)**

- **Synthesis means people with different backgrounds and experiences coming together to study a common question or pattern or prediction problem and to help each other to generate increased understanding**
Objective 2. Use the synthesis activities as test cases to evaluate the effectiveness of different modes of synthesis for advancing the field of hydrologic science.

Approach to synthesis
(i) bring together people with a wide range of experience and interests; (ii) a variety of complimentary expertise from multiple disciplines; (iii) motivate them with challenging problems that focus on clear targets; and (iv) under-pin these activities by common and unifying themes.

Central hypothesis that these principles will lead to self-organized sustained interactions between assembled scientists to produce transformational outcomes, including innovations and breakthroughs ..
Geographical Spread of Synthesis Team Members
Nucleation Sites

- Hydromorphology: Human-Nature Interactions and Adaptations (Project 1) – Upmanu Lall
- Interactions between hydrosphere and biosphere processes (Project 2) – Praveen Kumar
- Multi-Scale Interactions of Landscape Processes within Intensively Managed Watersheds (Project 3) – M. Sivapalan
- Evolution, structure and function of hydrologic subsystems in hillslopes (Project 4) – Peter Troch
- Stochastic transport and scaling in earth surface processes (Project 5) – Rina Schumer and Efi Foufoula-Georgiou

Unifying Themes

- Hydrology as a science of interacting processes
- Variability as the driver of interactions and ecosystem functioning
- Search for emergent behavior and organizing principles
- Complexity theory and non-equilibrium thermodynamics
Planning and Project Initiation
* Identify potential synthesis team members
* NCSA will deploy their ongoing developments related to Cyberinfrastructure technology for the support of this project. This will consist of technology to support cyber-collaboration, end-to-end sensor to desktop data access, and integrating models with data for high performance computing.
* Schedule initial meeting

Synthesis Team meeting
The final composition of synthesis teams will be decided after a meeting involving several potential members. The initial meeting of the synthesis team will then focus on defining the essential elements of the problem, breakup into smaller Synthesis Activity Groups (SAG), and devolution of the activities to the SAGs. The initial work will focus on integrated assessment of the needs of the problem, developing strategies for identifying data and modeling needs, etc. Each SAG will work autonomously, conducting independent meetings of short or extended durations and using Cyberinfrastructure for both collaboration and data analysis and modeling. We expect that each SAG will identify a partner site as a host for meeting, coordination, and support.

Synthesis of data, concepts, methods theories across disciplines
A joint meeting with all synthesis team members will be used to assess knowledge gaps and develop a plan for the next stage. New Synthesis Activity Groups will be formed that may or may not be the same as before. The activities of the SAGs will be devolved with one of the partner sites serving as the hub. Cyberinfrastructure will continue to play an important role in the coordination and communication of these activities. Furthermore, NCSA will continue to identify the CI needs of the community and incorporate it into their CI design protocols. This activity will be continued for the entire duration of the project.

Identify unresolved problems, new challenges, and advocate effective solution approaches
- Undertake pilot projects

We expect that at this stage each synthesis team will take up pilot projects to address issues that have been identified. This “learning by doing” will help us further assess the adequacy, applicability, and effectiveness of proposed ideas and data. The SAGs may be reconstituted again, if necessary. At this stage we expect that new additional activities will be spawned to carry out independent interdisciplinary research.

Evaluate performance and project success
We expect performance evaluation to be an ongoing activity supported by the Science Advisory Group. A comprehensive project assessment report along with “lessons-learned” report will be produced.
Project #5
Stochastic Transport and Emergent Scaling in Earth-Surface Processes

A working group co-sponsored by:
National Center for Earth-surface Dynamics (NCED),
UIUC, Hydrologic Synthesis Activities,
and The Desert Research Institute (DRI)

Rina Schumer and Efi Foufoula-Georgiou
Scale invariance has been observed in surface morphology

- Surface topography
- River network structure
- Braided river channel organization

Does it arise from scale invariant processes? e.g. sediment transport laws, landscape evolution
Hydrologic Synthesis Project #5

Earth Surface Modelers:
- Depositional Processes
- Sediment Transport
- Landscape Evolution
- Hydromorphology

Mathematicians
- Heavy-tailed Distributions
- Stochastic Processes
- Fractional Calculus
- Limit Theory

Other Scientists
- Transport in Porous Media
- Fracture Flow/Transport
- Biophysics
- Finance
What is Predictability?

- Translation of our understanding of how nature works into a perceptual model of the system (identification of relevant/dominant processes, how they are coupled).
- Appropriate mathematical representation (i.e., numerical or predictive model) to produce probabilistic statements.

What Limits Predictability?

- Inability to specify the details of landscape heterogeneity at the appropriate scale
- Lack of observability of dominant processes (e.g., preferential flow)
- Scale mismatch between mathematical description and relevant scale of dynamics
Heavy-tailed stochastic processes

What if model elements are best represented by heavy-tailed probability distributions?

![Graph showing exponential decay and power-law decay](image-url)
Working Group Goals

• Can earth surface model scale dependence be eliminated by generalizing to heavy tailed stochastic models?

• Are existing stochastic models useful?

• Do we need to develop equations governing new stochastic processes?

• Can the statistical properties observed in Earth surface structure be used to estimate parameters for process models?
First workshop – Nov. 2007
Lake Tahoe

- Talks on previous applications of heavy-tailed stochastic processes in other disciplines
- Talks on scaling issues in earth surface processes
- Fractional calculus/heavy-tailed stochastic processes short-course
Results

- **Selected paper topics**
  - Coupled continuous time random walks (CTRW) for modeling avalanche recurrence (Jerolmack, Benson, Baeumer, Meerschaert)
  - Fractal topography measurement (Stark)
  - CTRW model of bedload transport (Schmeeckle, Schumer, Fofoula-Georgiou)
  - Fractional Boussinesq equation for hillslope transport (Harman, Reeves, Sivapalan)
  - Scaling of sediment flux (Passalaqua, Fofoula-Georgiou, Schumer)
  - Assessment of subsurface biogeochemical processes from in-stream breakthrough curves (Packman, Meerschaert, Baeumer)
Project #4
Evolution, Structure and Function of Hydrologic Subsystems in Hillslopes

Peter Troch
Department of Hydrology and Water Resources
University of Arizona, Tucson
Hydrologic Subsystems in Hillslopes

- What are the **key controls** on and the **key interactions** between the soil, ecology, geomorphology and biogeochemistry that create hydrologic storages and flow-paths and partition incoming water into them?
- What **role** do these storages and flow-paths have in maintaining the regimes of soil, ecology, geomorphology and biogeochemistry, particularly with respect to the temporal variability imposed by the climate?
- Can an **organizing principle** be identified that could drive the evolution of the hydrologic system in a hillslope?
Community Consensus
Network behavior at all scales
Biogeochemical, soil, vegetation processes affecting hillslope hydrologic subsystems

Hillslope hydrology
(catena shape, topographic fine structure, pore structure, flow paths, $K(\Psi)$ distribution)

Spatial distribution of plants and microbes
(Veg. structure, C fixation, infusion of roots & C, plant litter decay)

Patterns of biogeo-weathering
(aq. geochem. conditions, $\Omega$ distribution, aggregation, pore complexity, biophysical microenvironments)

Evolution of subsurface connectivity
(macropores, preferential flow, gas/solute transport, bulk density changes)

Network structures are the evolutionary outcome of integrated climatic, geomorphological, ecological, pedological feedbacks
Soil-Landscape Relationships

- (Strong) link between soil properties and landscape position needs to be better understood to aid hydrologic controls on hillslope flow and transport processes

Craig Rasmussen
Research questions

• How do hillslope/landscape "connectivity" patterns "emerge" and evolve and what are the time-scales associated with these? The patterns of connectivity are interpreted broadly to include channels, heterogeneity of flow paths, vegetation, subsurface flow, etc.

• How is heterogeneity related to connectivity and how does connectivity give rise to threshold response - that is, what is the relationship between the static properties of hillslopes to the dynamic response?

• Is the emergence and evolution of self-organized connectivity a result of some global optimality (of some objective function) or local interactions?

• What is the relationship between variability of the driver (rainfall) and the emergence of connectivity? Do the connectivity patterns change with variability of rainfall, if so, in what way?

• How do the above change with the spatial and temporal scales?
art hsci ence

Experimental Biome
How does water move through a hillslope and what role does life play?

Biosphere provides controlled experimentation at spatial scales that have the complexity of real landscapes.

- Test hypotheses
- Validate models
- Observe emergent properties
Project activities

- Organize a series of workshops (1 each year, so 4 in total)
- Workshops are run by core group of people with different backgrounds (hydrology (McDonnell/Troch), biogeochemistry (Brooks), soil sciences (Rasmussen/Chorover), ecology (Huxman))
- Each year, a workshop is held at a different research site
  - Year 1: B2 Earth Sciences (November 18-19, 2007)
  - Year 2: H.J. Andrews/Panola/Shale Hills (?)
  - Year 3: Valles Caldera/Catalinas-Santa Rita/Sierra (?)
  - Year 4: Synthesis at B2-Earth Sciences
- Number of participants: <30
- Output: 2-pager that is distributed to the larger hydrologic community
- Follow-up: special session at AGU meeting
- Synthesis papers
Project #3
Multi-Scale Interactions of Landscape Processes within Intensively Managed Watersheds

Murugesu Sivapalan
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Straw-man Question
How do interacting mass fluxes of water, sediment, nutrients, carbon, as well as microbiota, and macrobiota throughout watersheds respond to various perturbations of the watershed system (weather events, climate change, land-use change, other human impacts)?

Lack of Appropriate Data!!!
Need for a hydrological observatory
Continental to Global
Regional/Watershed
Channel/Water-body
Benthic/Interfacial
Cellular

Need to link Structure, Transport, Transformation, and Microbial Activity across many spatial and temporal scales.

Aaron Packman
The issue of transferring knowledge between systems of different magnitude is an issue of scaling and is at the core of the scale linkage problem. To what extent is it possible to transfer findings from one scale of investigation to another?

(Slaymaker, 2006)

(After Phillips, 1999; Slaymaker, 2006)
• Goal: Create a theoretical (quantitative), predictive framework to address this question (and related questions).

• First step – develop a conceptual model of interacting processes with relevant time and space scales

• Employ quantitative models heuristically.

• Watershed-focused
• Event-based (timing, sequencing, magnitude)
• Scaling Analysis
• Connectivity (surface versus subsurface)
• Transmission
• Human Influence (intensively managed landscapes)
• Differential inertial responses
• Mass Balance Budgets
Sediment Dynamics in Intensively Managed Landscapes

Scaling Issues

• Move beyond basin sediment delivery ratio
  – SDR = yield/production
• Event-based modeling perspective
  – Lu et al. 2005 A theoretical exploration of catchment sediment delivery – accounts for stores, fluxes of sediment from hillslopes and channels in relation to event timing, magnitude and duration
  – Can be cast in spatially distributed form
  – Emphasizes “event conditioning” – how parts of a sediment system are prepared to respond to an event and how each part contributes to the overall response
  – Hot spots, hot times, thresholds, and external controls
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Project #2
Hydrosphere and Biosphere Interactions

Praveen Kumar
Department of Civil and Environmental Engineering
University of Illinois
Urbana, Illinois
Human Influence on the Biosphere

- Alteration of vegetation patterns
- Elevated CO$_2$
- Increase in temperature
- Alteration of the nutrient cycle
- Lowering of groundwater table
- Changes to the variability of water and energy cycle
Open/Dissipative System Paradigm

• Natural systems don’t exist – they evolve.
  – The evolution is driven by the exogenous variability imposed on them by weather, climate and anthropogenic factors, and endogenous variability generated by the subsystems as a result of the adaptive process.

  – The variability allows the system to explore a variety of states to find an optimal for its sustenance during the evolutionary process.

  – The response of the system, which we are most concerned with, evolves with that of the evolution of the system itself gives rise to combinatorial or co-operative effect new functional (emergent) patterns arise from the systematic alterations of historically discrete configurations of functional relationships.
Underlying Questions

- How does the biologically significant variability of the water cycle produce the observed emergent patterns in vegetation in space and time? ➔ Hydrological control on biology [Ecohydrology]
- How does the vegetation interact with terrestrial and atmospheric moisture to produce the variability in the water cycle? ➔ Biological control on hydrology
- How does the biosphere mediate the interaction between long time scale sub-surface hydrology and short time scale atmospheric hydrologic cycle?
- How are these altered by anthropogenic influences on
  - Energy Cycle
  - Water Cycle
  - Carbon Cycle
  - Nutrient Cycle
Hydrological control on biology

**Challenges**

- Dynamics of water stress and impact on vegetation and microbial processes
- Biological significance of hydrologic variability/pulsing (timing, magnitude, frequency, duration, intermittency)
- Network and hierarchical heterogeneity structure of surface and sub-surface flow pathways
- Plant induced changes in the composition of soil’s biotic, physical and chemical processes (plant-soil interaction)
- Lateral movement of water and resulting ecosystem form and function

**Approaches**

- Complex system approach recognizing non-linearities, thresholds, and feedbacks for different climates, soils and plant characteristics
- Discrete network modeling of subsurface flow (instead of continuum modeling) ➔ focus on patterns of flow
- Non-equilibrium systems resulting from recurring or continual disturbance ➔ suboptimal functioning of ecosystems
- Time scales of transient response related to longer memory processes in the system
Biological control on hydrology

Challenges

• Describe dissipative processes in hydrologic cycle
• CO₂ fertilization → WUE → Climate-carbon-hydrology feedback
• Roles of organic matter/roots, nutrient and carbon cycling on plant water uptake
• Plant strategies for water consumption (eg. hydraulic redistribution)
• Feedbacks that give rise to spatial self-organization
• Intensification of hydrologic cycle → causes and consequences
• High latitude hydrology-biogeochemistry

Approaches

• Non-equilibrium thermodynamics: Max entropy production
• Dynamic vegetation models
• Coupling water and energy cycles → mapping sources, sinks and atmospheric moisture transport pathways
• Effective use of data
  – remote sensing [GRACE, MODIS,TRMM, A-Train]
  – assimilation of streamflow and groundwater data
Short Term Targets: Synthesis Papers

- Causes and consequences of complexity in ecohydrologic systems
- Carbon, Nutrient and Water cycle interactions
- Using emergent patterns to constrain predictive uncertainty
- Interaction of “microbial lifestyle” with the water cycle

Targets:
- Outline Dec 2007
- Draft Spring 2008
- Submission Summer 2008

The synthesis paper will help identify emergent problems that the group will address through research.
Hydrologic Change: A formal line of scientific inquiry

Human impacts and impacts on humans are mediated through water. The long history of connection to the human enterprise could provide a boost to hydrologic research, as the dynamics of the coupled human-natural system is explored through appropriate case studies where retrospective documentation could be achieved.
Hydrologic Change Science: involves identification of emergent patterns or structure as inter-linked systems evolve in space and time and the attribution of these patterns to specific types of interactions or conditions, and hence towards a new theoretical framework for both long term and short term “predictions”.

Upmanu Lall
• For more information and updates:
  http://cwaces.geog.uiuc.edu/synthesis/index.html

• AGU Fall 2007 special session on synthesis:
Thanks

- **UIUC PIs:** Praveen Kumar, Bruce Rhoads and Don Wuebbles
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