

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

Appendix B: UIUC Synthesis Project White Paper: A Guide to UIUC-led Synthesis Activities

Preamble

This document aims to provide a guide to ongoing research activities focused on improving the predictability of water cycle dynamics in a changing environment, through inter-disciplinary *synthesis*.

We view synthesis as the process of developing novel insights through the integration of new observations, theories, methods of analysis and perspectives drawn from diverse fields. The hydrologic synthesis project offers a platform to bring together people with different perspectives and experiences to study the most important open questions in the area of hydrologic predictions and produce *breakthroughs and transformative outcomes* for the science through formulation and testing new hypotheses about water cycle dynamics. The ultimate goal is not only to increase our understanding of water cycle dynamics but also our ability to predict it in the context of human-induced (exogenous as well as endogenous) changes to the natural environment.

Breakthroughs tend to occur when small groups of highly motivated scientists are driven by acute challenges encountered in real problem-solving situations and/or given the freedom and encouragement to experiment with new ideas. Hydrologic synthesis thus requires a convergence of novel ideas or concepts, data and methods of analysis from different disciplines. For these reasons, the current synthesis activities are being implemented along the following lines:

- i) Bring together people with a wide range of experience and interests; a variety of complimentary expertise from multiple disciplines;
- ii) Motivate them with challenging problems that focus on clear targets;
- iii) Under-pin these activities by common and unifying themes.
- iv) Establishing "partnerships" between individuals, research centers, and agencies to leverage each other's capabilities.

Hypothesis: These principles will lead to self-organized sustained interactions among scientists to produce transformational outcomes, including innovations and breakthroughs, in the sense of "the whole being more than the sum of the parts."

Hydrologic Predictions in a Changing Environment

Hydrology has explored a large range of potential ways to understand and enhance the predictability of natural systems. Recently, this task has become even more difficult in the context of prediction under global change (climate change, human-induced land use changes etc.), which requires a major change of our worldview. Current predictions typically consider climate as an exogenous forcing that acts on a landscape with fixed structure. Such treatment is not unreasonable where the focus is on understanding the short term response of specific land-atmosphere hydrologic fluxes to perturbations of the subsystem forcing at watershed scales. This has led to models that are useful essentially to reproduce observed behavior but that are difficult to extrapolate to considerably different situations, namely to predict ungauged catchments or climate change or land use impacts.

We are now aware that in natural and man-made systems every biotic and abiotic component is permanently changing its shape or its position and that this greatly increases the complexity and hence decreases the predictability of hydrologic systems.

The co-evolution of the biotic and abiotic components in any particular ecosystem could (in theory) be simulated from suitably complex models that include all the relevant system feedbacks and couplings; but we are aware of the limits of the usefulness of such models even if we do not yet fully understand all inherent limits of predictability.

It is readily apparent that the interplay and interaction of the biotic and abiotic, and of the natural and man-made components is not random but leads to observable patterns. These observable patterns contain information on the physical, evolutionary and socio-economic mechanisms from which they have emerged. Therefore, the existence of patterns can be assumed to reduce the dimensionality of the prediction problem but also to help to understand the limits of predictability.

Hydromorphology or Hydrologic Change Science

Hydromorphology, is defined, by analogy to geomorphology or to climate dynamics, as the science relating to the long term evolution of the hydrologic system, i.e., at time scales of century to millenia. Since water links most earth systems, including the human and life systems, hydromorphology is an integrative field that examines the interactions of the earth systems across space and time. Hydrologic change in this context, is not just a before and after analysis, but a causal evolution of the system, potentially from one equilibrium state to another across the interacting earth systems. The challenge of how to describe this long term evolution as a function of setting, location and scale emerges as a key issue in defining this science or paradigm.

What is 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:

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

These four problems are of course highly inter-connected (e.g. understanding how the dominant processes are linked might require a redefinition of the system or a new type of mathematical representation).

Hypothesis: Hydrologic systems are very complex but patterns at all scales reduce this complexity.

What limits predictability?

Each of the above points brings its specific problems that include

- i) Identification of appropriate spatial and temporal resolution of system inputs
- ii) Inability to specify the details of landscape heterogeneity at the appropriate scale
- iii) Lack of observability of dominant processes (e.g. preferential flow)
- iv) Scale mismatch between mathematical description and relevant scale of dynamics

This list could be further extended. The main question is: Is there something that brings them all together?

Hypothesis 1: Many limits of predictability are directly related to our lack of understanding how hydrologic behavior at the prediction scale emerges from behavior at other scales.

Hypothesis 2: We can learn a lot about how this behavior emerges if we study observed spatial and temporal patterns of hydrologic behavior.

What are patterns?

Landscapes are interconnected systems that include biotic and abiotic, and natural and human subsystems. The behavior of such systems is the result of complex interactions and feedbacks (across places, scales and processes) that lead to a co-evolution of the observable system structures and responses. Where these structures and responses tend to reproduce themselves over time, they become visible in the landscape, as vegetation patterns, river networks or soil catena or in the observed time series, for example as distributions of inter-event times and amplitudes of events.

Hypothesis 1: Many observed spatial patterns are strongly related to (perhaps hydrologically more relevant) unobserved patterns.

Hypothesis 2: Many observed spatial patterns are strongly related to unobserved temporal patterns and vice-versa.

Hypothesis 3: Many hydrologically relevant spatial and temporal patterns co-emerge from threshold processes at various scales.

What can we read in the patterns?

The analysis of observed patterns offers new perspectives for the understanding of how information is transferred across scales. This viewpoint has been adopted long time ago by ecological modelers. Levin [1992, p. 1950], for example, points out that the key is not “to determine what information is preserved and what information is lost as one moves from one scale to the other” but why the preserved information is preserved and how this is related to the evolution of the system.

Hypothesis 1: The study of observed patterns gives insights into the emergence of behavior at the scale of prediction, in the past, and hopefully in the future.

Hypothesis 2: The study of observed patterns gives us evidence on the specific types of interactions among system components (natural and human-induced).

Hypothesis 3: The study of observed patterns gives evidence on probable unobserved patterns that are relevant for prediction.

Why does emergent behavior increase predictability?

Predictions, especially in a changing environment, must deal with system evolution arising from external driving forces as well as from process interactions and feedbacks across many spatial and temporal scales. Understanding emergent patterns means learning from easily observable structure and response to make inferences about unobserved structure and responses. For example the study of vegetation patterns can give valuable insights into water and nutrient flow paths.

Hypothesis 1: The study of observed patterns gives evidences on probable unobserved patterns that are relevant for prediction.

Which questions should we investigate?

- Investigation of emergent patterns - top-down questions:
 - Pattern description, measurement and identification;
 - What can we learn from existing datasets?
 - How should we design new observatories?
- Theoretical questions: ‘deep why type questions’:
 - Why do these patterns emerge?
 - Under what circumstances do we expect them 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?

Project Objectives and Working Hypotheses

In the light of the above, we propose to summarize the synthesis activity objectives and working hypotheses as follows:

Ultimate Goal

- Improved predictions of water cycle dynamics in a changing environment through increased understanding

Working Hypotheses

- The water cycle dynamics are very complex and therefore too difficult to predict using traditional (purely statistical or purely mechanistic) methods
- Observable patterns help us to reduce the complexity through reduced dimensionality, and thus help to improve predictability
- Patterns (both observed and so far unobserved) reflect emergent properties arising out of complex interactions and feedbacks between a multitude of processes involving biotic and abiotic, natural and man-made components
- Study of observed patterns yields new insights and leads to increased understanding; their study should try to answer the following questions:
 - How can we observe, describe them?
 - Why do they emerge?
 - How do they relate to the overall system response?
- Study of observed patterns and especially of their emergences gives insights into unobservable or as yet unobserved patterns, and help to make improved predictions
- Study of patterns needs a multitude of perspectives (concepts, data, methods etc.) from different disciplines
- Synthesis offers the platform to bring together people with these different perspectives to study the prediction problem and to help generate increased understanding of how predictability, emergent behavior and patterns are related.

Implementation of Synthesis Activities

In the following, we enumerate some key concepts upon which these working hypotheses rely. We also present the chosen methodological approach and the expected outcomes. The implementation plan of the planned synthesis activities are outlined under the following headings, leading to specific and highly focused set of research activities:

- Open problems
- Convergence of new theories
- Convergence of new observations and data
- Convergence of methods (both models and methods of data analysis)
- Convergence of people: inter-disciplinary teams
- Synergistic activities

Open problems

To bring specificity to the synthesis activities, it is important to identify a small number of open problems that are cross-cutting as well as compelling, and can form the platform for generating transformative outcomes and elevating hydrologic science to a new and truly inter-disciplinary earth science that can confidently addressing emerging problems of management in a changing environment.

Based on a survey of research activities and a number of vision papers that have been published in various journals in the past two years, the following four promising open problems have been identified to form the basis of the planned synthesis activities (also see Table 1):

- Human-nature interactions and adaptations (Theme 1)
- Role of the biosphere in water cycle dynamics (Theme 2)
- Human induced changes to water cycle dynamics (Theme 3)
- Structure of landscapes and their evolution through time (Theme 4)
- Stochastic transport and scaling in earth-surface processes (Theme 5)

The chosen open problems and associated research questions thus become *nucleation sites* for the proposed synthesis activities and, collectively, and do have the following attributes:

- They involve complex interactions between multiple, interconnected processes acting across many scales and places.
- They will help focus our efforts on real prediction problems operating at a range of scales, and centered on real places.

- They will embrace multi-disciplinary interactions and synthesis of theories, data, methods, and concepts operating over many scales.

The specific thematic research activities that will be described below will center on these five open research problems.

Table 1: Identified core open problems

Problem	Key subjects (themes)	Example questions
Human-biosphere-hydrosphere interactions	Human induced changes in the water quantity, quality and variability.	Human impacts on the hydrosphere/biosphere and resulting human adaptations. Separation of natural and human-induced variability
Role of biosphere in water cycle dynamics	Water / carbon / energy dynamics	What are the active and passive roles of the biosphere in regulating the water cycle?
Human induced changes to water cycle dynamics	Climate change, land use / land cover change	Intensification of the global and local hydrologic cycle, extreme events, changes to river networks and floodplain morphology
Structure of landscapes, their impacts and function, and how they evolve through time	Hydro-pedology, soil ecology, biogeochemical cycling	Flow pathways, old-water-new water paradox, flow networks in the subsurface, development of closure relations for predictive models
Stochastic transport and emergent scaling behavior in earth-surface processes	Geology, geomorphology, hydrology, stochastic calculus, physics	Can scale dependence in earth surface models be eliminated by generalizing to heavy tailed stochastic models? Can statistical properties observed in landscape structure be used to estimate parameters for process models?

Convergence of theories and perspectives

All five of the chosen open problems (themes) involve interactions between biotic and abiotic components, namely, water, nutrients, carbon, and sediments, characterized through properties of associated fluxes, flow paths, stores, residence times, and state transformations (physical and chemical). All of them involve non-linear interactions between many of these components giving rise to emergent patterns. These emergent patterns contain information on the physical, evolutionary mechanisms (including socio-economic ones in the context of human impacts)

which they emerge from. Advances in predictability will come through improved understanding the processes, process interactions and feedbacks give rise to these patterns.

In this sense, a number of new perspectives and scientific theories underpin the exploration of these interactions and will act as unifying themes (see also Table 2):

- Hydrology as the 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

Focusing on these unifying themes in the context of the open problems identified above will help formulate and test new hypotheses that can be tested through organized synthesis activities. For example, synthesis of theories, observations, modeling and predictions could address the following set of questions related to each of these perspectives and theories:

- What are the manifestations of these theories?
 - ⇒ Example: Vegetation patterns as an (assumed) manifestation of an organizing principle (e.g. minimization of water stress in arid areas).
- Why do these manifestations occur?
- How can we observe these manifestations?
- How can we model them?
- What can we learn from them in terms of system predictability and our predictive capability?
- How do human activities influence them?

Success in these explorations will pave the way for breakthroughs and transformative outcomes in future hydrologic research activities.

Table 2: Convergence of new theories and perspectives

“Theory”	Issues / questions (examples)
Interacting processes	<ul style="list-style-type: none"> - What types of interactions are possible, and what patterns of hydrologic behavior results? Across places, across scales and across processes. - How do process interactions influence system predictability? How do resulting patterns influence our ability to make predictions? - What is the functional role of the biota? While ecology studies biota-abiota interactions to learn something about the distribution of the biota we are interested in biota-abiota interactions to learn something about the patterns of the abiotic system components. - Can observed interactions and resulting patterns tell us something about unobserved interactions relevant for prediction?
Variability as the driver of interaction	<ul style="list-style-type: none"> - Assuming that variability is what communicates information from one compartment to another, i.e. connecting fast and slow processes (variability as having a functional role), what is the role of space, time and space-time variability? - What is the role of timing, sequencing, frequency, magnitude, thresholds? - What can we learn by observing events, discrete structures? - How is variability connected to self-organization? - If we increase our understanding of how variability drives interaction, how does this increase our ability to make predictions?
Emergent patterns and organizing principles	<ul style="list-style-type: none"> - Can we identify organizing principles useful for prediction directly at the scale of interest? - Can organizing principles help to infer unobserved process interactions or to infer unobserved system structures? - Examples: landscape resilience, optimality, competition
Non-equilibrium thermodynamics	<ul style="list-style-type: none"> - Complexity, emergence, fractals

Convergence of new observations and data

In the following, we give a list of observation methods that offer new promising perspectives for the synthesis activities (see Table 3).

Table 3: Promising observation methods

“Category”	Examples	Perspectives
Old techniques but new uses	High-resolution ground-based Lidar	Observation of landscape structures and their evolution
	Satellite images	
	Reanalysis of large climatologic data sets	What can we learn from existing datasets?
	LTER HIS	
New (sensor) technologies	Low-cost sensor networks	Observation of spatial and temporal process patterns
	Fiber optics	Observation of spatial and temporal process patterns that imply temperature changes
	Real-time isotopic analysis	Observation of temporal patterns of flow paths
	HMF	
New information technology	Geoinformatics and data mining	Extract dependencies (entropy, order, control)
	Information and organization	Copulas

Convergence of Methods

The generation and testing of hypotheses as manifestations of the outlined theories do not necessarily imply the development of new modeling approaches. In the context of synthesis, we would however like to point out that modeling activities should NOT be focused on developing and calibrating more complex process models. Promising approaches could include the following:

- Low dimensional (virtual reality) models
 - ⇒ Use simple models to study specific hydrologically relevant process interactions in detail
- New statistical methods to describe or infer interacting processes (e.g., copulas)
- Develop prototypes of new modeling frameworks that focus on interacting processes, and evaluate their ability to reproduce emergent patterns or behavior

Convergence of people: inter-disciplinary teams

The synthesis activities will lead to research collaborations around identified key issues of hydrologic prediction. The activity groups will therefore bring together people who are open-minded, collaborative and innovative, and who have substantial experience working in their fields of specialization.

The synthesis group as a whole would ideally include people whose core competences are in the fields of modeling, field observations, mathematics, complex systems theory, hydroclimatology, geomorphology, pedology, biogeochemical cycling, and landscape ecology.

The group will be composed by around 24 core members (of which 8 are the current theme leaders) and loosely connected “external” collaborators. The former will receive funding to participate to project meetings; the latter will generally cover their costs by their own funding.

The “fixed” 8 core members of the group (the synthesis project leaders) are:

- ⇒ Bruce Rhoads (UIUC), Praveen Kumar (UIUC), Murugesu Sivapalan (UIUC), Don Wuebbles (UIUC), Peter Troch (Arizona), Efi Foufoula-Georgiou (Minnesota), Larry Winter (NCAR), Upmanu Lall (Columbia), Jim Myers (NCSA)

Additional core members could include (full list yet to be completed; important: these people should be identified as a function of the competences required for the overall synthesis group):

- ⇒ Larry Band (UNC), Paul Brooks (Arizona), Francina Dominguez (Arizona), Darren Drewry (UIUC), Ciaran Harman (UIUC), Marwan Hassan (UBC, Vancouver), Jon Chorover (Arizona), David Gochis (NCAR), Travis Huxman (Arizona), Henry Lin (Penn State), Craig Rasmussen (Arizona), Jeff McDonnell (Oregon State), Ramakrishna Nemani (San Diego State), Aaron Packman (Northwestern), Amilcare Porporato (Duke), Ben Ruddell (UIUC), Jennifer Tank (Notre Dame), Rina Schumer (Nevada), Peter Thornton (NCAR), Enrique Vivoni (New Mexico Tech).

The remaining people will be chosen in such a way as to assemble competencies in all the relevant disciplines needed to carry out synthesis activities under the five chosen unifying themes (see Table 3 below). These will include 3 young scientists supported by CUAHSI and a number of graduate students from the various partner institutions and affiliated with synthesis team members.

We have already identified a number of external collaborators from our international partner organizations:

- ⇒ Tom Battin (University of Vienna, Austria), Axel Kleidon (Max Planck Institute, Jena), Michael Raupach (CSIRO, Canberra, Australia), Michael Roderick (ANU, Canberra, Australia), Patricia Saco (University of Newcastle, Australia), Bettina Schaeffli (TU Delft, The Netherlands), Karsten Schulz (University of Munich, Germany), Fuqiang Tian (Tsinghua University, Beijing, China).



	Theme 1 Regional/Global	Theme 2 Regional	Theme 3 Large Watershed	Theme 4 Hillslope/Small Watershed
Hydrology				
Geomorphology				
Ecology				
Pedology				
Biogeochemical Cycling				
Meteorology/Climatology				
Mathematics/Systems Theory				

Synergistic Activities

According to the principle “play a catalytic role, support grassroots activities”, the synthesis activities will be articulated around a four-pronged approach:

- Collaborative activities

Organize *mini-conferences* that bring together people from a variety of disciplines and provide incentives to promote follow-up collaboration

- Competitive activities:

Announce (e.g. bi-annual) *prizes* for the best papers that address one or more key questions. Prizes are awarded on the basis of inter-disciplinary synthesis, advancement of novel and creative ideas, as well as solid science using existing datasets in an enlightening way.

- Integrative activities:

Convene *AGU sessions* around each of the key nucleation themes, cutting across key scientific questions

- Educational activities:

Organize research seminars or workshops for graduate students. (a) as a platform to “promote” the relatively new theories and worldviews converging in on the synthesis project, and (b) to stimulate productive exchanges between the current and future generation of researchers.

The activities under each research theme will be organized around the following matrix of activities and objectives focused on chosen process interactions and emergent patterns associated with each of the unifying themes.

	Describe/ Observe	Explain/ Understand	Predict	Human impacts
Collaborative				
Competitive				
Integrative				
Educational				

All synthesis activities will be framed by a continuous assessment of where we are in terms of *understanding predictability and prediction ability in a changing environment*. All approaches should emphasize synthesis of ideas data and methods from different disciplines and opportunities involving use of novel and creative ideas.

Outcomes

Besides concept papers (that lay out the central issues), there will be review papers, reports and conference presentations.

At the end of four years, a monograph on the advancements can be based on the products that come out of chosen approaches (including collaborations, prizes, and conference presentations). The monograph will track and highlight the advances that have been made in “predictability patterns”, and richness of the field that has been achieved through the synthesis across different disciplines.

Brief Descriptions of Potential Thematic Synthesis Activities

Theme 1: Hydromorphology: Human-Nature Interactions and Adaptations

Climate dynamics is marked by structured variability at preferred time scales in response to changes in solar insolation, orbital forcing etc, and internal feedbacks across ocean, atmosphere, land and the cryosphere. Hydrologic fluxes play a crucial role in earth system evolution at these time scales, through their role in changing the equilibrium vegetation, shaping terrain, through changes in the spatial energy balance due to changes in clouds, snow and ice, and through changes in the loading of earth's plates via the ice distribution. This role is acknowledged in studies of Earth System History, even though hydrologists have not been very active in such studies.

Over most of human history, humans have adapted to these earth system changes via migration, population adjustments and technological innovation. At the beginning of the 21st century, it is clear that these adaptation strategies have allowed humans to become agents of planetary change. The CO₂ induced global climate change is the most notable example of such an impact. Our thesis is that human induced hydrologic modifications are an equally important agent of local and planetary change that has thus far received limited scientific attention. The urgency of developing this area as a scientific research theme is underscored by the fact that water scarcity has now emerged as a global concern, suggesting that either water will emerge as the defining constraint for planetary carrying capacity, or that the pace of hydrologic change will continue to increase dramatically with subsequent effects on ecology, landscape, climate and human society.

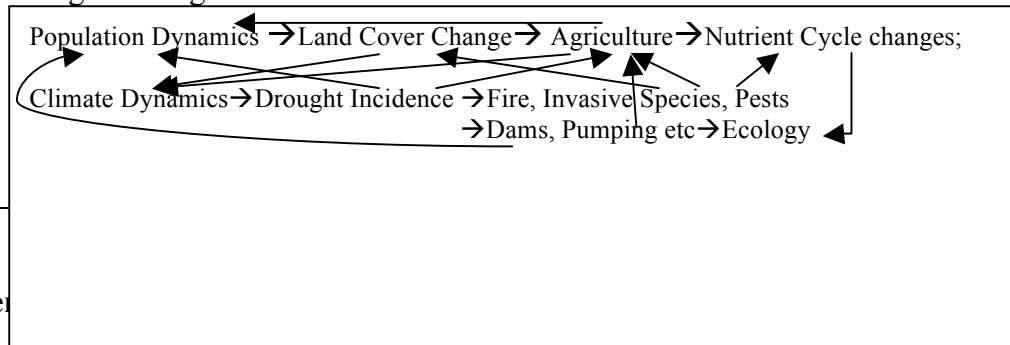
While there has been some data reconstruction and systematic research into the relationship between climate, geomorphology, vegetation and society, water has not been an explicit currency or theme in this research. The focus on hydromorphology intends to address this gap, recognizing that water may provide the key mode of communication across the earth systems, influencing both threshold driven event dynamics and the stability and regime transition of vegetation, climate, geomorphic and social dynamics. Event dynamics and regimes are likely to be related in that the location, frequency, and intensity of events such as floods and droughts will in turn be determined by operative climate regimes that may have long term persistence. Human, geomorphic and ecological impacts and response to these events may in turn induce a threshold transition in the “local” regime in those systems towards a new mode, which may in the long run influence regional or global climate (as the regional technology spreads through society). For instance, persistent drought or flood may lead to innovation in agricultural (crop choice) or irrigation practices, which may become culturally systematized and then spread across the globe, systematically changing land-atmosphere interactions. This would have been a slow process a few thousand years ago, and may take place rapidly now. Similarly, flood control responses may significantly alter the quantity and quality of sediment and change geomorphic futures. There is already evidence of some of these patterns of evolution. The challenge put forth in this synthesis theme is to systematically develop this knowledge base considering cross-system interactions in which hydrology (or water related transport across all media) plays a role, with specific attention to the interplay between local and global evolution, scale and thresholds, stable and unstable regimes, and system predictability.

Given the breadth of the theme, the goals of the synthesis activity are to:

1. Assemble a group of leading thinkers from different fields (at least climate, hydrology, ecology, agriculture, geomorphology, economics and anthropology) with experience in evolutionary issues and system dynamics, to present and assess existing knowledge and trends. This assessment will be issued as a scientific report that defines the key social and scientific concerns with hydromorphology at regional to global scales. This report could form the basis for a NSF research area definition, and also for an IPCC like process that addresses Global Water (Hydrologic Change).
2. Compile and analyze global (and U.S.) data sets (Model simulated or “real” data) to explore key elements of hydrology for which a data based investigation can proceed to formulate and refine hypotheses that emerge from the group. Two key themes that we anticipate being developed are:

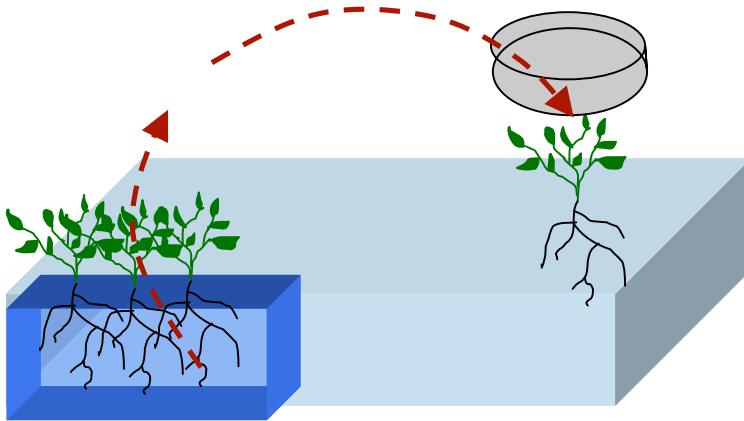
a. Climate Dynamics → Regimes and Modes of Atmospheric Moisture Transport → Space-time clustering of floods → geomorphic processes → Flood Control trajectories and Population/Socio-economic demographics → Geomorphic processes → Coastal zone cumulative impacts

b. At regional to global scales:



Theme 2: Inter

Vegetated terrestrial ecosystems and the overlying atmosphere are dynamically linked through the continuous transfer of mass, energy and momentum. The hydrologic variability interacts with the vegetation at time scales ranging from hours to days to inter-annual and decadal. The existing distribution of ecosystems is a result of evolutionary selections in response to environmental constraints which are themselves modified as terrestrial systems evolve until reaching a dynamic equilibrium. However this balance is changing, often rapidly, in response to anthropogenic influences such as climate change, land use/land cover change, and urban and agricultural expansions. Evidence suggests that vegetation response is adaptive in that they alter their survival strategies in response to environmental change, for example, through development of deep rooting and using hydraulic redistribution to better utilize the available moisture in the deeper soil layers. Yet little is known on how this impacts the hydrologic cycle and its variability. Active and adaptive control of vegetation and atmospheric flow moves soil-moisture that is no longer constrained by watershed boundaries (see illustration below). How do the atmospheric and terrestrial moisture, and vegetation interact to produce the observed variability in the water cycle and how does/will this variability change in response to the anthropogenic influences? What are the ecological consequences of this change? These broad questions lie at the heart of understanding the interaction between the hydrosphere and biosphere.



Some specific questions to address are:

- How does biosphere mediate the interaction between long time scale sub-surface hydrology and short time scale atmospheric hydrologic cycle?
- How has this interaction given rise to the observed self-organized patterns of ecosystems and how do these ecosystems sustain the hydrologic regime needed for their own sustenance?
- How are the dynamic regimes of ecohydrologic interactions affected by the anthropogenic impacts of land use/land cover change, elevated CO₂ and temperature, water use, etc?
- How do these linkages and changes there in alter the biogeochemical cycling in a region?

Theme 3: “Accelerating” water cycle dynamics: Multi-scale feedbacks with biogeochemical cycles in watershed systems

Many landscapes in the US and elsewhere have been extensively modified by human activity. These landscapes now consist of broad expanses of agricultural land with interspersed towns and cities. Transformation of land-cover conditions has dramatically altered hydrological, ecological geomorphological and biogeochemical processes compared to pre-settlement conditions. Altered processes in turn have produced environmental problems of societal importance, including exacerbated flooding, degradation of water quality, threats to ecosystems, and enhanced rates of erosion and sedimentation. A holistic approach to the management of these problems requires understanding of *interactions* among various landscape processes. Thus far, most research has involved disciplinary studies aimed at individual problems and processes (e.g. flooding and accelerated runoff), rather than integrated investigations of process interconnections. Scientific understanding of basic process interactions in such landscapes currently is inadequate to guide effective, landscape-scale efforts at integrated environmental management.

In particular, research is needed to determine the extent to which the dynamics of interactive processes can be predicted over time and space within the context of real-world events, such as weather events, runoff events, pollution events, erosion events, and events that cause ecological

disturbance. The importance of event dynamics is clearly illustrated by the catastrophic effects of an event such as Hurricane Katrina on the Gulf Coast. This natural disaster also highlights that human activities, including policies, decisions and patterns of development, are key components of the dynamics of human-dominated landscapes, and that important feedbacks occur between human and natural processes in such environments. The dynamics of landscapes processes and our capacity to predict the interactive effects of process dynamics in the context of an event-based framework is further complicated by the fact that the magnitude-frequency characteristics of events in any particular region are likely to be systematically altered over the next several decades by global climate change.

Examples of research questions relevant to this theme include:

- 1) How do anthropogenic changes in landscape heterogeneity and watershed processes alter the dynamic regimes of the coupled physical-ecological-biogeochemical systems at different scales?
- 2) How do key drivers such as changes in land-use change and climate influence the magnitude and frequency characteristics of hydrological, ecological, biogeochemical and geomorphological processes?
- 3) How sensitive are sediment and biogeochemical fluxes to hydrologic and land-cover changes associated with agricultural land use and urbanization, how does this sensitivity vary with the type and intensity of land-use change, with geologic materials, and with watershed topography, and how do variability and changes in water quality, water quantity, and sediment fluxes impact aquatic habitats and ecosystem functions?
- 4) What variables are important for the prediction of interacting processes in the water cycle for different regions, and what levels of predictability can be attained given the uncertainty of process understanding, the heterogeneity of process dynamics, and the complexity of interacting processes? What is the implication of this predictability, or limitation thereon, for management, legislative, and regulatory decisions?

To what extent are human activities now an important component of the dynamics of hydrological processes in particular environments and to what extent are these activities exerting sustained effects on hydrological events and human responses to these events?

Theme 4: Evolution, structure and function of hydrologic subsystems in hillslopes

Hillslopes offer a useful elementary scale to construct catchment hydrologic models, and to understand the role of water in the landscape. However, hillslopes exhibit enormous complexity and heterogeneity, much of which is not easily observable. The complexity is driven by the interactions between water, biogeochemistry, ecology and soils, within the constraints set by the climate and the geologic history of the system. These interactions create complex, non-random patterns and structures in space-time. Current models have difficulty accounting for these interactions and unobserved structural complexity. Current models cannot account for apparent paradoxes (i.e. old water – new water problem) and perform poorly without extensive calibration data, or under changing conditions. A new approach is needed.

A new approach may ask: why do the complex structures exist at all? Taking the view that the hydrology of a landscape has evolved along with its soils, ecology and geomorphology, we may ask if the hydrologic subsystem of a hillslope has a functional role in the maintenance of the overall system. This functional role may be expressed as an organizing principle – a constraint on possible ways that the hydrologic flowpaths may be organized such that the functional role is met. Examples might be maximizing net carbon profit, maintaining geomorphic form-function relationships, efficient resource use by biota, minimum entropy production etc. If a relationship can be established between an organizing principle and the structure of hydrologic flow-paths and storages, it can form the basis for developing closure relations at the hillslope scale that have meaningful relationships to the underlying dynamics. In this way, heterogeneity and complexity of hillslopes are no longer problems to be overcome, but is rather keys to making meaningful predictions.

Formulating and testing organizing principles will necessarily require the synthesis of knowledge from many disciplines. One approach is to construct virtual reality models of generalized hillslopes, and use them used to ask, given a set of observable constraints (climate, underlying geology, ecologic and biogeochemical parameters) which structures and responses are ‘behavioral’ – in the sense that they fulfill the function set by the organizing principle. Organizing principles are thus posed as testable hypotheses that can be used to guide field observations and analysis of existing data sets.

Questions:

1. What are the key interactions between the soil, ecology, geomorphology and biogeochemistry that create hydrologic storages and flow-paths and partition incoming water into them?
2. 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?
3. Can an organizing principle be identified that could drive the evolution of the hydrologic system in a hillslope?
4. Given the interactions identified in the first two questions, what types of hydrologic structures and responses produce the functionality required by the organizing principle for a given set of constraints of climate, geology and observed data?
5. Does the application of an organizing principle require an assumption that the hillslope system is in some sort of equilibrium, or can it be applied to hillslopes experiencing climate/land use change?

Theme 5: Stochastic Transport and Scaling in Earth-surface Processes

National Center for Earth-surface Dynamics (NCED) and the University of Illinois at Urbana-Champaign (Synthesis Project)

Scale invariance has been extensively explored in Earth-surface process morphology (e.g., surface topography, river network structure, braided river channel organization, etc.). However, it has not been explored as much in Earth-surface processes (e.g., landscape and hillslope evolution models, braided river models, sediment transport laws, etc.). Relating the scaling observed in

morphology to the stochastic differential equations underlying the processes responsible for the emergent morphology remains largely unexplored.

Many of the classic differential equations used to describe physical processes arise as the scaling limits of stochastic models. These models use probability theory to predict the outcome of processes that contain “random” elements. For example, it is common to represent transport phenomena with a random walk model or the exceedance of extreme thresholds with a Poisson process. The governing distributions obtained in the long time limit are solutions to stochastic PDEs that accurately describe the physical process over various time and space scales. However, the equations that arise from classical stochastic theory are often scale-dependent.

If the random components of a process are characterized by frequent extreme events and best fit by a power-law distribution, then classical stochastic theory does not apply. The inclusion of heavy-tailed distributions in a stochastic process requires a generalization of the limit theorems used to obtain long time governing distributions. Similarly, equations governing scaling limits of heavy-tailed stochastic processes are a generalization of classical PDEs – they include fractional derivatives. These non-integer order (e.g., $\frac{d}{dt} C \sim t^{-1.3}$) derivatives acting on equation parameters, are useful tools for treating seemingly scale-dependent physical processes. For example, fractional advection-dispersion equations have been used to model super- and sub-diffusive contaminant transport in both aquifers and rivers. In these applications, the “scale dependence of dispersivity” was eliminated because fractional derivatives can scale the dispersion coefficient appropriately.

Power-law relationships are frequently observed in Earth surface processes. For example, power-law sediment residence times are caused by eddies or braided channels, super-diffusive transport on hillslopes arises as a result of channeling, and scaling in sediment transport rates arises as a result of the self-organization of river bed morphology. This suggests that heavy-tailed stochastic models and fractional PDEs may be powerful tools for describing processes that take place on the Earth’s surface from the hillslope to the whole river network scale.

We have created a working group to explore ideas, in research and applications, in the area of stochastic transport and emergent scaling in earth-surface processes. By convening experts in Earth-surface processes and mathematicians and scientists who have successfully applied heavy-tailed stochastic processes and fractional differential equations in other disciplines, we have begun to identify:

1. Earth-surface processes to which existing heavy-tailed stochastic processes can be immediately applied and modeled with fractional calculus tools.
2. Outstanding theory required for the development of novel scale-invariant models for Earth surface processes

We intend to meet twice yearly for a period of two years. During the first meeting in Lake Tahoe we introduced mathematical theory and discussed potential applications. Each subsequent meeting will then focus on a particular area in Earth surface modeling.