**University of Illinois at Urbana-Champaign**
**Hydrologic Synthesis Project**

To Dr. Thomas Torgerson, Program Officer:

I wish to submit this interim report to the NSF Hydrological Sciences Program for NSF# EAR 06-36043, “Water Cycle Dynamics in a Changing Environment: Advancing Hydrologic Science through Synthesis”, PIs: Murugesu Sivapalan, Praveen Kumar, Don Wuebbles and Bruce L Rhoads.

This report covers achievements to date and consists of this cover page, 23 pages of the main report and 97 pages of appendices. We look forward to receiving your feedback on our progress.

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University of Illinois at Urbana-Champaign
September 30, 2010

WATER CYCLE DYNAMICS IN A CHANGING ENVIRONMENT (NSF EAR 06-35043)
**Interim Report: Major Achievements**

## I. INTRODUCTION

### Context

Human activity in today's world is beginning to rival geologic-scale forces. The main challenge to predictions in such a changing environment involves understanding interacting earth system processes that have led to the structure and function of existing hydrologic systems, and to use this understanding to predict how they will evolve in the context of rapid human-induced changes. Increasingly predictions must include the implications of human behavior, understanding legacy effects of past behavior, and the emergent behavior of human-impacted hydrological systems.

On the basis of these arguments, complexity, predictability and emergent patterns were adopted as the fundamental thrusts of the UIUC synthesis project, and led to postulation of the following set of 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, especially of their emergences, gives insights into unobservable or as yet unobserved patterns, leads to deeper understanding and helps 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 different perspectives to study the prediction problem and to help generate increased understanding of how predictability, emergent behavior and patterns are inter-related.

### Project Approach & Goals

Furthermore, our efforts to improve predictability of water cycle dynamics sit within a context in which we have sought a more formal definition for synthesis and effective synthesis science. Our working definition reflects the project's commitment to providing a platform to bring together different perspectives and experiences to study the most important open questions in the area of hydrologic predictions:

> *the process of developing novel insights through the integration of observations, theories, methods and perspectives drawn from diverse fields*

To bring coherence and specificity to the synthesis activities, the group identified the following **five open and cross-cutting themes**, forming the platform for generating transformative outcomes:

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

These themes branch across scales and sub-disciplines within the earth sciences and truly capture the breadth of understanding hydrologists require to address future problems. Our efforts to date consistently return to this foundational organization in service to the UIUC synthesis project's aggressive **goal of producing transformative outcomes** for the science.

To delve deeper into mechanics of successful synthesis, more specific boundaries can be placed on the approach. We feel that synthesis, and specifically hydrologic synthesis, is an approach that couples innovative and collaborative techniques in both management of research and the scientific content of the research itself. Additionally, we believe 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.

The project's White Paper stated this core hypothesis:

> *[The process] 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."*

To this end, we have tested three different approaches to engagement with the five thematic groups.

1. **Patterns-based Team Science** - The project has initiated detailed and more traditional questions-based projects in the areas of Groups 2 and 3. Within this effort, we have leveraged graduate student time and enthusiasm, through two summer institutes, during Summer-2009 and Summer-2010), and subsequent ongoing virtual collaborations, as a key mechanism for achieving these outcomes. From June 24 to August 10, 2010 15 full- and part-time graduate students participated in the second Hydrologic Synthesis Summer Institute, our intensive 7 week residential research program at the University of British Columbia. This model provides a mechanism to facilitate scientific breakthroughs and by which graduate students may engage in interdisciplinary research in a way that is not often available in their normal course of study.

2. **Community Leadership** - The project has provided thought leadership at the level of Theme 1 and across all themes through the formation of a forward-thinking workgroup focused on an agenda for water research. Through this we have explored the usage of in-person meetings, teleconferences and internet communications to facilitate broad thinking and collaboration within the assembled groups.
3. **Opportunistic Partnerships** - The project has provided the expertise of the team at-large to support major grassroots efforts under Theme 4 (Biosphere 2, Arizona) and Theme 5 (STRESS, NCED/Minnesota). Reaching beyond the immediate synthesis community, we contributed key problems involved in hydrologic predictions to the in-process research activities, helping to cross-fertilize innovation and leverage funds for the greater good. Our relationship with the STRESS team, in particular, has in turn, provided access to novel mathematical approaches and models that were found to be valuable our own research work.

**<u>Science Outcomes</u>**

Our efforts have resulted in more than 25 peer-reviewed publications (see Appendix B) and contribute to an extensive, yet cohesive body of work that could only result from this type of project. For each theme, we can claim specific contributions to the community:

1. Providing leadership in global change through coordinating efforts (reports, papers, proposals etc.) to develop a vision for hydrology under new contexts and paradigms.
2. Improving understanding and prediction of the inter-annual variability of water balance and the buffering role of vegetation in this process.
3. Enhancing understanding of biogeochemical cycling at watershed scale through new insights gained into up-scaling from the reach scale.
4. Designing of artificial hillslopes for a major, long-term experiment now underway at Biosphere 2 near Tucson, Arizona.
5. Facilitating connections within earth sciences and delivery of new mathematical approaches from the earth surface dynamics community to the hydrologic community through collaborations with the National Center for Earth Surface Dynamics (NCED).

This report provides updates on progress in each of the five themes, with a focus towards our efforts in the third year in themes 1-3, as well as our initial findings on the process of synthesis. Results and achievements of the work for themes 4 and 5 has been reported previously; relevant publications for these efforts are listed in Appendix B.

**References**

Sivapalan, M., Kumar, P., Rhoads, B., Wuebbles, D., Harman, C., Schaefli, B. (2008). UIUC Synthesis Project White Paper: A Guide to UIUC-led Synthesis Activities. *NSF Annual Report*.

## II. Findings & Major Achievements

**Theme 1: Human-nature interactions and adaptations**

**Topic:** Water resource projections over decades to centuries at river basin to regional scales: A vibrant research agenda for systems in transition

**History:** Conceptualized in 2007, vision paper written in 2009 / published in 2010, ongoing collaborative effort to define research agenda

The problems of water scarcity, environmental degradation and water-related natural hazards arising from the expansion of the human imprint on Earth pose enormous challenges to the way we conduct hydrologic science (Wagener et al., 2010). However, they also provide an unprecedented opportunity to utilize technological and theoretical advances in measurement, modeling, and visualization of both variability and change in our world, these being prerequisites for detecting, interpreting, predicting, and managing evolving hydrologic systems. By addressing these challenges and capitalizing on the opportunities, we can help to bring about a paradigm shift in hydrologic science, fundamentally revising and advancing the concepts, theories and methodologies that underpin our science. The required scientific revolution can best be achieved by a community-wide effort that focuses on regional implications of change (in climate, land cover, land use and population), providing the catalyst needed to bring about the changes we believe are required.

Through teleconferences and in-person meetings in 2010 (so far Bozeman, MT, March 2010; Durham, NC, October 2010) the synthesis team is in the process of preparing the outlines of a long-term, sustained and vibrant research agenda focused on *water resource projections over decades to centuries at river basin to regional scale*. It is hoped that the quest to achieve better regional scale (spatial) and decades to century scale (temporal) predictions will help to uncover deficiencies in our quantitative understanding and in our ability to provide information at the scales most relevant for decision-making.

We initiated development of the research agenda through a series of teleconferences during 2009, which led to the publication of a paper in *Water Resources Research* (Wagener *et al.,* 2010, attached), articulating the need for a paradigm shift in the science of hydrology to deal with a changing world with an expanding human footprint. The paper also presented the key elements of the needed paradigm shift, and argued that it will only be through a cross-disciplinary long-term community effort (involving hydrology and other Earth as well as the biological and social sciences), with a unified focus on the regional implications of environmental change, that the required fundamental transformation of our science can be achieved.

The focus of our in-person meeting, assembled in Bozeman, MT, was the development of a broad conceptual framework that will underpin the details of the proposed research agenda, and the outlines of the research report that will eventually submitted to NSF and published in appropriate scientific forums (see below). An early draft of the report arising from these deliberations and subsequent contributions by various writing teams is included in Appendix G, the outline for which is below.

**Conceptual Framework for Research Agenda and Outline of Final Report**

1. SWOT analysis – where we are and where we want to get to
2. Framework for addressing problems – how we will get there?
    a. How will we know we got there? (evaluate implementation, relevance)
3. Vision statement
    a. How to changing drivers propagate and/or translate to ecosystem state (dynamics?) and water availability and what are the higher order feedbacks?
        i. Human behavior and management
        ii. Vegetation and land surface change
        iii. Morphology and storage
        iv. Driver characteristics – frequency, order, intensity, magnitude
4. Cycles of learning/knowing – observations/models/theories
5. Research agenda for change prediction & management
    a. Theory of observations/experimentation
    b. System evolution subject to basic governing principles
    c. New modeling paradigm for interdisciplinary problems
    d. Predictability of change
    e. Discovering institutions for resilience
6. How do we implement the agenda, a vision for the future

## Next Steps

1. A follow-up 3-day meeting will be held at the University of North Carolina in October 20-22, 2010. During the meeting a more detailed research agenda will be developed around the broad conceptual framework agreed upon in Bozeman, including experimental, monitoring, modeling and theoretical that will be needed to advance the proposed new research agenda. In doing so, the meeting will also consider the outcomes and experiences from the synthesis activities under Themes 2 and 3, and in particular the patterns-based approach to predictions to underpin the proposed research agenda.

2. A small writing team will compile the final report, which will be made available to the entire synthesis team for internal review. Upon completion of the final draft, we propose to invite a small team of external reviewers to join the writing team to help improve the report through a process of consultation, critical reviews and editing. We hope to submit the final report to NSF by May 31, 2011.

**References**

Wagener, T., M. Sivapalan, P. A. Troch, B. L. McGlynn, C. J. Harman, H. V. Gupta, P. Kumar, P. S. C. Rao, N. B. Basu, and J. S. Wilson (2010), The future of hydrology: An evolving science for a changing world, *Water Resour. Res.,* 46, W05301, doi: 10.1029/2009WR008906.

## Theme 2: Role of the biosphere in water cycle dynamics

**Topic:** Catchment ecohydrology: Water balance partitioning at the catchment scale and the role of vegetation

**History:** Initial work and paper completed in 2008, focus of 2009 Summer Institute, follow-up work and papers through 2010

Activities under this theme were inspired by early work done by Horton (1933) on the role of vegetation in growing-season water balance at catchment scale. Horton (1933) observed in one catchment in NE USA that the ratio of catchment total vaporization, (including interception, evaporation and transpiration), to catchment wetting, (the fraction of precipitation that is available to plants), hereafter termed the Horton index, was remarkably constant from year to year, suggesting an active role of vegetation water uptake proportional to the inter-annual available water variability. Indeed, based on his analysis Horton had hypothesized that the "*natural vegetation of a region tends to develop to such an extent that it can utilize the largest possible proportion of the available soil moisture supplied by infiltration*" (Horton, 1933, p. 456).

In recent work Troch et al (2009) had extended Horton's analysis to ~90 catchments from the MOPEX database and confirmed Horton's observations for the growing season. They also found that the Horton index computed for the hydrologic year is strongly affected by climate between catchments but also between years within a catchment, and that in all catchments the Horton index converges to 1 during the driest years in a 30 year period.

The goal of the research undertaken in the 2009 Summer Institute was to (a) further investigate the physical and climatic controls on mean Horton Index and to (b) explore whether vegetation and water balance dynamics were related in ways that could produce the buffering of the Horton Index first noted in Horton's 1933 study. To do this we expanded the studied catchments to include more than 400 MOPEX sites across the continental USA, and explored water balance dynamics, vegetation dynamics, and physical features of the catchments. The main results of our synthesis effort are summarized below.

Empirical Results: Vegetation

Variability in vegetation cover (as measured by NDVI) between catchments and across multiple years was better predicted by Horton Index than by other indicators (such as aridity index or precipitation). Furthermore, there was symmetry between the spatial (between catchments) and temporal (between years) patterns of variation.

Modeling Results: Water Balance

1. Inspired by the Horton Index, we developed 3 kinds of models to explore the controls on the patterns of variability of water balance: an empirical model, a simple process model and a functional model. The empirical model relates the Horton index statistically to observed climate (the aridity index) and landscape properties (slope and elevation). The process-based model is a soil moisture accounting model driven by a stochastic rainfall model and was used to derive the probability density function of annual Horton index analytically. The functional model is based on a two-step partitioning of incoming precipitation: (1) at the surface precipitation is partitioned between quick flow and wetting; (2) in the subsurface, wetting is partitioned between slow flow and evapotranspiration. These models led to following discoveries: (i) there is indeed a symmetry between water balance variability between catchments and between years, (ii) the empirical and process models confirmed the roles of climatic aridity, within year variability of climatic drivers, drainability (i.e., slope), and soil depth (correlated with vegetation type and potentially related to rooting depth and thus vegetation dynamics) as the dominant drivers of variation in the Horton Index.

2. However, the simple water balance models did not fully capture the controls on inter-annual variability of Horton Index. This is hypothesized to reflect an inadequate treatment of within-year and within-catchment variability of vegetation response, and to a lesser extent, rainfall-runoff processes.

3. The functional model of annual water balance, following L'vovich (1979) also allowed a robust estimation of the sensitivity of annual water balance to changes in annual precipitation. The four parameters of the functional model varied in a spatially coherent manner across the United States. However, they defied simple physical explanations. Future research is needed to link physical and ecological factors (e.g. climate, soils, topography and vegetation) to these parameterizations of catchment function.

4. In order to further elucidate the roles of within-year and within-catchment variability, we analyzed high resolution flux-tower data from 14

Ameriflux sites across the country. This analysis highlighted significant differences in the within-year vegetation dynamics and functioning. In particular we identified that temperature played a significant role in controlling vaporization in many sites. Significantly, patch-scale water balance partitioning also appeared to be strongly influenced by the presence of deep moisture sources which provided a subsidy beyond the input of rainfall at a site, and highlighted the potential importance of within-catchment lateral flow processes on water balance prediction.

5. The inability to account for the lateral subsurface flow subsidy in patch scale observations and models meant that it was not generally possible to predict Horton Index for a catchment on the basis of partitioning at the patch scale.

6. This significant scale gap between patch and catchment scale estimates of water balance and the Horton Index highlighted the need for a theoretical framework to address spatial scale dependence in water balance prediction, with the ultimate goal of allowing water balance to be scaled between the patch and the catchment scale.

7. We explored a preliminary approach towards such a framework in the form of a simple conceptual model that linked feedbacks between vegetation cover and evapotranspiration along a converging flowpath network (similar to a river network). These features resulted in both vegetation cover and water balance self-organizing in space around the imposed network, and naturally resulted in non trivial spatial scaling of both.

8. This model confirmed that invoking fundamental principles could result in spatial variability in the Horton Index across spatial scales. It also highlighted a set of physical controls on the Horton Index at the catchment scale, expressed in terms of 4 dimensionless similarity variables: (i) aridity index, $R$, (ii) a drainage competitiveness index, $D$, (iii) a vegetation acclimation index $G$, and (iv) a network bifurcation index $\beta$.

9. We propose that this theoretical framework could form the basis for an inter-disciplinary research agenda for the emerging sub-field of catchment ecohydrology. This research agenda may be organized around the four dimensionless similarity indices, and could focus on improved representation of the complex coupled processes linking soils, topography, vegetation and hydrology in catchments.

10. The proposed conceptual model of vegetation organization and water balances at the catchment scale represents a culmination of systematic analysis of catchment water balance data, flux tower data and vegetation cover data, supported by parsimonious models in a top-down manner. It

represents a particular mode of hydrologic synthesis that is built around patterns deciphered from observations.

**Next Steps**

15 papers from this theme have been submitted to the WRR special section on "Approaches to Synthesis: Watersheds as Dynamic, Cascading, Hierarchical, Non-linear Space-Time Filters", of which over half arose out of the first summer institute held in 2009, as detailed in Appendix C. Five of these papers had students as first authors.

**References**


Horton, R.E. (1933). The role of infiltration in the hydrologic cycle, *Trans. Amer. Geophys. Union,* 14, 446-460.

L'vovich, M. I. (1979). *World Water Resources and Their Future.* English translation of Russian original. Amer. Geophys. Union, Washington D. C., 415p.

Thompson, S. E., C. J. Harman, P. A. Troch, P. D. Brooks and M. Sivapalan (2010). Scaling of ecohydrologically mediated water balance partitioning: A synthesis framework for catchment ecohydrology. *Water Resour. Res..* In review.

Troch, P. A., G. F. Martinez, V. R. N. Pauwels, M. Durcik, M. Sivapalan, C. J. Harman, P. D. Brooks, H. V. Gupta and T. E. Huxman (2009). Climate and vegetation water-use efficiency at catchment scales. *Hydrol. Process.,* 23, 2409-2414.


## Theme 3: Human induced changes to water cycle dynamics

**Topic:** Catchment Biogeochemistry: Hydrologic and Biogeochemical Filtering of Reactive Solute Export from Diverse Catchments

**History:** Initial work and paper completed in 2008, focus of 2009 Summer Institute, follow-up work and papers through 2010

**Context**

Catchments are characterized by complex interactions between multiple, dynamic processes at nested spatial and temporal scales. These processes are, in turn, controlled by a variety of climate, topographic, geologic, pedologic, vegetative, hydrologic, and biogeochemical forcing that serve as deterministic and stochastic "drivers". Impacts of such transient perturbations cascade through the hillslopes and the converging stream networks which drain them. These propagated impacts are then manifested as the hydrologic, biogeochemical, and ecological responses of the catchments observed at various spatiotemporal scales. Thus, landscapes may be conceptualized as nonlinear, hierarchical, dynamic filters, acting in series and/or in parallel, to buffer or magnify or otherwise modulate the stochastic and deterministic input signals (drivers) to produce spatiotemporal patterns in concentrations and loads at multiple scales. Here, we focus only on the hydrologic and biogeochemical behavior of “natural” (forested; least impacted; LTER sites), and “managed” (croplands; mixed land use & land cover (LULC)) catchments to explore the role of human impacts on catchment responses. We examined the relative role of “natural” stochastic hydro-climatic forcing (e.g., rainfall; net radiation) and a gradient of anthropogenic forcing (e.g., changes in LULC; persistent land/crop management) in controlling the observed catchment responses, and the coupling/decoupling of hydrologic and biogeochemical processes.

**Synthesis**

Our synthetic approach was based on evaluating available long-term and multi-scale monitoring data and new parsimonious modeling analyses to examine emergent patterns in diverse catchments along human impact gradients. We present: (1) The outcomes of a large, inter-disciplinary, collaborative effort to synthesize available data on catchment responses observed in diverse catchments in North America, Europe, and Australia, revealing the emergence of surprisingly simple patters resulting from the links between hydrologic and biogeochemical process controls; (2) Explanations for the persistence and consistency of these patterns; (3) Lessons learned from efforts to develop and evaluate parsimonious models to describe the coupled hydrologic and biogeochemical responses; and (4) implications of our synthesis findings to catchment management.

**Synthesis Outcomes**

Despite daunting process complexity and associated uncertainties, our analysis shows that human modifications and intensive management of watersheds have led to a decrease in catchment complexity and more predictable responses, typical of an engineered, less-complex system when compared to the more complex “natural” catchments (i.e., with least human impact). Human alterations decrease catchment complexity by: (1) imposing greater structural homogeneity; (2) altering the connectivity and the “travel time” distributions; and (3) overwhelming the natural structural and functional diversity by imposing dominant and persistent anthropogenic forcing (i.e., legacy effects dominate) to achieve greater homogeneity of functionalities (thus, decreasing uncertainty of the outcomes).

Our analysis revealed that persistent anthropogenic forcing has lead to the emergence of effective biogeochemical stationarity and the dominance of hydrologic flows in determining nutrient (N & P) loads exported from managed catchments, similar to responses observed for geogenic constituents in less-impacted and managed catchments. These are identified as being the “transport-limited” cases. In contrast, pesticides in managed catchments and nutrients in less-impacted catchments represent “supply limited” cases, where exported loads are only weakly correlated to hydrologic fluxes. Frequency domain analyses helped identify the spatial and temporal scales at which biogeochemical stationary emerges for different dissolved solutes (nutrients and pesticides), as a result of aggregation of loads from heterogeneous sub-watersheds delivered to the stream network. We also explored the scale-dependence of the biogeochemical cycling rate constant for nitrate ($k_e$; $T^{-1}$), and the relative role of hydrologic and biogeochemical controls on ke. The inverse stage dependence was observed to arise as an emergent pattern by coupling the mechanistic Transient Storage Model with a network model. Analytical modeling indicated that for the same mean annual discharge, "dry" domains ($\lambda/k_c < 1$; $\lambda$=runoff frequency, $k_c$=inverse of catchment residence time) were more efficient in processing nitrate than "wet" domains ($\lambda/k_c > 1$). The probability distribution functions of ke and the nutrient delivery ratio (NDR), representing the intra-annual variability resulting from stochastic hydrologic forcing in stream networks could be adequately predicted using analytical approaches.

Our work shows that simpler and more efficient conceptual and modeling approaches can be used for predicting hydrologic and biogeochemical responses in managed catchments. A parsimonious model, HEIST (Harman *et al.,* WRR 2010), was developed to predict the progressive, episodic transport of reactive solute through the vadose zone under stochastic rainfall/ET forcing. We tested HEIST predictions against a standard numerical code HYDRUS that explicitly solves transient flow and transport scenarios. We also derived analytical expressions for the probability density functions (pdfs) for the travel-time and waiting-time distributions, and the delivery ratio. Previously developed hillslope model, TELM (Basu *et al.,* 2009), was coupled to MRF model (Botter *et al.,* 2010), also published earlier, to satisfactorily predict hydrologic flows and pesticide loads from a managed catchment in Illinois (Little Vermillion River Watershed (LVRW), Illinois). The model predictions compared well with long-term monitoring data collected by previous workers. A new stream network model was developed by adding biogeochemical components to the existing THREW model (Sheng Ye *et al.,* WRR, 2010). This new model was then used, with the LVRW as a watershed template, to perform parameter sensitivity analyses to identify key hydrologic, biogeochemical, and stream morphological characteristics that govern nutrient cycling in stream networks at the watershed scale. These model simulations were used along with those of reach-scale and whole basin-scale model simulations to examine scaling of nutrient cycling along large networks.

**Practical Implications**

Practical implications of our synthesis to watershed management and few key research gaps are identified below:

1. Persistent legacy nutrient sources built up over decades of intensive land management will persist for decades or centuries, suggesting that nutrient loads exported from catchments may not decrease significantly even if no further fertilizer/manure additions are made. This finding calls into question the strategies (e.g., BMPs) employed currently to mitigate adverse ecological impacts of intense land management.

2. In-stream processing of nutrients, and other anthropogenic constituents, at multiple scales can be readily made, given the information on hydrologic forcing (discharge dynamics) and the procedures we developed for estimating effective rate parameters, but without necessarily needing explicit information about the stream network itself.

3. Examination of additional watersheds and available monitoring data is needed to confirm our initial findings about the temporal trajectories of catchments along increasing human impact gradients, and for their recovery under some restoration scheme.

4. Recent studies have examined stream networks as ecological corridors. Linking such models to the modeling approaches we have developed here to predict the hydrologic-biogeochemical responses to ecological responses would be highly useful.

5. Our analysis was limited to export of dissolved constituents from catchments. But, many reactive constituents of environmental concern (e.g., P, metals, pesticides; pharmaceuticals; hormones; etc.) exhibit strong association with particulate, suspended solids (especially, the fine size fraction, with large reactive surface area) as a result of sorption, complexation, or precipitation. Some constituents (e.g., pesticides; pharmaceuticals; hormones; some metals and metalloids) can also bind with dissolved organic carbon. Thus, export of these types of constituents is directly linked to transport of fine particulate solids and dissolved organic carbon.

**Next Steps**

8 papers from this theme have been submitted to a WRR special section on “Approaches to Synthesis: Watersheds as Dynamic, Cascading, Hierarchical, Non-linear Space-Time Filters”, as detailed in Appendix C, of which 6 arose from the 2009 summer institute.

**References**

Basu, N. B., P. S. C. Rao, E. H. Winzeler, S. Kumar, P. R. Owens, and V. Merwade (2010a), Identification of dominant controls on hydrologic responses in engineered watersheds: 1. hydrograph prediction, Water Resour. Res., doi:10.1029/2009WR007803.

Botter, G., N. B. Basu, S. Zanardo, P. S. C. Rao, and A. Rinaldo (2010), Stochastic modeling of nutrient losses in streams: Interactions of climatic, hydrologic, and biogeochemical controls, Water Resour. Res., 46, W08509, doi:10.1029/2009WR008758.

Harman, C. J., P. S. C. Rao, N. B. Basu, P. Kumar and M. Sivapalan (2010). Climate, soil and vegetation controls on the temporal variability of vadose zone transport. Water Resources Research (in review).

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export vs. internal processing. We advanced flexible theoretical models for the effects of in-stream and subsurface flows on both conservative and reactive transport in rivers, and were able to show that these models produce realistic net downstream transport behavior. Potentially, these models can be used to explicitly evaluate connections between hydrologic transport and net reaction, uptake, and/or processing of carbon, nutrients, and contaminants in streams, but we found that our overall attempt to perform a synthesis of this behavior in many streams was hindered by a lack of sufficiently detailed and contemporaneous information on stream flow, conservative transport, and reactive transport.

Important outcomes of this effort are:

- analysis of the sensitivity of in-stream tracer measurements to experiment duration, exchange rates, background variability, and measurement sensitivity;
- specific recommendations for improved design of stream tracer studies; greatly improved understanding of requirements to separate local biogeochemical transport rates from solute fluxes to reactive regions;
- a suite of improved models for stochastic solute transport in rivers including in-stream and subsurface retention and reaction;
- and demonstration of how particular geomorphic and hydrologic controls operate together in select types of streams.

**Next Steps**

1. These contributions will be crystallized through follow-on activity over the next 6-9 months. A suite of key presentations on these topics have been submitted to and accepted for the AGU fall meeting (Appendix X). In parallel, each of the key outcomes described above will be developed into a stand-alone publication led by one of the participating students. We are exploring a primary venue for publication of these results that encompasses both the theoretical development and data synthesis; most likely a special issue or special section of *Limnology and Oceanography (Fluids and Environments)* or *Water Resources Research*.

2. In order to reach additional end-users in the stream ecology / biogeochemistry community, we will also explore a more directed paper presenting recommendations for the design of experiments intended to assess the net reaction and uptake of carbon and nutrients during propagation through river networks. The Journal of the *North American Benthological Society* is a likely venue for this type of synthesis paper.

**Topic:** Catchment Biogeochemistry: Links between sediment dynamics and nutrient cycling at the watershed and river basin scale

**History:** As a focus of the 2010 summer institute, this work is an outgrowth of our 2009 efforts on this theme and closely mirrors the previous topic's approach.

Research over the past two decades has developed strong links between hydrology and the cycling and downstream flow of biogeochemical elements like nitrogen. Sediment cycling is also a key factor influencing the downstream flow of important biogeochemical elements, particularly highly adsorptive elements like phosphorus. Yet the linkages between biogeochemical cycling and sediment dynamics are not as well developed. To date, most research and models on biogeochemical cycling at the watershed scale have focused on dissolved constituents, like nitrate, the most soluble and mobile nitrogen species. Research on the links between sediment dynamics and biogeochemical cycling across various spatial and temporal scales is critical to understanding the aquatic cycling and downstream transport of carbon and key plant nutrients like phosphorus, as well as the evolution of nutrient limitation in coastal systems.

**Activities**

For two weeks, we led the students in research on the links between sediment dynamics and nutrient cycling at the watershed and the basin scales.

The following research questions were investigated:

- What are the spatial and temporal patterns in the terrestrial sources of sediment and nutrients (nitrogen and phosphorus)? How are these patterns linked to land use, land cover and climate?
- What are the controls on the transient storage of sediment [and nutrients] in the channel environment?
- How does land use and climate variability influence stoichiometric ratios (e.g. N:P, N:Si)?

To address these questions, we used data from i) Goodwin Creek watershed in Mississippi (14 sediment + flow stations), ii) approximately 400 sediment and flow stations from the Mississippi River Basin, and iii) monthly nutrient and sediment data from available stations across the Mississippi River Basin, including an Upper Mississippi River Basin dataset. In addition, data from Japan and Spain was used to investigate temporal patterns of sediment supply and storage.

- Spatial pattern of suspended sediment yield, sediment sources and sediment sinks in the Mississippi River Basin

- Temporal patterns of sediment dynamics along the Missouri and Lower Mississippi River
- Links between suspended sediment yield and land cover / land use across the Mississippi River Basin
- Influence of climate variability on N:P in downstream waters
- Reach sediment balance for the Goodwin Creek watershed: suspended sediment and bed load dynamics, channel stability and bank erosion
- Reach sediment balance for the Goodwin Creek watershed: Network modeling

**Outcomes**

Through the session, the students learned to work with a large landscape with complex hydrology, land use, land cover and climate and to study the dynamics of complex interacting human-natural systems. The students tested for patterns in large data sets for the Mississippi Basin (land use, land cover, sediment, nutrients, hydrology). By working on the reach, watershed and river basin scale, the students gained an appreciation of the different processes operating at each scale. Students also gained valuable exposure to modeling approaches to watershed scale sediment dynamics.

We developed the first scaled sediment yield map for the Mississippi River Basin utilizing all available suspended sediment data collected by governmental agencies (scale of 1 $km^2$ to 10000 $km^2$). The students identified patterns in sediment sources and sinks along the basin, and linked these patterns to spatial and temporal variability in land cover and land use.

Following this analysis, we linked the temporal patterns in sediment dynamics in the Missouri River to human and environmental history. The key finding was the importance of the memory of the landscape which dictate spatial pattern in sediment dynamics within the river basin. We identified that most of the sediment in the main stem of the Missouri River system comes from valley bottoms, not from hillslopes and the landscape. This finding may have important implications for conservation tillage. Soil conservation at the field and slope scale has been successful at reducing landscape erosion. Dam construction also led to reduction in sediment flux from the river basin. However, this led to a river system starved of sediment which triggered likely greater bank erosion and valley erosion. This valley erosion may be the main source of sediment to the system. Improved soil management effort should consider valleys and banks in addition to hillslopes. Controlling sediment load to the Mississippi Delta will require treating the basin as an integrated geomorphic unit.

In addition, the students evaluated the temporal and spatial patterns in nitrogen, phosphorus and silica loading across the Mississippi River Basin. This analysis provided the students with an opportunity to investigate differences between the dynamics of dissolved constituents and particulate matter. The students tested hypotheses about how climate variability and change influence stoichiometry. One key finding was that in agricultural river basins, N:P increases during years of higher rainfall and higher flow.

Through the work in this session, we also identified a few major gaps in our understanding of the hydrogeomorphic functioning of the watersheds. First, scale has not been less of concern in geomorphology than hydrology. Our work on the spatial and temporal variability of sediment dynamics in the Mississippi Basin highlighted the importance of scale in the study of the geomorphic dynamics of large river basins. Integrating hydrology and geomorphology is critical to achieving progress in understanding of the effects of scale on sediment dynamics. This could lead to a concept paper developing the linkages between geomorphology and hydrology at the basin scale. Second, our work on the Missouri River Basin identified the importance of geomorphic connectivity of the landscape to understanding sediment availability and flow in rivers. This could be a key subject for a synthesis paper and the development of new conceptual models. Third, we learned the importance of considering the environmental history of the river basin in the linking land use to river dynamics. In the literature, sediment dynamics are often linked to current land use. Our work on the history of the Missouri River Basin could be an important example of how past environmental change influences current sediment dynamics. Finally, we learned that the ratio of nitrogen to phosphorus, a key ecological indicator, can also be representative of the difference between water and sediment flux in rivers. The linkages between stoichiometry, geomorphology and hydrology could lead to an important conceptual paper.

**Next Steps**

The research will be summarized in seven presentations at the Fall AGU meeting (Appendix D). Each of these presentations is a potential manuscript. In addition, the mentors will be preparing a synthesis manuscript on the topic.

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**Topic:** Harmful algal blooms in rivers: Invasion and blooming behavior of *Didymosphenia geminata*

**History:** This topic, a focus of the 2010 summer institute, bridges our past and present activities within this theme, utilizing an important open ecological question as a vehicle for these connections.

For this topic, we explored the factors that control the spread and persistence of the invasive, mat-forming diatom Didymosphenia geminata in rivers. This organism has recently received considerable interest as it has been responsible for extensive nuisance blooms in rivers in North American and New Zealand. It is thought that this organism represent a component of the normal benthic community in parts of North America, and the factors that have led to increased blooming behavior are not known. Conversely, this organism was introduced to New Zealand in 2004, and since then has spread rapidly through many major streams and rivers of high ecological value.

We used existing data sets from Vancouver Island, Colorado, Quebec and New Brunswick, and the South Island of New Zealand to explore relationships between human disturbance, flow variability, river geomorphology and geochemistry, and the growth and persistence of *D. geminata*. Prior studies have generally only focused on the distribution and occurrence of this organism, but through the interdisciplinary synthesis activity we were able to interrogate the growth rates, morphology, proliferation, and persistence of the organism in response to hydraulic conditions, channel morphology, flow variability, light levels, pH, and nutrient levels. This required synthesis of hydrologic, geomorphic, physiographic, and geochemical data with organism surveys. We were able to identify geomorphic structures that provide favorable habitat for *D. geminata* blooms, determine ranges of chemical concentrations (notably pH) that appear to greatly hinder growth of the organism, and discriminate controls on growth rate and morphology (related to nutrient concentrations) from controls on long-term persistence (directly resulting from response to hydrodynamic shear in high flows).

These results demonstrate how different approaches and perspectives are needed to attain holistic synthesis of complex ecological phenomena. In this instance, interpretation of prior synoptic surveys have been confounded by the difficulty in discriminating cell division from biomass production (most of which is inert stalk material) and in identifying controls on growth of new mats relative to persistence through flow variations. We were able to make substantial progress on this problem by interpreting spatial and temporal trends in *D. geminata* morphology and abundance in terms of geomorphic, hydrologic, and geochemical variability.

**Next Steps**

1. These results will be presented in a series of talks at the AGU Fall Meeting (Appendix D) focusing on an updated conceptual model for *D. geminata* growth and persistence, supported by individual talks examining the behavior of this organism at a number of different sites. We are continuing the analysis by bringing in additional data sets, most notably further analysis of hydraulic and geomorphic controls at some sites, and additional time-series analysis using higher-frequency measurements in New Zealand rivers.

2. These results will also be published as a journal special issue or special section, most likely in *Limnology and Oceanography (Fluids and Environments)*, as that new journal is focusing specifically on studies that

examine the mechanics and dynamics of interactions between fluids, life, and geological systems.

## Theme 4: Structure of landscapes and their evolution through time

**Topic:** Long term artificial hillslope experiement at Biosphere 2

**History:** With the aid of the UIUC synthesis project, the Biosphere 2 team finalized the conceptual design of the experiment (EOS paper), performed model simulations prior to building the hillslopes (Hopp *et al.,* 2009; Dontsova *et al.,* 2009; Ivanov *et al.,* 2010), and recently completed the technical design/engineering. See Appendix B for papers.

**Next Steps**

Instrumentation plan/design (what sensors go where and how many; what data acquisition system works best, etc) and irrigation system design are currently underway. Construction is scheduled to start November 2010.

## Theme 5: Stochastic transport and scaling in earth-surface processes

**History:** This group (including many of our synthesis team members) collectively studies subsurface transport of water and solutes, solute and sediment transport in streams, erosion, deposition and stratigraphy. Synthesis of existing data in all of these fields demonstrated the similarity of properties that emerge when transport occurs in spatially and/or temporally heterogeneous settings.

This interdisciplinary collaborative group has published 16 papers in a special issue of JGR – Earth Surface (see Appendix X). Additionally, the STRESS collaboration yielded a second workshop, STRESS II, which met in November 2009 at the Tahoe Center for Environmental Research in Incline Village, Nevada – as previously detailed in our annual report.

While the methods afforded by this theme have always underpinned activities within each of the other themes, these concepts were integrated more fully with our catchment-scale activities (Theme 3) during the 2010 summer institute. An existing short course was expanded to include hands-on exercises for the summer students so they had the tools to synthesize existing data on nutrient (N, P) and sediment transport in streams using transport models (CTRW, fractional ADE, heavy-tail models).

## III. Framework, Future Vision, Transformational Contribution

We have demonstrated, through three different synthesis projects (involving hydrology-ecology, hydrology-biogeochemistry and hydrology-sediment interactions) that a patterns based approach to inter-disciplinary synthesis can indeed lead to transformative outcomes. In particular, the analysis of massive datasets (e.g., catchment water balance, vegetation patterns, patterns of nutrient and sediment export at a range of scales), the extraction of emergent patterns behind the data (e.g., constancy of the Horton Index, chemostasis, scaling of sediment delivery ratio), and the interpretation of these patterns physically through the use of parsimonious models has been shown to lead to deeper understanding of the underlying processes and process interactions (across scales and places).

The results of this work are included in several articles submitted to peer-reviewed journals. While these articles, individually, can be deemed to be standard, yet taken together they constitute advances on a broader front which can be claimed to be transformative in view of the new questions they pose, and new avenues for research that they open up (in the sense of "*the whole being more than the sum of the parts*"). In both of the completed projects (hydrology-vegetation interactions and coupled hydrological-biogeochemical processes at the catchment scale) we have completed two "synthesis of synthesis" papers, which present broad new theoretical frameworks for the study of the emerging subfields of catchment ecohydrology and catchment biogeochemistry. In each case, the theoretical framework is built around the stream network structure, which provides the connective tissue to link processes across scales and to explain the observed scaling behavior that is exhibited in data. These synthesis projects have enabled scientists from many different disciplines to interact around the common framework adopted, and debate or assess the merits of alternative parameterizations of hydrological, biogeochemical and sediment transport processes at a range of scales for making predictions at the river basin scale. The keys to explaining the observed scaling behavior are understanding and reproduction of the interactions and feedbacks between hydrological, ecological and biogeochemical processes, including the associated legacy effects due to the equalizing role of topography on down-slope and downstream fluxes and storage of water, sediments and nutrients.

In the remainder of the project we would like to attempt two higher level synthesis activities. In the first case, we would like to attempt a unification of the outcomes of the synthesis projects carried out under Themes 2 and 3 through the development of a broad conceptual/theoretical framework that integrate the hydrological, biogeochemical and ecological process interactions (ecohydrology involving vegetation-water interactions at the catchment scale, and hydroecology dealing with the interactions between streamflows, biogeochemistry and stream ecology) at the river basin scale, with explicit treatment of stream network structure, hydraulic geometry and river morphology, and topography and soil catena). This will be presented in grand synthesis paper that will be an extension of the two synthesis papers already completed from Themes 2 and 3.

Even though the objective of the UIUC synthesis project is to improve predictability of water cycle dynamics in a changing environment, the models and theoretical frameworks adopted as part of the completed projects (under Themes 2 and 3) did not involve a direct and active human role. For this reason, we would like to use the experience gained from adopting the patterns-based approach to predictions organized under Theme 1, i.e., developing a new research agenda for dealing with predictions of changing water cycle dynamics in the context human-nature interactions and feedbacks. A conceptual framework to be developed as part of this research agenda will be utilized to propose the design of new monitoring networks that can reveal the future evolution of these coupled systems and the development of a new generation of models that explicitly incorporate the human role in the water cycle, through the use of emergent patterns that arise through complex human-nature interactions in the landscape.

## IV. PLAN FOR SYNTHESIS IN THE FINAL YEAR

### *Complete publication of WRR special issue (Themes 2&3)*

The results and findings from work to-date under Groups 2 and 3 have been submitted to a special section of *Water Resources Research* under the theme: “Approaches to Synthesis: Watersheds as Dynamic, Cascading, Hierarchical, Non-linear Space-Time Filters.” Dr John Selker and Dr Graham Sander serve as lead editors with Murugesu Sivapalan serving as guest editor. Submissions were accepted between May 15 and October 31, 2010.

This special section is concerned with advancing the predictability of the propagation of human-induced changes (climatic, land-use and land-cover) through the hydrologic system, both in time and over space. Systematic data analysis and synthesis -- aided by parsimonious models to elucidate consistent patterns – can generate new insights into the dominant process controls on observed variability and changes, and yield valuable clues towards development of a new generation of models for future predictions. This “patterns-based” approach will be illustrated through papers that share the common perspective of the landscape as comprising a set of dynamic, cascading, hierarchical, non-linear filters, which propagate and modify the variability inherent to the climatic and land-use inputs, and highlight the relative roles of climatic, transport (hydrologic) and reaction (biogeochemical) timescales, the role of memory or legacy effects, and the buffering role of ecosystems (e.g., vegetation, micro-organisms).

The papers included in this special section amply demonstrate the feasibility to develop a novel, unified and robust predictive framework that is focused on the cascading of hydrologic variability across a range of scales (local-- hillslope --watershed --river basin), and their impact on nutrient transport and export. Submitted papers from this project and from colleagues within the community are listed in Appendix C.

***Prepare a second special journal issue (Theme 3)***

As we facilitate the next phase of the student-mentor work coming out of our recent summer institute, we are working towards a single objective: a coherent, integrated body of work tightly connected with our broad vision, and one that can be disseminated through a second special issue to be published in either *Water Resources Research* or *Limnology and Oceanography (Fluids and Environments)*. This will be an extension of the first special issue of *Water Resources Research*, but will in particular be devoted to comprehensively covering the following three topics:

- Solute transport and (dissolved) nutrient dynamics from the cellular scale to the river network scale
- Links between sediment dynamics and (particulate) nutrient cycling from the reach scale to river basin scale
- Harmful algal blooms in rivers: Invasion and blooming behavior of *Didymosphenia geminate*

The special issue will build on the results from the 2010 summer institute, but will also include invited papers from outside the synthesis team in key niche areas, as well as two "synthesis of synthesis" papers that provide a review and distillation of the results from the entirety of the synthesis projects, along with a forward-looking research agenda for future research activities in this general area.

*Collaborate with the CUNY project to communicate summer institute best practices*

The summer institute model is just one tool employed as part of our three-pronged approach to testing modes of hydrologic synthesis. While we feel the critical process outcomes are in the **connection between patterns-based inquiry and team science**, the summer institute (as a large expenditure), deserves special analysis. Project coordinator Jennifer Wilson, with CUNY postdoc Caroline Hermans, will present feedback from students and faculty mentors on their experiences with the collective five summer programs at AGU this fall. *Summer Synthesis Institutes: A Novel Approach for Transformative Research and Student Career Development* was submitted to ED05. Developing Geoscience Expertise: Bridging the Gap Between Master and Novice.

***Conduct SWOT analysis for the synthesis process***

As we wrap up this project, the PIs and key leaders will be undertaking a thorough internal, informal assessment to identify lessons learned and help the community identify an optimized, sustainable vision for future synthesis. At the foundation of this effort will be consistently communicating the definition of synthesis by which we've operated, as a frame of reference.

Our initial insights tell us that in order to facilitate appropriate and ideal conditions for scientific breakthrough, project PIs/managers must (1) balance self interest (disciplinarity) with group interests (inter/intra/trans-disciplinarity), (2) sacrifice certain levels of detail to find common grounds, (3) seek approximate solutions to difficult problems to move the field substantially, and (4) provide clear leadership and a framework for success. These elements are essential to providing continuity of theme and focus across all activities as well as provide the appropriate level of flexibility to enable creativity and innovation.

While we can roll up these experiences into simple generalizations, it is more difficult to define the degree success or failure for each theme and topical endeavor. As we approach this analysis for components of the project, we will operate with two core questions in mind: (1) What are the SWOTs of a patterns-based approach? and (2) What are the SWOTs of team science? Furthermore, it is imperative that the connections and overlaps between these questions be explored, to full understand how teams collect, analyze and produce scientific outcomes. We are greatly looking forward to feedback from the external panel regarding our approaches to synthesis.

### *Disseminate framework for synthesis & research agenda*

The water management challenges posed by global change dictate that we specifically address predictions of changing water cycle dynamics, with implications for how we observe, predict and manage water resources at large time and space scales, guided by new questions and methodologies that are geared towards addressing change, nonstationarity and adaptations by both humans and nature.

The culmination of our activities will result in two groups of products for the community's consideration: (1) the collective body of publications, framed by high impact review papers and (2) a comprehensive research agenda that can be considered by NSF in its long-range funding plans as well as by CUAHSI and other organizations for use in their strategic planning.

## V. LIST OF APPENDICES

- **Appendix A -** UIUC Synthesis Project White Paper
- **Appendix B -** List of Publications to Date
- **Appendix C -** Index for WRR Special Issue
- **Appendix D -** List of Presentations & Posters at Fall 2010 AGU
- **Appendix E -** Wagener et al. (2009). The future of hydrology: An evolving science for a changing world. *Published in WRR*
- **Appendix F -** Schaefli et al. (2010). Hydrologic Predictions in a Changing Environment: Behavioral Modeling. *Submitted to HESS*
- **Appendix G -** Draft of "Water Research Agenda" Report

**Annual reports can be found at**

**http://cwaces.geog.uiuc.edu/synthesis/reports/**

# **Appendix A**: 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 | - What types of interactions are possible, and what patterns of hydrologic behavior results? Across places, across scales and across processes.<br>- How do process interactions influence system predictability? How do resulting patterns influence our ability to make predictions?<br>- 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.<br>- Can observed interactions and resulting patterns tell us something about unobserved interactions relevant for prediction? |
| Variability as the driver of interaction | - 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?<br>- What is the role of timing, sequencing, frequency, magnitude, thresholds?<br>- What can we learn by observing events, discrete structures?<br>- How is variability connected to self-organization?<br>- If we increase our understanding of how variability drives interaction, how does this increase our ability to make predictions? |
| Emergent patterns and organizing principles | - Can we identify organizing principles useful for prediction directly at the scale of interest?<br>- Can organizing principles help to infer unobserved process interactions or to infer unobserved system structures?<br>- Examples: landscape resilience, optimality, competition |
| Non-equilibrium thermodynamics | - 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):

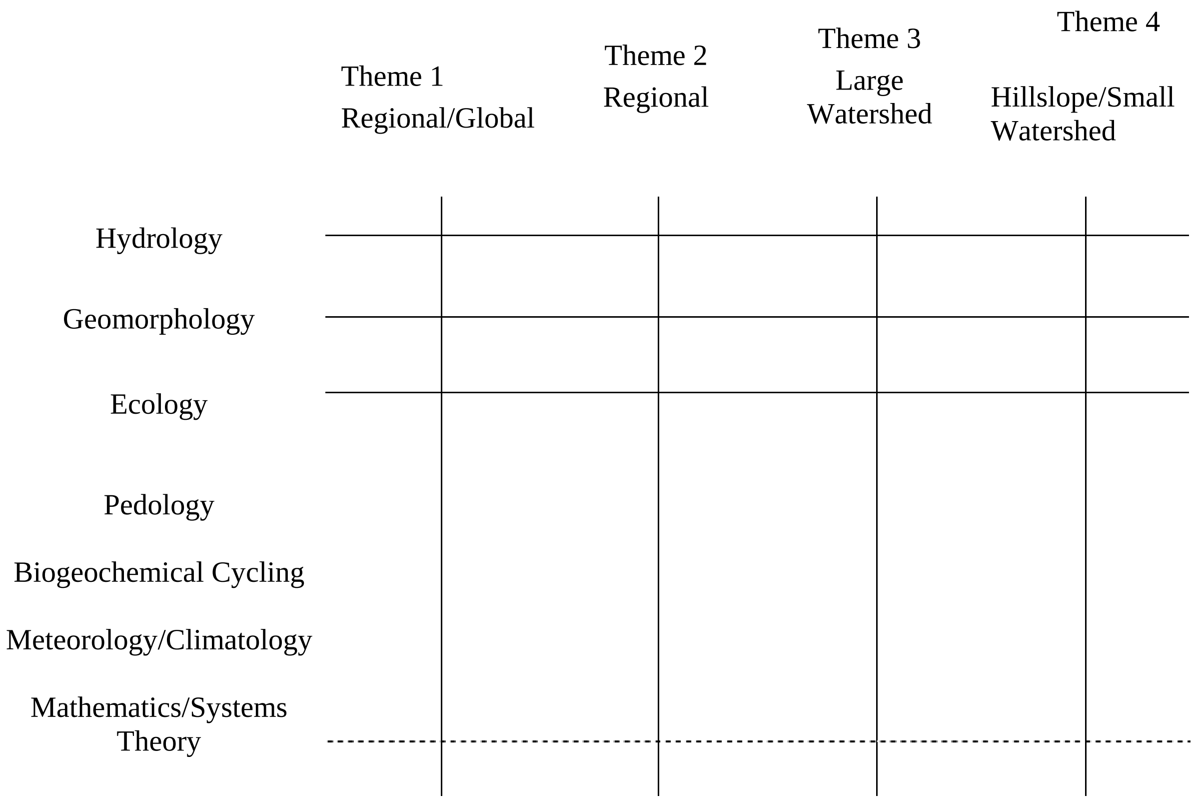
- ⇨ Larry Band (UNC), Paul Brooks (Arizona), Francina Dominguez (Arizona), Darren Drewry (UIUC), Ciaran Harman (UIUC), Marwan Hassan (UBC, Vancouver), Jon Chorover (Arizona), David Gochis (NCAR), Travis Huxman (Arizona), Henry Lin (Penn State), Craig Rasmussen (Arizona), Jeff McDonnell (Oregon State), 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 (Nex 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 Schaefli (TU Delft, The Netherlands), Karsten Schulz (University of Munich, Germany), Fuqiang Tian (Tsinghua University, Beijing, China).

⇨




## 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

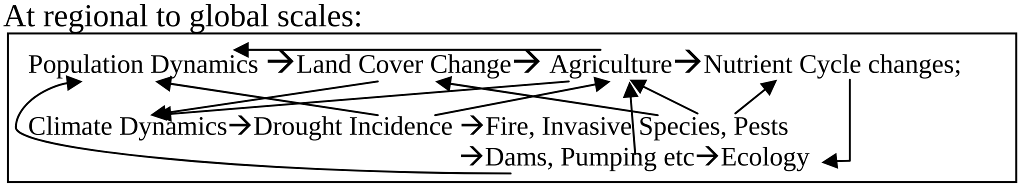
Climate dynamics is marked by structured variability at preferred time scales in response to changes in solar insolation, orbital forcing etc, and internal feedbacks across ocean, atmosphere, land and the cryosphere. Hydrologic fluxes play a crucial role in earth system evolution at these time scales, 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 $CO_2$ 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:

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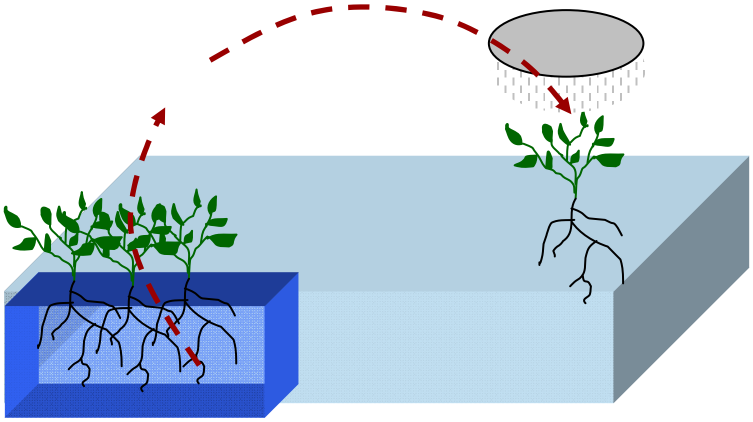
**Theme 2: Interactions between the hydrosphere and biosphere processes**

Vegetated terrestrial ecosystems and the overlying atmosphere are dynamically linked though 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?

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**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?

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**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?

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**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 <u>morphology</u> (e.g., surface topography, river network structure, braided river channel organization, etc.). However, it has not been explored as much in Earth-surface <u>processes</u> (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., $\partial^{1.3}C / \partial t^{1.3}$ ) 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 derivates 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.

**Appendix B: List of Publications to Date**

* Indicates student lead author

| Lead Author | Theme | Title | Journal | Year | Status | Full Citation |
|---|---|---|---|---|---|---|
| Wilson | Broad | Blazing new paths for interdisciplinary hydrology | EOS | 2010 | published | Wilson, J.S., C. Hermans, M. Sivapalan, C.J. Vörösmarty (2010). Blazing new paths for interdisciplinary hydrology, Eos Trans. AGU, 91(6), 53-54. |
| Schaefli | Theme 1 | Hydrologic Predictions in a Changing Environment: Behavior Modeling | HESS | 2010 | submitted | — |
| Wagener | Theme 1 | The Future of Hydrology – An Evolving Science for a Changing World | WRR | 2010 | published | Wagener, T., M. Sivapalan, P. A. Troch, B. L. McGlynn, C. J. Harman, H. V. Gupta, P. Kumar, P. S. C. Rao, N. B. Basu, and J. S. Wilson (2010), The future of hydrology: An evolving science for a changing world, Water Resour. Res., 46, W05301, doi:10.1029/2009WR008906. |
| Troch | Theme 2 | Climate and vegetation water-use efficiency at catchment scales. | HP Today | 2009 | published | Troch, P. A., G. F. Martinez, V. R. N. Pauwels, M. Durcik, M. Sivapalan, C. J. Harman, P. D. Brooks, H. V. Gupta and T. E. Huxman (2009). Climate and vegetation water-use efficiency at catchment scales. Hydrological Processes, 23 (16), 2409-2414. |
| Rao | Theme 3 | Nutrient Loads Exported from Managed Catchments Reveal Emergent Biogeochemical Stationarity | GRL | — | in review | — |
| Dontsova | Theme 4 | Solid phase evolution in the Biosphere 2 hillslope experiment as predicted by modeling of hydrologic and geochemical fluxes | HESS | 2009 | published | K. Dontsova, C. I. Steefel, S. Desilets, A. Thompson and J. Chorover (2009). Solid phase evolution in the Biosphere 2 hillslope experiment as predicted by modeling of hydrologic and geochemical fluxes. Hydrology and Earth System Sciences, 13(12), 2273-2286. |
| Hopp | Theme 4 | Hillslope hydrology under glass: confronting fundamental questions of soil-water-biota co-evolution at Biosphere 2 | HESS | 2009 | published | L. Hopp, C. Harman, S. Desilets, C. Graham, J.J. McDonnell and P.A. Troch (2009). Hillslope hydrology under glass: confronting fundamental questions of soil-water-biota co-evolution at Biosphere 2. Hydrology and Earth System Sciences, 13 (11), 2105-2118. |
| Huxman | Theme 4 | The hills are alive: Earth science in a controlled environment | EOS | 2009 | published | Huxman, T., P. Troch, J. Chorover, D. D. Breshears, S. Saleska, J. Pelletier, X. Zeng, and J. Espeleta (2009). The hills are alive: Earth science in a controlled environment, Eos Trans. AGU, 90(14), 120. |
| Ivanov | Theme 4 | Hysteresis of soil moisture spatial heterogeneity and the "homogenizing" effect of vegetation | WRR | — | published | Ivanov, V. Y., S. Fatichi, G. D. Jenerette, J. F. Espeleta, P. A. Troch, and T. E. Huxman (2010), Hysteresis of soil moisture spatial heterogeneity and the “homogenizing” effect of vegetation, Water Resour. Res., 46, W09521, doi:10.1029/2009WR008611. |
| Furbish | Theme 5 | Rain splash of soil grains as a stochastic advection-dispersion process, with implications for desert plant-soil interactions and land-surface evolution | JGR - ES | 2009 | published | Furbish, D. J., E. M. Childs, P. K. Haff, and M. W. Schmeeckle (2009), Rain splash of soil grains as a stochastic advection-dispersion process, with implications for desert plant-soil interactions and land-surface evolution, J. Geophys. Res., 114, F00A03, doi:10.1029/2009JF001265. |
| Furbish | Theme 5 | Statistical description of slope-dependent soil transport and the diffusion-like coefficient | JGR - ES | 2009 | published | Furbish, D. J., P. K. Haff, W. E. Dietrich, and A. M. Heimsath (2009), Statistical description of slope-dependent soil transport and the diffusion-like coefficient, J. Geophys. Res., 114, F00A05, doi:10.1029/2009JF001267. |
| McElroy | Theme 5 | Nature of deformation of sandy bed forms | JGR - ES | 2009 | published | McElroy, B., and D. Mohrig (2009), Nature of deformation of sandy bed forms, J. Geophys. Res., 114, F00A04, doi:10.1029/2008JF001220. |
| Schumer | Theme 5 | Real and apparent changes in sediment deposition rates through time | JGR - ES | 2009 | published | Schumer, R., and D. J. Jerolmack (2009), Real and apparent changes in sediment deposition rates through time, J. Geophys. Res., 114, F00A06, doi:10.1029/2009JF001266. |
| Schumer | Theme 5 | Fractional advection-dispersion equations for modeling transport at the Earth surface | JGR - ES | 2009 | published | Schumer, R., M. M. Meerschaert, and B. Baeumer (2009), Fractional advection-dispersion equations for modeling transport at the Earth surface, J. Geophys. Res., 114, F00A07, doi:10.1029/2008JF001246. |
| Stark | Theme 5 | Landslide rupture and the probability distribution of mobilized debris volumes | JGR - ES | 2009 | published | Stark, C. P., and F. Guzzetti (2009), Landslide rupture and the probability distribution of mobilized debris volumes, J. Geophys. Res., 114, F00A02, doi:10.1029/2008JF001008. |
| Bradley * | Theme 5 | Fractional dispersion in a sand bed river | JGR - ES | 2010 | published | Bradley, D. N., G. E. Tucker, and D. A. Benson (2010), Fractional dispersion in a sand bed river, J. Geophys. Res., 115, F00A09, doi:10.1029/2009JF001268. |

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| Harman * | Theme 5 | A subordinated kinematic wave equation for heavy-tailed flow responses from heterogeneous hillslopes | JGR - ES | 2010 | published | Harman, C. J., D. M. Reeves, B. Baeumer, and M. Sivapalan (2010), A subordinated kinematic wave equation for heavy-tailed flow responses from heterogeneous hillslopes, J. Geophys. Res., 115, F00A08, doi:10.1029/2009JF001273. |
| Tucker | Theme 5 | Trouble with diffusion: Reassessing hillslope erosion laws with a particle-based model | JGR - ES | 2010 | published | Tucker, G. E., and D. N. Bradley (2010), Trouble with diffusion: Reassessing hillslope erosion laws with a particle-based model, J. Geophys. Res., 115, F00A10, doi:10.1029/2009JF001264. |
| Ancey | Theme 5 | Stochastic modeling in sediment dynamics: Exner equation for planar bed incipient bed load transport conditions | JGR - ES | — | published | Ancey, C. (2010), Stochastic modeling in sediment dynamics: Exner equation for planar bed incipient bed load transport conditions, J. Geophys. Res., 115, F00A11, doi:10.1029/2009JF001260. |
| Foufoula-Georgiou | Theme 5 | Rethinking geomorphic transport: Stochastic theories, broad scales of motion, and non-locality | JGR - ES | — | published | Foufoula-Georgiou, E., and C. Stark (2010), Introduction to special section on Stochastic Transport and Emergent Scaling on Earth's Surface: Rethinking geomorphic transport—Stochastic theories, broad scales of motion and nonlocality, J. Geophys. Res., 115, F00A01, doi:10.1029/2010JF001661. |
| Foufoula-Georgiou | Theme 5 | A non-local theory of sediment transport on hillslopes | JGR - ES | — | published | Foufoula-Georgiou, E., V. Ganti, and W. Dietrich (2010), A nonlocal theory of sediment transport on hillslopes, J. Geophys. Res., 115, F00A16, doi:10.1029/2009JF001280. |
| Ganti * | Theme 5 | Normal and anomalous diffusion of gravel tracer particles in rivers | JGR - ES | — | published | Ganti, V., M. M. Meerschaert, E. Foufoula□Georgiou, E. Viparelli, and G. Parker (2010), Normal and anomalous diffusion of gravel tracer particles in rivers, J. Geophys. Res., 115, F00A12, doi:10.1029/2008JF001222. |
| Hill | Theme 5 | Heavy tailed travel distance in gravel bed transport: an exploratory enquiry | JGR - ES | — | published | Hill, K. M., L. DellAngelo, and M. M. Meerschaert (2010), Heavy□tailed travel distance in gravel bed transport: An exploratory enquiry, J. Geophys. Res., 115, F00A14, doi:10.1029/2009JF001276. |
| Voller | Theme 5 | Can anomalous diffusion describe depositional fluvial profiles? | JGR - ES | — | published | Voller, V. R., and C. Paola (2010), Can anomalous diffusion describe depositional fluvial profiles?, J. Geophys. Res., 115, F00A13, doi:10.1029/2009JF001278. |
| Zaliapin | Theme 5 | Transport on river networks: A dynamic-tree approach | JGR - ES | — | published | Zaliapin, I., E. Foufoula□Georgiou, and M. Ghil (2010), Transport on river networks: A dynamic tree approach, J. Geophys. Res., 115, F00A15, doi:10.1029/2009JF001281. |

Appendix C

**Water Resources Research Special Section on:**
**On Hydrologic Synthesis: Watersheds as Non-linear Hierarchical Space-Time Filters**

0. Preface: Sivapalan (2010).

**Theme 1: Hydrosphere-Biosphere Interactions at Catchment Scale**

1. Thompson, S. E., C. J. Harman, P. A. Troch, P. D. Brooks and M. Sivapalan (2010). Scaling of ecohydrologically mediated water balance partitioning: A synthesis framework for catchment ecohydrology. *Water Resources Research*. **In review.**

2. Sivapalan, M., M. A. Yaeger, C. J. Harman, Xiangyu Xu, and P. A. Troch (2010). Functional model of water balance variability at the catchment scale. 1: Evidence of hydrologic similarity and space-time symmetry. *Water Resources Research*. **In resubmission.**

3. Harman, C. J., P. A. Troch and M. Sivapalan (2010). Functional model of water balance variability at the catchment scale. 2: Elasticity of fast and slow runoff components to precipitation change in the continental United States. *Water Resources Research*. **In resubmission.**

4. Zanardo, S., C. J. Harman, P. A. Troch, P. S. C. Rao and M. Sivapalan (2010). Climatic and physical controls on inter-annual variability of catchment water balance and vegetation water-use: a stochastic approach. *Water Resources Research*. **In review.**

5. Voepel, H., B. L. Ruddell, R. Schumer, P. A. Troch, P. D. Brooks, A. Neal, M. Durcik, and M. Sivapalan (2010). Hydrologic controls on catchment-scale vegetation productivity. *Water Resources Research*. **In review**.

6. Thompson, S. E., C. J. Harman, P. A. Troch and M. Sivapalan (2010). Predicting evapotranspiration at multiple timescales: Comparative hydrology across AMERIFLUX sites. *Water Resources Research*. **In review**.

7. Brooks, P.D., P. A. Troch, M. Durcik, E. Gallo, B. Moravec, M. Schlegel, and M. Carlson (2010). Predicting regional-scale ecosystem response to changes in precipitation: Not all rain is created equal. *Water Resources Research*. **In revision.**

8. Collins, D. B. G. (2010). The partitioning of evaporation along an aridity gradient. *Water Resources Research*. **In review.**

9. Schaefli, B., R. van der Ent, R. A. Woods, H. H. G. Savenije et al. (2010). An analytical model for soil-atmosphere feedback. *Water Resources Research*. **In review**.

10. Niu, G.-Y., P. A. Troch, C. Paniconi, R. L. Scott, M. Durcik, X. Zeng, T. E. Huxman and D. E. Goodrich (2010). The role of water subsidy on vegetation dynamics in a semi-arid grassland catchment: Comparison between field measurements and 3-D ecohydrological modeling. *Water Resources Research*. **In review**.

11. Tague, C., J. W. Kirchner, and J. R. McConnell (2010). Combing streamflow and spatial patterns of vegetation summer w 1 ater stress as indicators of watershed scale drainage properties. *Water Resources Research*. **In Review.**

12. Cheng, Lei, Zongxue Xu, Dingbao Wang and Ximing Cai (2010). Assessing inter-annual variability of ET at the catchment scale using satellite-based ET datasets. *Water Resources Research*. **In Review.**

13. Lowry, C. S., C. E. Moore, S. P. Loheide II, and J. D. Lundquist (2010). Groundwater controls on vegetation composition and patterning in mountain meadows. In preparation, to be submitted to *Water Resources Research*. **75% completion**.

14. Hwang, T. and L. E. Band (2010). Groundwater subsidy. In preparation, to be submitted to *Water Resources Research*. **70% completion**.

15. Wright, O., E. Istanbulluoglu and T. Wang (2010). Budyko hypothesis and the annual water balance in a base-flow dominated region: Implications on hydrologic persistence and climate change predictions. In preparation, to be submitted to *Water Resources Research*. **70% completion**

16. Schymanski, S. J., M. Sivapalan and M. L. Roderick (2010). Applicability of the vegetation optimality model across catchments and climates. In preparation, to be submitted to *Water Resources Research*. **80% completion**

17. Xu, X.-Y, M. Sivapalan, R. Donohue and M. L. Roderick (2010). Links between space-time variability of annual water balance and vegetation cover in Australia. In preparation, to be submitted to *Water Resources Research*. **50% completion**

**Theme 2: Hydrological and Biogeochemical Process Interactions at Catchment Scale**

18. Rao, P.S.C, N.B. Basu, M. Sivapalan, M.A. Hassan, A.I. Packman, G.S. McGrath and S.D. Donner (2010). Exploring emergent hydrologic and biogeochemical patterns in catchments at multiple scales. In preparation, to be submitted to *Water Resources Research*. **80% completion**

19. Thompson, S.E., N.B. Basu, J. Lascurain Jr., A. Aubeneau, and P.S.C. Rao (2010). Hydrologic controls drive patterns of solute export in forested, mountainous watersheds. *Water Resources Research*. **In revision.**

20. Harman, C. J., P. S. C. Rao, N. B. Basu, P. Kumar and M. Sivapalan (2010). Climate, soil and vegetation controls on the temporal variability of vadose zone transport. In preparation, to be submitted to *Water Resources Research*. **90% completion.**

21. Guan, K., S.E. Thompson, C. J. Harman, N. B. Basu, P. S. C. Rao, M. Sivapalan, A. I. Packman and P. K. Kalita (2010). Spatio-temporal scaling of hydrological and agrochemical export dynamics in a tile-drained Midwestern watershed. In preparation, to be submitted to *Water Resources Research*. **In review.**

22. Ye, Sheng, M. Sivapalan, N. B. Basu, P. S. C. Rao, T. Covino, Hongyi Li and S. Wang (2010). Nutrient retention and removal in river networks: Modeling exploration of multi-event flow dynamics and scale effects. In preparation, to be submitted to *Water Resources Research*. **80% completion**.

23. Basu, N.B., P.S.C. Rao, S. Zanardo, S. D. Donner, Sheng Ye, and M. Sivapalan (2010). Spatio-temporal averaging of Removal Rate Constants in River Networks: Is there an emergent pattern? In preparation, to be submitted to *Water Resources Research*. **95% completion**

24. Stewart, R. J., W. M. Wollheim, M. N. Gooseff, M. A. Briggs, J. M. Jacobs, B. J. Peterson, C. S. Hopkinson (2010). Separation ofriver network scale nitrogen removal among main channel and two transient storage compartments. *Water Resources Research*. **In review**.

25. Riveros-Iregui, D. A., B. L. McGlynn, L. A. Marshall, D. L. Welsch, R. E. Emanuel and H. E. Epstein (2010). A watershed assessment of a process soil $CO_2$ production and transport model. *Water Resources Research*. **In review**.

**Appendix D:** List of Presentations and Posters at Fall AGU
in H05: Water Cycle Dynamics in a Changing Environment and H11: Stochastic Transport and Emergent Scaling on the Earth's Surface
Highlight indicates work directly related to the UIUC synthesis project

Appendix D

| Author | Title | Type | Session |
|---|---|---|---|
| Abdelnour, Alex | Catchment hydro-biochemical response to climate change and future land use | Oral | H05 |
| Albertson, John | Interannual rainfall variability, vegetation dynamics, and runoff controls in Mediterranean climates | Oral | H05 |
| Aubeneau, Antoine | Linking observed break-through curves from tracer injections in streams to experimental and environmental conditions | Oral | H05 |
| Basu, Nandita | Anthropogenic signatures in nutrient loads from managed catchments | Oral | H05 |
| Cohen, Sagy | Modeling global scale sediment flix, a new component in the spatially distributed Framework for Aquatic Modeling of Earth Systems (FrAMES) | Oral | H05 |
| Cullis, James | A conceptual model for the growth, persistence, and blooming behavior of the benthic mat-forming diatom Didymosphenia geminata | Oral | H05 |
| Fryirs, Kirstie | (Dis)connectivity in catchment-scale sediment cascades: Forecasting responses in sediment flux associated with various forms of environmental change | Oral | H05 |
| Hassan, Marwan | Historic trends in sediment dynamics along the Mississippi River | Oral | H05 |
| Kettner, Albert | Are human influences responsible for the existence and possible drowining of (parts of) the Ebro Delta, Spain? | Oral | H05 |
| Molini, Annalisa | A stochastic-dynamical approach to snow accumulation-melting in a changing climate | Oral | H05 |
| Niu, GuoYue | The role of water subsidy on vegetation dynamics in a semiarid grassland catchment: Comparison between field measurements and 3-D ecohydrological ı | Oral | H05 |
| Patil, Sopan | Spatial variabiity in streamflow predictions across United States: Role of climate and topography in predictability at ungauged basins | Oral | H05 |
| Simon, Andrew | Trends in precipitation and stream discharge over the past century for the continental United States: Implications | Oral | H05 |
| van Vliet, Michelle | Daily water temperature and river discharge modeling for climate change impact assessment in large river basins globally | Oral | H05 |
| Wollheim, Wilfred | Dynamics of nitrogen saturation in river networks | Oral | H05 |
| Worman, L E | Effects of watershed management practice on short-term variation in stream discharge | Oral | H05 |
| Ali, Faran | Suspended sediment dynamics in the Mississippi River basin | Poster | H05 |
| Aubeneau, Antoine | Linking observed break-through curves from tracer injections in rivers to experimental and environmental conditions | Poster | H05 |
| Aubeneau, Antoine | Stochastic modeling of reactive solute transport in rivers | Poster | H05 |
| Baraer, Michael | Proglacial hydrology in the Cordillera Blanca, Peru | Poster | H05 |
| Bartholomeus, Rudd | Climate change effects on vegetation characteristics and groundwater recharge | Poster | H05 |
| Carrillo, Gustavo | Analyzing catchment hydrologic function through process-based behavior modeling | Poster | H05 |
| Cheng, Lei | Explore inter-annual variability of catchment water-energy balance based on remote sensed ET datasets | Poster | H05 |
| Cong, Zhentao | Understanding hydrological trends with Budyko hypothesis | Poster | H05 |
| Cullis, James | Factors affecting the growth of Didymosphenia geminata in New Zealand rivers: Flow, bed disturbance, nutrients, light, and seasonal dynamics. | Poster | H05 |
| Drummond, Jennifer | The effects of solute breakthrough curve tail truncation on residence time estimates and mass recovery | Poster | H05 |
| Garcia, Tatiana | Short time scale series analysis of Didymosphenia geminata in Ortei River, New Zealand. | Poster | H05 |
| Geris, Josie | Multiscale monitoring and analysis if the impacts of rural land use changes on downstream flooding | Poster | H05 |
| Gillis, Carole-Anne | The role of water chemistry and geomorphic control in the presence of Didymosphenia geminata in Quebec | Poster | H05 |
| Leong, Doris | Sensitivity of stoichiometric ratios to temporal variability in streamflow | Poster | H05 |
| Patil, Sopan | A network model for simulating sediment dynamics within a small watershed | Poster | H05 |
| Ran, Lishan | Reach scale sediment balance of Goodwin Creek watershed, Mississippi | Poster | H05 |
| Russo, Tess | Stream channel surface water - groundwater interactions in a fire impacted watershed | Poster | H05 |
| Xu, Na | Simulating streamflow and dissolved organic matter export from small forested watersheds | Poster | H05 |
| Xu, Xiangyu | Environmental change in the Mississippi River basin | Poster | H05 |
| Furbish, David | A probabilistic definition of the bed load sediment flux: Theory | Oral | H11 |
| Jerolmack, Doug | Linking stochastic sediment transport to physical processes | Oral | H11 |
| Packman, Aaron | Stochastic models for the transport of dissolved and suspended material in rivers | Oral | H11 |
| Perron, Talor | The branching instability in valley networks | Oral | H11 |
| Rinaldo, Andrea | River networks as ecological corridors for species, populations and pathogens of water-borne disease | Oral | H11 |
| Singh, Arvind | Large to small scale coupling and time irreversibility in gravel bedform dynamics: experimental evidence and implications for modeling | Oral | H11 |
| Voller, Vaughan | Effect of Subsidence Styles and Fractional Diffusion Exponents on Depositional Fluvial Profiles | Oral | H11 |
| Yager, Elowyn | Stochastic predictions of bedload flux and sediment availability in steep channels | Oral | H11 |
| Atterberry, Wallace | Diffusion-dominated subdiffusion in repacked sand: A combined study of stochastic models and laboratory experiments | Poster | H11 |
| Bradley, Nate D. | Tracking Radio-Tagged Bedload in an Alpine Stream | Poster | H11 |
| Chen, Yu-Chen | Investigating the evolution of gravel bar at river confluence during flood events using a 2D many-fraction river morphodynamic model | Poster | H11 |
| Cienciala, Piotr | Statistical charactersitics of fluvial displacements of individual particles | Poster | H11 |
| Engelder, Todd | Quantifying the effect of hydrologic variability on sediment transport in alluvial rivers | Poster | H11 |
| Patil, Sopan | Intra-stream variability in tracer breakthrough curves: Geomorphic controls on tailing behaviors | Poster | H11 |
| Roseberry, John | A probabilistic definition of the bedload sediment flux: Experiments | Poster | H11 |
| Zaliapin, Ilya | Static and dynamic Tokunaga stream networks: Statistical properties | Poster | H11 |

WATER RESOURCES RESEARCH, VOL. 46, W05301, doi:10.1029/2009WR008906, 2010

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Appendix E

# The future of hydrology: An evolving science for a changing world

Thorsten Wagener,[1] Murugesu Sivapalan,[2,3,4] Peter A. Troch,[5] Brian L. McGlynn,[6] Ciaran J. Harman,[3] Hoshin V. Gupta,[5] Praveen Kumar,[3] P. Suresh C. Rao,[7] Nandita B. Basu,[8] and Jennifer S. Wilson[2]

Received 15 November 2009; revised 17 February 2010; accepted 10 March 2010; published 12 May 2010.

[1] Human activities exert global-scale impacts on our environment with significant implications for freshwater-driven services and hazards for humans and nature. Our approach to the science of hydrology needs to significantly change so that we can understand and predict these implications. Such an adjustment is a necessary prerequisite for the development of sustainable water resource management strategies and to achieve long-term water security for people and the environment. Hydrology requires a paradigm shift in which predictions of system behavior that are beyond the range of previously observed variability or that result from significant alterations of physical (structural) system characteristics become the new norm. To achieve this shift, hydrologists must become both synthesists, observing and analyzing the system as a holistic entity, and analysts, understanding the functioning of individual system components, while operating firmly within a well-designed hypothesis testing framework. Cross-disciplinary integration must become a primary characteristic of hydrologic research, catalyzing new research and nurturing new educational models. The test of our quantitative understanding across atmosphere, hydrosphere, lithosphere, biosphere, and anthroposphere will necessarily lie in new approaches to benchmark our ability to predict the regional hydrologic and connected implications of environmental change. To address these challenges and to serve as a catalyst to bring about the necessary changes to hydrologic science, we call for a long-term initiative to address the regional implications of environmental change.

**Citation:** Wagener, T., M. Sivapalan, P. A. Troch, B. L. McGlynn, C. J. Harman, H. V. Gupta, P. Kumar, P. S. C. Rao, N. B. Basu, and J. S. Wilson (2010), The future of hydrology: An evolving science for a changing world, *Water Resour. Res.*, *46*, W05301, doi:10.1029/2009WR008906.

## 1. Global Change Challenges

[2] Human activities now rival geologic-scale forces [*Kieffer*, 2009], with a footprint that is deepening and widening rapidly across the planet (Figure 1) [*Sanderson et al.*, 2002]. Manifestations of this footprint are visible in declining snowpacks resulting from human-induced climate change [*Barnett et al.*, 2008], in quickly shrinking aquifer storages due to excessive pumping of groundwater [*Rodell et al.*, 2009], in significantly distorted river flow regimes due to the building of dams [*Poff et al.*, 2007], and in altered groundwater recharge due to changes in land use [*Scanlon et al.*, 2006]. These are just a few examples of the human-induced hydrologic change where demands of a growing population for energy [*King et al.*, 2008], water [*Jackson et al.*, 2001], food [*Vörösmarty et al.*, 2000], and living space [*Zhao et al.*, 2001] radically alter our environment. Many freshwater services we have historically relied on to protect our natural ecosystems and to provide for human needs are becoming irretrievably degraded as a consequence of human activity, at considerable cost to sustainability of both nature and human habitation [*Palmer et al.*, 2004; *Grimm et al.*, 2008; *Brauman et al.*, 2007; *Wagener et al.*, 2008]. The cumulative consequence of growing demand and a dwindling resource base is increased competition for a resource that is already scarce in many regions of the world, contributing to a decline in water security [*Postel and Wolf*, 2001; T. Allan, Avoiding war over natural resources, 1998, available from Global Policy Forum at http://www.globalpolicy.org/component/content/article/198/32890.html]. Together with this decline in freshwater services, we also face increases in hydrologic hazards such as floods and droughts due to an increase in hydrologic variability, especially in the least resilient of nations [*Milly et al.*, 2002; *Sheffield and Wood*, 2008].

[3] Enabling society to address these problems, and to develop appropriate policies and management plans to

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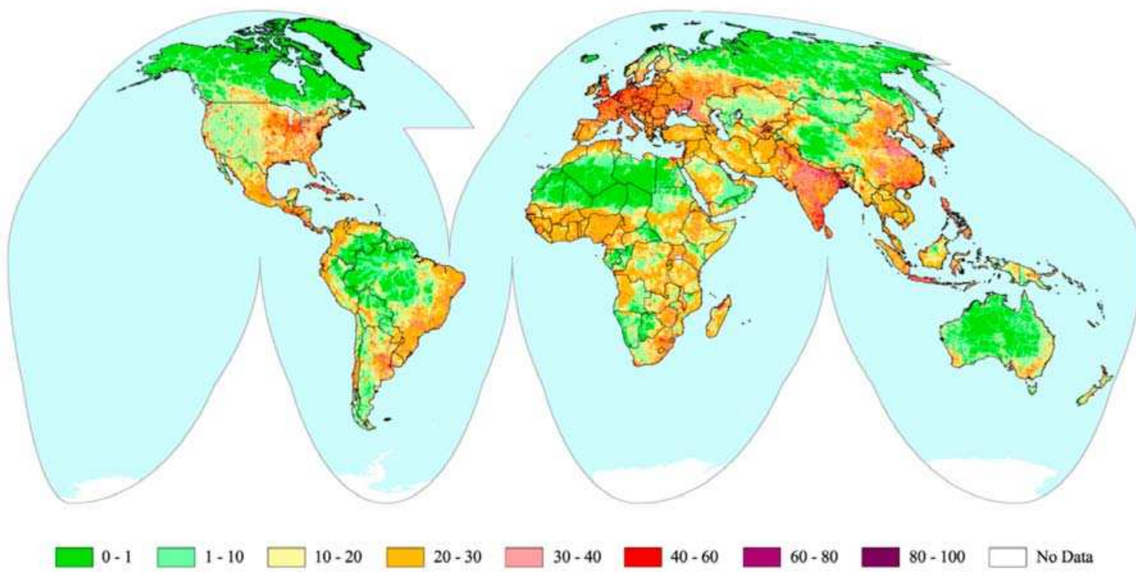


**Figure 1.** *Sanderson et al.* [2002] estimated the human footprint by quantifying how strongly humans impact the land surface, with a higher value of their human influence index indicating larger human impact (www.wcs.org/humanfootprint/). Their index integrates human population density, land transformation, human access, and electrical power infrastructure. Their study suggests that over 80% of the land surface is impacted by human activity [from *Sanderson et al.*, 2002].

alleviate them, requires an ability to provide reliable predictions of freshwater occurrence, circulation, distribution, and quality under human-induced and natural change. To be robust and credible, such predictions must be underpinned by a greater understanding of the hydrologic and biogeochemical cycles and their interactions with land-forming and life-sustaining processes in the landscape, including an explicit treatment of the impacts of water-human-ecosystem interactions and associated feedbacks. Environmental management under global change requires new understanding of the connective and evolving role of water across a wide range of Earth and socioeconomic systems and across a wide range of time and space scales. This now poses enormous challenges to the conduct of hydrologic science [*Killeen and Abrajano*, 2008], requiring new ways to observe and analyze how our environment is changing because of both human and natural stressors and demanding new approaches to prediction and management.

## 2. Challenges to Hydrologic Science

[4] The main challenge facing hydrologic science is to deal with human-induced change. While the need to deal with the issue of change is not new to hydrology, the saving grace in most cases has (for a long time) been the availability of historical observations with which we could calibrate hydrologic models or from which we could extrapolate in time. This approach remains valid so long as system changes are not too severe [*Sivapalan et al.*, 2003] and the critical assumption of stationarity can be justified [*Milly et al.*, 2008]. Many of the research tools and educational materials adopted in the past have been founded on this assumption of stationarity. However, to make predictions in a changing environment, one in which the system structure may no longer be invariant or in which the system might exhibit previously unobserved behavior due to the exceedance of new thresholds, past observations can no longer serve as a sufficient guide to the future, and the credibility of our predictions cannot simply be achieved by reproducing historical observations. Instead, what is required is a greater consistency between model and real-world system, including new strategies to demonstrate this consistency [*Gupta et al.*, 2008]. Historical observations of system characteristics and behavior will, of course, remain crucial to furthering understanding of hydrological processes and for evaluating process representations in models, although their value when moving beyond the range of observed behaviors is less clear and could possibly be much diminished.

[5] In an era of global change, the ability to respond appropriately to new societal needs and to make predictions at scales relevant to society will require us to develop a holistic and quantitative understanding of the changing (sometimes transient) behavior of hydrologic systems and their subsystems. Earth systems have coevolved over geologic timescales, and we can expect that they will continue to do so at potentially much greater rates because of human impacts (Figure 2). Predictions of hydrologic responses now need to allow for adaptive temporal evolution of vegetation, soils, and river networks (among other things) under human-induced environmental changes, although the changes might occur at different and varying rates. This requires hydrologists to develop a new understanding of how all the associated components (climate, soils, vegetation, and topography) have coevolved in the past and how they might do so in the future.

[6] Hydrology has made enormous strides in understanding the behavior of small, relatively homogeneous (and unchanging) systems (e.g., at the soil column or river reach level) over relatively short time scales, but more research is needed to understand hydrologic system complexity at

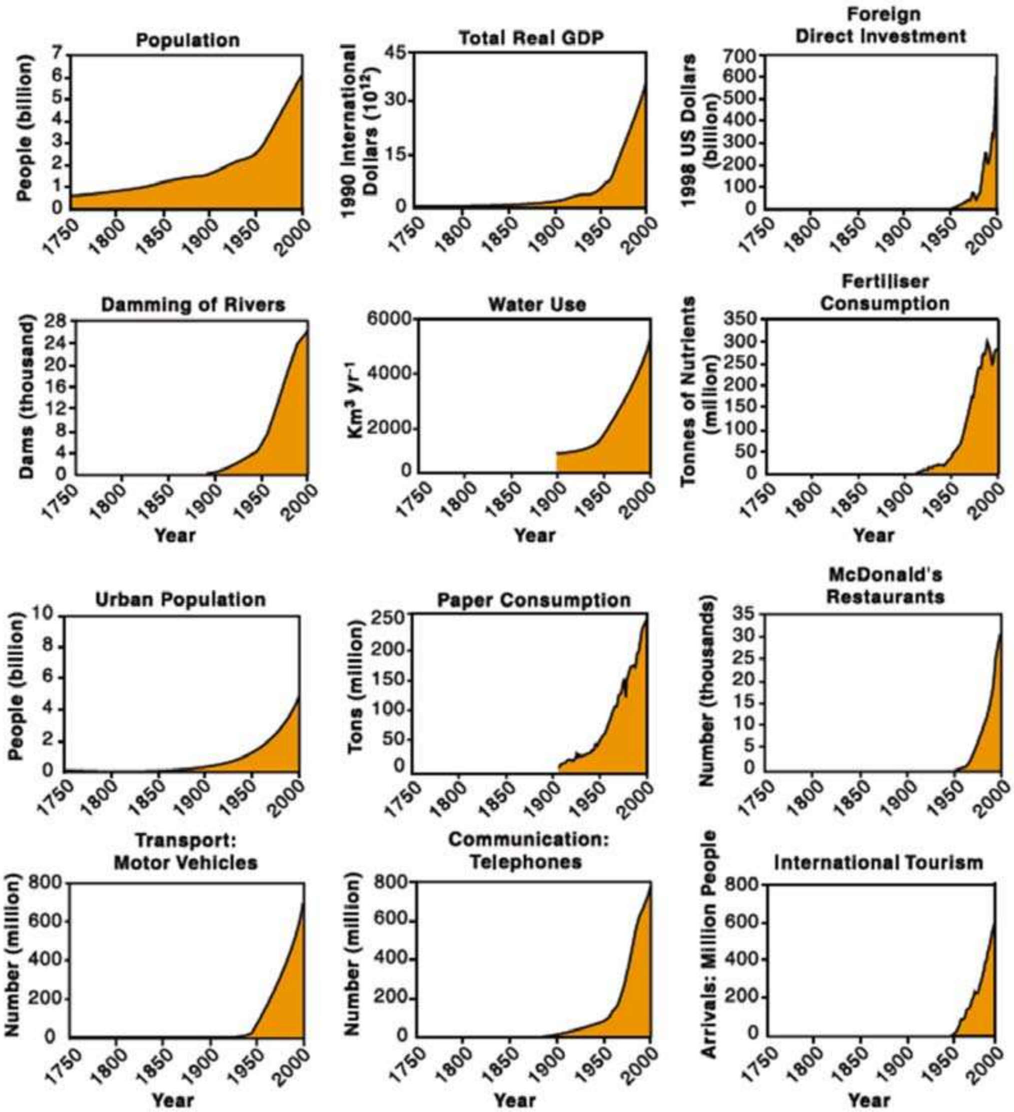


**Figure 2.** We see an unprecedented change in human activity, with often-unknown impacts on our environment and on the water cycle (from *Steffen et al.* [2004] with kind permission of Springer Science+Business Media).

larger scales (e.g., catchments, regional aquifers, river basins, and whole ecosystems), and over much longer time scales than we have typically addressed (e.g., decadal to century scales). System complexity under these circumstances arises from nonlinear, heterogeneous, and highly dynamic processes involving hydrologic, biogeochemical, ecologic, and human systems, with strong interactions and feedbacks, sometimes producing surprising behavior at larger scales [*Gordon et al.*, 2008], not easily derived from understanding the components of the system in isolation. Lack of understanding of the complexity of whole-system behavior across space and time scales, combined with an inability to observe many of the systems' structural and functional characteristics and internal process dynamics (e.g., subsurface or stream network structures and processes and linkages between hydrologic, biogeochemical, and ecological processes), limits our ability to make hydrologic predictions at scales relevant to many societal challenges.

[7] One challenge in this regard is that such quantitative understanding will have to be generated even as measurement and monitoring resources are declining in many places [*Mishra and Coulibaly*, 2009]. Assessments of the implications of change also require an ability to benchmark the effects of change against earlier system states. It is particularly worrying that we have already lost track of the degree to which humans have changed the environment [*Blackbourn*, 2006; *Walter and Merritts*, 2008] and to what extent these changes are already reflected in the water cycle. This problem of shifting baselines (i.e., an ambiguity in identifying the correct baseline against which we should measure significant changes to the system) makes it even more difficult to assess the impacts of change [*Pauly*, 1995] (Figure 3).

## 3. Hydrologic Change Science

[8] Collectively, these challenges to hydrology call for profound changes in the ways we conduct hydrologic sci-

**Figure 3.** What is the baseline against which we measure the impacts of change? The photograph shows the Marshall Gulch catchment near Tucson in Arizona, United States. Does the current state of this system represent the natural baseline? (Photo taken by Craig Rasmussen.)

ence. Nonstationarity necessitates system evolution to be considered as an integral part of system behavior rather than as an exception [*Vörösmarty et al.*, 2004; *Milly et al.*, 2008], with significant challenges for observation and analyses to help understand and ultimately predict how the magnitudes of change will manifest themselves across scales and places [*Heinz Center*, 2008; *Blöschl*, 2006; *Blöschl et al.*, 2007].

[9] Predicting the response of hydrologic systems in a changing environment requires that the water cycle be considered as a complex, interconnected system that includes not just the physical but also the biogeochemical, ecological, and human subsystems whose interactions contribute to land-forming (i.e., structure-forming) and life-sustaining processes. The complexity of the hydrologic system may be thought of as a series of hierarchies (Figure 4). At the most basic level (inner ring), water, nutrients, carbon, and sediments are characterized in terms of various fluxes, flow paths, stores, residence times, and state transformations (both physical and chemical). The nonlinear interactions between these components, through self-organization, give rise to emergent patterns in the landscape, such as river network structure, hydraulic geometry, soil catena, and vegetation patterns. Many models attempt to exploit these properties to improve predictability (middle ring). These units of conceptualization, through the understanding they generate, then form the basis for deciphering the interactions between human, physical, biogeochemical, and ecological systems that give rise to observed emergent patterns, identified here as units of engagement (outer ring). These interactions can, of course, cascade both ways. For example, human impacts modify extant patterns (e.g., stream network structure), which in turn alter flow paths, residence times (e.g., of nutrients, resulting in reduced denitrification), and physical and chemical transformations in the aquatic environment, ultimately impacting ecosystem health. It is evident that a variety of hierarchies and interfaces across disciplines exist that need to be understood, characterized, and modeled to predict the evolution of system behavior. A major scientific challenge is to understand how interacting processes have led to the structure and function of existing hydrologic systems and how they will evolve in the context of human-induced and natural changes to the environment [*Wagener et al.*, 2007].

[10] In the past 20 years, under the umbrella of hydrogeomorphology and ecohydrology, hydrologists have made enormous progress in exploring a variety of interacting Earth surface processes, including hydrologic ones, involved in the coevolution of climate, soils, topography, and vegetation in natural settings [*Rodriguez-Iturbe and Rinaldo*, 1997; *Rodriguez-Iturbe and Porporato*, 2005; *Eagleson*, 2008]. This body of work has enabled significant advances toward a predictive understanding of the space-time structure and functioning of stream networks [e.g., *Willgoose*, 2005], vegetation [e.g., *Rodriguez-Iturbe et al.*, 1999; *Newman et al.*, 2006], and stream-vegetation interactions [e.g., *Ivanov et al.*, 2008a, 2008b; *Istanbulluoglu*, 2009a]. A sound theoretical basis for learning from existing and readily available geomorphologic and vegetation patterns now exists, which can be used to predict likely future evolutionary changes [*Porporato et al.*, 2004; *Istanbulluoglu*, 2009b] and their ecosystem impacts [e.g., *Paola et al.*, 2006; *Rodriguez-Iturbe et al.*, 2009]. This provides hope that a new generation of

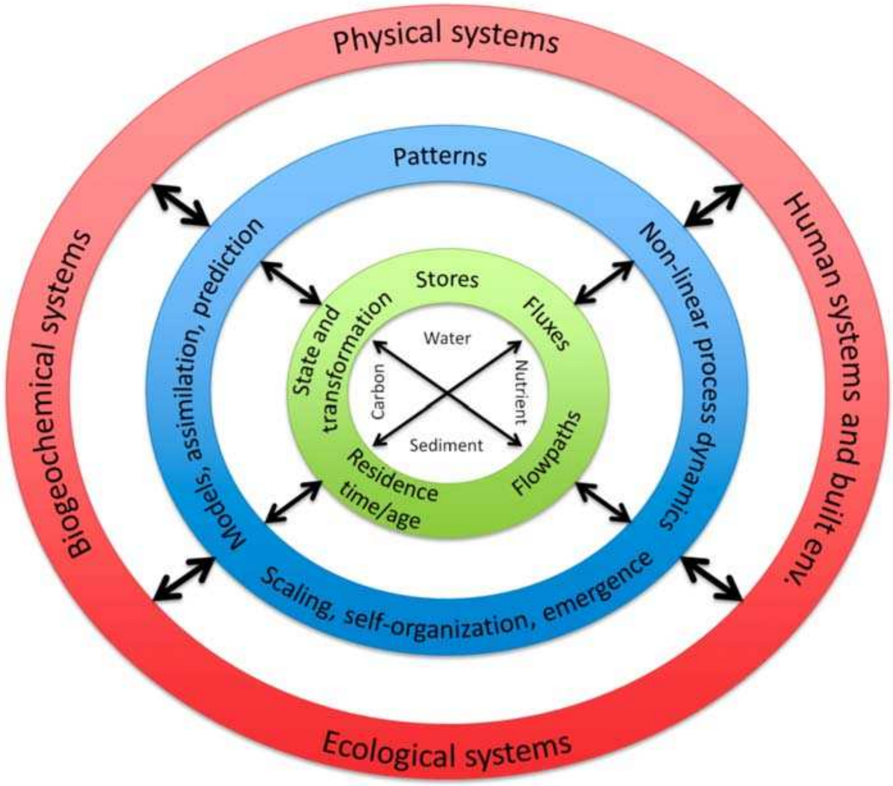


**Figure 4.** Hierarchies in coupled physical (oceans, atmosphere, rivers or lakes, and aquifers), ecological (habitats, disturbance regimes, and life cycles), biogeochemical (nutrient cycles, carbon cycle, and contaminants), and human (human impact, engineering works, water use, and management) subsystems that constitute the hydrological system: the innermost circle represents units of representation, the middle circle represents units of conceptualization, and the outer layer represents units of engagement (courtesy Praveen Kumar).

predictive models can be developed that incorporate organizing principles such as ecological optimality and minimum energy expenditure and basic thermodynamic principles such as maximum entropy production as a way to overcome the paucity of historical observations and inadequate characterization of landscape heterogeneity [*McDonnell et al.*, 2007; *Schymanski*, 2008; *Hwang et al.*, 2009; *Kleidon and Schymanski*, 2008].

[11] In light of the dominant role of humans in the landscape and their interference in the hydrologic cycle, the substantial progress made so far needs to be extended to human-impacted landscapes [*Jackson et al.*, 2009]. Current and future experimental catchments must be embedded in larger-scale studies of hydrological variability and changing controls to aid in understanding the time scales over, and extent to which, system characteristics are changing. By embedding local (place-based) in-depth studies in the regional context, we can better understand (changing) hydrological behavior across environmental gradients. Such gradients form the basis of comparative hydrology [*Falkenmark and Chapman*, 1989], which attempts to understand how system behaviors and controls vary in space. An understanding of spatial variability can provide a first-order assessment of potential temporal change by trading space for time [*Wagener*, 2007]. Given that long-range model projections suffer from large uncertainties, the strategy of using spatial gradients as proxy for temporal gradients might be an important first step [*Troch et al.*, 2009]. Nevertheless, because of human interferences in the landscape, the character of many of the interactions and feedbacks that maintain the system in equilibrium may become irretrievably altered such that future system responses may diverge from what has been historically observed, imposing limits to what the past can tell us about the future [*Kumar*, 2007]. New observations must therefore include those that enable a deeper understanding of the legacy effects of past and future human behaviors and support understanding of human-induced emergent behaviors of hydrological systems across varying scales [*Braden et al.*, 2009; *Botter et al.*, 2010].

## 4. Needs of an Evolving Science of Hydrologic Change

[12] Human activity has impacted almost all parts of the landscape, so much so that hydrologic and human systems are now intrinsically coupled. Explicit recognition of this fact must move us toward a coherent holistic, quantitative, and predictive science of hydrology that is attuned to the needs of both nature and humans in a changing world. In recognizing the challenges of dealing with human-induced change so as to achieve a sustainable cohabitation of

humans with nature, and in understanding the limitations of the current approach to hydrologic science, we arrive at certain broad questions that underpin the newly evolving science of hydrologic change.

[13] 1. How will the hydrologic system and its associated (sub)systems respond to, and evolve under, natural and human-induced changes in climate and the environment?

[14] 2. How are natural, managed, and engineered processes reflected in the various freshwater services that nature provides?

[15] 3. How can hydrologic systems be managed toward sustainability?

[16] Given such a perspective, the roles of current and future hydrologists must expand to seek greater understanding of how each system component receives, stores, transports, and releases water, energy, and dissolved and suspended constituents; how it interacts with the living world; and how it contributes to overall system behavior [*McDonnell et al.*, 2007; *Hopp et al.*, 2009; *Dontsova et al.*, 2009]. Hydrologists need to work much more closely with experts from other disciplines, geologists, soil scientists, biologists, geochemists, ecologists, and social scientists, among others, to understand how the system functions at a much more fundamental level, as well as at the holistic level. This will promote a deeper understanding of the characteristics of the system, and of its components, under changing conditions. Through interdisciplinary collaborative efforts, a new balance can be struck between the reductionist and holistic approaches to experimental and theoretical (model-based) exploration of change. Hydrologists must become both synthesists, observing and analyzing the system as a holistic entity using top-down strategies, and analysts, understanding the functioning of individual system components through bottom-up approaches, while operating firmly from a strategy of well-designed hypothesis testing.

[17] The evolution of hydrologic science must also involve new kinds of observations (of processes and process interactions) and new ways to monitor and measure change. Remote sensing, for example, offers opportunities to measure environmental change at much larger scales than previously feasible, e.g., the GRACE mission to monitor changes in water storage [*Rodell et al.*, 2009]. Observational strategies must explicitly consider the role of humans in the water cycle and must include measurements of water extraction for human use, return flow, water quality, and effects of infrastructure constructed to serve human needs. Modern technology facilitates the development of new (numerous, cheap, and qualitative yet useful) sensors and sensing techniques that can be used to monitor human water use and interactions with the water cycle (i.e., participatory sensing). This offers significant opportunities to improve system analyses and predictions via data-model fusion, real-time learning, and recursive forecasting. In comparison with the past, a greater use of controlled field and laboratory experiments across space and time scales is also needed [*Kleinhans et al.*, 2010; *Hopp et al.*, 2009; *Holländer et al.*, 2009; *Dontsova et al.*, 2009], which helps to improve our understanding of interacting processes under transient conditions. Further, a more opportunistic use of observations and monitoring in the aftermath of nature's experiments at larger scales in real landscapes (e.g., following accidents or natural disasters) can provide highly valuable data regarding extreme conditions [e.g., *Jung et al.*, 2009].

[18] For hydrologic science to be better attuned to the needs of people, it must also be more explicitly connected to societal water uses and their ecosystem impacts. An understanding of the freshwater services provided by, and hazards arising from, hydrologic system responses must be explicitly linked to societal relevance and used to support sustainable resource management [*Brauman et al.*, 2007; *Wagener et al.*, 2008]. We must understand, and be able to project, the variability of such services under different scenarios, including their relationship to economic gains and losses [*Clark et al.*, 2001]. There have been continental- or global-scale modeling assessments of water scarcity under projected climate change and population growth scenarios, which include increased water demand for food and energy production, and various technological and economical measures to increase resilience, e.g., the adoption of virtual water trade [*Rockström et al.*, 2009; *Liu et al.*, 2009]. Such analyses must contribute to understanding of the importance of green water fluxes and virtual water trade in support of regional decision making. Nevertheless, in doing so, the advancement of hydrologic understanding has to remain an important concern, and the adoption of tailored solutions that contribute little to hydrological innovation should be avoided since such solutions remain limited in their value as building blocks toward a coherent hydrologic theory. The importance of this focus on understanding has previously been discussed in the context of problem solving versus puzzle solving [*Eagleson*, 1991], which helps to contrast the engineering and scientific approaches to hydrologic research.

[19] Such a redirection of both effort and emphasis would help to fill current gaps in our understanding of coupled human-nature systems (examples of such gaps are poor understanding of nonlinear couplings and feedbacks and of scaling of hydrologic services), thereby addressing the significant challenges of characterizing evolutionary environmental change and the acceleration or deceleration of such change. It is abundantly clear that the sum total of such changes in our approach to hydrologic science (research, education, and practice) will constitute nothing less than a paradigm shift in the sense of a scientific revolution as described by *Kuhn* [1996]. Figure 5 presents a summary of the ideas that constitute key elements of the paradigm shift.

[20] Finally, it is not just the practice of hydrologic science that must become more holistic but also the approach to primary and continuing education of hydrologists. The educational system that supports the teaching of hydrology must undergo a paradigm shift away from the current practice of imparting a narrow set of basic concepts and a disciplinary set of skills to engineers and scientists. Given the great complexity of the problems facing a changing world, the teaching of hydrology must adopt a greater emphasis on learning from observations and from collective experiences in dealing with the environment around us (akin to the constructivist approach of *Piaget* [1967]). This calls for the teaching of new skill sets, including the ability to read, interpret, and learn from patterns in the landscape; comparative studies to supplement place-based studies; learning through case studies; use of space for time sub-

| Current | Future |
|---|---|
| Humans are external to the hydrologic system | Humans are intrinsic to the hydrologic system, both as agents of change and as beneficiaries of ecosystem services |
| Assumption of stationarity: past is a guide to the future | Nonstationary world: past is no longer a sufficient guide to the future, expected variability could be outside the range of observed variability |
| Predicting response, assuming fixed system characteristics: boundary value problem with prescribed fixed topography, soils, vegetation, climate | Both system and response evolve: no longer a boundary value problem, boundary conditions and interfaces themselves evolve and are coupled. Becomes a complex adaptive system |
| Learning from studying individual places (often pristine experimental catchments) to extrapolate or upscale to other places | Comparative hydrology: learning from individual places embedded along gradients (e.g. changing climate, human imprint) and across spatial scales |
| Hydrologists as analysts of individual processes *or* features at small scales (akin to a microscope) or as synthesists of whole system behavior at large scales (akin to a telescope) | Hydrologists as both analysts *and* synthesists (akin to the *macroscope*) studying the coupled system across a range of time and space scales |
| Observations to characterize input-output behavior in individual (mostly) pristine places | Observations to track the evolution of both structure and response in coupled systems and subsystems |
| Observe and analyze pristine places and extrapolate to make predictions of human impacts | Observe and analyze real places where humans live and interact with the hydrologic system at range of scales |
| Model predictions derive credibility by reproducing historical observations | Model predictions derive credibility via more in-depth diagnostic evaluation of model consistency with underlying system and testing of behavior outside of observed range |
| Observation, prediction (modeling) and management are separate exercises (without feedbacks!) | Real-time learning: observations (sensing, including participatory human sensing), modeling and management are interactive exercises with feedbacks and updating |
| Strong separation between engineering and science approaches to hydrology education | Integration of qualitative and quantitative aspects into a holistic teaching of hydrology |
| Focus on teaching established solutions to current problems | Focus on teaching of evolving skill sets with a strong scientific basis that can be adapted to solving new problems and to understanding new phenomena |

**Figure 5.** Key elements of the needed paradigm shift in hydrologic science (building on work by *Sivapalan* [2005]).

stitutions; and modeling of interacting processes such as human-nature interactions and feedbacks. Above all, the new generation of hydrologists must be trained to become both analysts *and* synthesists. This will inevitably require dissolution of the historical separation between science and engineering in our approach to hydrology education. Teaching methods should be rooted in the scientific and quantitative understanding of hydrologic processes, providing flexible hydrologic problem-solving skills, which can be adapted to provide solutions for new problems and to understand new phenomena. For our science to evolve, these skills must necessarily continue to advance, which provides new challenges to the continuing education of practicing hydrologists. *Kleinhans et al.* [2010] argue that it is necessary for hydrology and other Earth sciences to go beyond the traditional inductive and deductive lines of reasoning by adopting a formalized use of observed patterns and known laws of nature to arrive at hypotheses on the causes of these patterns, in this way arriving at improved understanding. Hydrology education can benefit from recognition of this logical style of reasoning. While these arguments provide some perspective on the kind of paradigm shift that appears to be needed in hydrology education, a considerable new effort at the community level will be required toward the joint development and continuing evolution of holistic education materials and to promote the mutual exchange of experiences as a community of teachers and practitioners (Modular Curriculum for Hydrological Advancement (MOCHA), 2009, http://www.mocha.psu.edu).

## 5. Call to Action

[21] The problems of water scarcity, environmental degradation, and water-related natural hazards arising from the expansion of the human imprint on Earth pose enormous challenges to the way we conduct hydrologic science.

However, they also provide an unprecedented opportunity to utilize technological and theoretical advances in measurement, modeling, and visualization of both variability and change in our world, these being prerequisites for detecting, interpreting, predicting, and managing evolving hydrologic systems. By addressing these challenges, we can help to bring about a paradigm shift in hydrologic science by fundamentally revising and advancing the concepts, theories, and methodologies that underpin our science.

[22] How do we, as a community, facilitate this paradigm shift? What are some of the actions we can undertake to help evolve our science? We believe that the required scientific revolution can best be achieved by a grass roots–driven and community-led long-term initiative that focuses on the regional implications of change (in climate, land cover, land use, and population), thereby providing the catalyst needed to bring about the change we believe is required. The quest to achieve better regional-scale predictions will help to uncover deficiencies in our quantitative understanding and in our ability to provide information at the scales most relevant for decision making. We believe that it will only be through a cross-disciplinary long-term community effort (involving hydrology and other Earth as well as the biological and social sciences), with a unified focus on the regional implications of environmental change, that the required fundamental transformation of our science can be achieved. Significant progress has already been made in strengthening interdisciplinary collaboration across the Earth sciences. In addition to this, we are now poised to capitalize on recent advances in the technological ability to observe, store, analyze, visualize, and transmit relevant data collected over large parts of the world at appropriately fine resolutions.

[23] Examples of where such community-driven initiatives have brought about greater focus and coherence to hydrologic research, teaching, and practice abound. The First International Hydrologic Decade led to the launch of a large number of experimental basins around the world, which brought about major advances in data collection and process understanding [*Keller*, 1976]. The recent Predictions in Ungauged Basins (PUB) decadal initiative of the International Association of Hydrological Sciences launched in 2002 [*Sivapalan et al.*, 2003] quickly went far beyond a dependence of predictive models on calibration, and highlighted limitations in theory, in the ability to observe and predict and ultimately in our capacity to assess the hydrologic implications of environmental change [*Sivapalan*, 2003; *Blöschl*, 2006; *Kirchner*, 2006; *Wagener*, 2007; *Troch et al.*, 2008]. By elevating the profile of the fundamental question of how to transfer information from one location to another and from gauged to ungauged catchments, PUB led to a sharper focus in research, energized the hydrologic community, enhanced integration across disciplines and subdisciplines, and is bringing about significant advancements and greater coherence in our understanding of catchment responses and our ability to predict them. Driven by the increasing speed of environmental change, the proposed new initiative must shift the focus from extrapolating in space to extrapolating in time (using space for time proxies as appropriate) by creating a particular emphasis on the regional implications of global and local change. This will help provide guidance for adaptation efforts, as it is at the regional scale that human decision making and environmental stresses intersect [*Barron*, 2009].

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Appendix F

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# Hydrologic Predictions in a Changing Environment: Behavioral Modeling

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**Abstract.** Most hydrological models are valid at most only in a few places and cannot be reasonably transferred to other places or to far distant time periods. Transfer in space is difficult because the models are conditioned on past observations at particular places to define parameter values and unobservable processes that are needed to fully characterize the structure and functioning of the landscape. Transfer in time has to deal with the likely temporal changes to both parameters and processes under future changed conditions. This remains an important obstacle to addressing some of the most urgent prediction questions in hydrology, such as prediction in ungauged basins and prediction under global change. In this paper, we propose a new approach to catchment hydrological modeling, based on universal principles that do not change in time and that remain valid across many places. The key to this framework, which we call behavioral modeling, is to assume that these universal and time-invariant organizing principles can be used to identify the most appropriate model structure (including parameter values) and responses for a given ecosystem at a given moment in time. The organizing principles may be derived from fundamental physical or biological laws, or from empirical laws that have been demonstrated to be time-invariant and to hold at many places and scales. Much fundamental research remains to be undertaken to help discover these organizing principles on the basis of exploration of observed patterns of landscape structure and hydrological behavior and their interpretation as legacy effects of past co-evolution of climate, soils, topography, vegetation and humans. Our hope is that the new behavioral modeling framework will be a step forward towards a new vision for hydrology where models are capable of more confidently predicting the behavior of catchments beyond what has been observed or experienced before.

## 1 Introduction

### 1.1 Hydrologic change - the prediction challenge

The world is presently experiencing rapid and large scale modifications of the land surface (e.g. deforestation, urbanization) and changes to the climate. In the context of this ongoing global change, understanding and predicting the related hydrologic changes is one of the most urgent questions that hydrologists face today (Barnett et al., 2008; Stonestrom et al., 2009; Blöschl and Montanari, 2010). Perhaps the greatest challenge comes from the fact that the consequences for hydrology will arise from both changes in the forces acting on the landscape (climate, land management), and from the way change is transmitted through the various associated systems and subsystems. As a result, both the ecosystem structure (e.g., vegetation patterns, drainage network, soil properties) and its hydrologic response (e.g., water balance, extremes) undergo modifications. For example, in Alpine catchments where the glaciers are gradually disappearing due to a warmer climate predicting the consequences for discharge (e.g. Horton et al., 2006; Huss et al., 2008) involves predicting how fast and to what extent the ice may melt, how vegetation may evolve on the newly ice-free surfaces, and how the rainfall-runoff behavior regime is modified in the ”new” catchment that emerges as a result. As the ice melts away in these catchments, weathering and new erosion processes emerge on the moraines exposed to the atmosphere, vegetation succession occurs, new vegetation emerges and accesses different soil moisture compartments, soil structure as well as soil biology changes as a result of modified hydric conditions. In short, all biotic and abiotic components of the ecosystem are undergoing simultaneous, interdependent changes.

### 1.2 A challenge to the status quo

These interdependent changes present a fundamental challenge to the way predictions are typically made in catchment hydrology. The most common approach adopted in present-day change predictions is the adoption of likely or alternative future ”scenarios” regarding climate, land cover or land use, and other hydrological parameters (Mahmoud et al., 2009). The structure of the catchment ecosystem is considered essentially as fixed, with climate as an exogenous forcing (akin to solving a boundary value problem). In the Alpine example above, the future scenarios could specify the extent of glaciers and of forested areas under climate change, chosen to represent likely future conditions in a seemingly plausible way. A typical approach to assigning plausible future values to model parameters and forcings is the use of external (not coupled) model outputs (e.g., global climate models, land use evolution models) or the use of expert judgment. The likely impacts of these change scenarios on hydrological responses are then evaluated using models developed for the present or past conditions.

The following two examples illustrate the scenario-based approach to hydrologic prediction. Zierl and Bugmann (2005) simulated the future hydrologic responses of Swiss Alpine catchments under global IPCC (Intergovernmental Panel on Climate Change) land use change scenarios using a physically-based ecohydrological model. They decreased forest cover in valley bottoms and increased forested areas close to the timberline without, however, considering the evolution of the timberline itself due to projected climate change. Schaefli et al. (2007) created future scenarios of glacier surface area using an empirical relationship with snow accumulation area, and simulated the resulting precipitation-runoff transformation with a conceptual hydrological model. Apart from updating the glacier surface, all other model parameters, such as those relating evapotranspiration to soil moisture were kept unchanged, even though in reality the vegetation composition is highly likely to change.

If we attempt to predict long-term hydrologic change where both the landscape structure and the hydrologic response evolve, feeding back on each other, then past response alone cannot be a sufficient guide to future response, and current hydrologic behavior (including both landscape structure and hydrologic response) cannot readily be extrapolated to predict future behavior, such as through the use of assumed future change scenarios. Such scenario-based predictions can only be seen as informed guesses, producing rough estimates of possible future conditions, accounting only partially for likely directions of natural and anthropogenic ecosystem evolution.

An alternative approach is to broaden the prediction problem to the coupled modeling of the landscape structure, the climatic drivers and the hydrologic response, including the feedbacks resulting from their co-evolution. This approach has long been recognized in climate and earth system sciences, and has motivated the development of several fully-coupled, highly detailed, physically-based land-atmosphere or earth system models that aim to include all relevant biological, geomorphologic, pedologic, hydrological and meteorological processes and appropriate initial and boundary conditions (e.g. Doherty et al., 2000; Levis et al., 2004). In this type of model, the ecosystem (both structure and response) evolves as a result of interactions and feedbacks between all the encoded (hydrological, land forming and life sustaining) processes.

The trajectory of ecosystem evolution in these highly complex coupled models depends very much on the realism and accuracy of the various process descriptions and the associated parameter values. Under these circumstances, what confidence do we have that such predictions turn out to match reality, or even come close to what might actually happen in the future? The descriptions of individual processes, process interactions and feedbacks are intrinsically imprecise and uncertain, and may highly depend on initial conditions, which are also possibly unknown.

### 1.3 A way forward

In this paper, we present a possible new approach to hydrologic predictions, which we call behavioral modeling. This new approach presents an elegant way forward to critically learn from observations of past behavior to predict future behavior in probabilistic terms, i.e. to use understanding of past behavior to choose amongst many possible trajectories of future system evolution. The rationale of this new approach, which will be elaborated in more detail in the remainder of this paper, can be summarized as follows: The current structure of an ecosystem is a legacy of its historical evolution, and therefore contains information about that evolution, which we can potentially summarize in terms of (an) organizing principle(s). This principle, in turn, can potentially be used to develop a predictive framework that combines it with observed data and any other prior knowledge. In this sense, the organizing principle acts as a ”likelihood function”: it tells us which, among all physically possible outcomes (given conservation laws of mass, momentum and energy, as well as local constraints), are the most probable ones.

Section 2 of this paper elucidates the rationale and fundamental assumptions of the proposed approach. We then discuss the nature of the organizing principles in more detail (Section 3), drawing on examples in the literature where these principles have already been identified and applied. In Section 4 we describe the practical application of the approach and its relationship to established modeling approaches and other usages of the term *behavioral* in hydrology. We use examples to illustrate the major challenges involved in developing such a new modeling framework, and the open science questions that need to be addressed as we proceed in this direction (Section 5). We conclude (Section 6) by providing a perspective on possible ways forward to achieve these goals.

## 2 Predicting hydrologic change: behavioral modeling

### 2.1 The structure problem

Hydrologic predictions at the catchment scale are hampered by what we call the ”structure problem”: the difficulty to provide a mapping between the catchment’s bio-geomorphic structure exerting a dominant control on the hydrological processes and the necessary model structure to predict these processes (i.e., to extrapolate them in space or in time).

This structure problem manifests itself differently for different model types. Prediction methods of the bottom-up type rely on physical descriptions of all relevant processes; detailed knowledge of the topology/connectivity of surface and subsurface flow paths is crucial to predicting storage, release and redistribution of water, dissolved mass, and energy within the system. Such bottom-up models suffer from the fact that current technologies do not enable us to observe these structures and associated hydrologic processes in situ everywhere.

An alternative, top-down, approach is to infer dominant catchment structures from data by attempting to reproduce observed integral responses, such as residence time distributions of water leaving the catchment as expressed in the form of the hydrograph - or in the form of tracer breakthrough curves. Due to their integral nature, such signals are of ”low dimension”, and the inference of model structures from such integral catchment responses suffer from ”equifinality” and uncertainty: several types of model structures chosen to reflect the bio-geomorphic structures in the landscape may yield the same integral response. This is a serious drawback when one considers the fact that in a changing environment the catchment architecture can be expected to also evolve due to changes in the system boundary conditions.

### 2.2 Structure and organization in catchments

Many researchers in the hydrologic community have come to the realization that a possible way to overcome both ”structure” problems mentioned above is to add an intermediate level of abstraction that helps connect landscape structure to model structure, for example using the concept of hydrologic ecosystem functions, which is receiving increasing interest in hydrology (Sivapalan, 2005; Wagener et al., 2007).

Following Black (1986), Wagener et al. (2007) define the hydrologic functions of a catchment as consisting of partitioning, storage (retention) and release of water (Fig. 1a), and suggest that we need something more than mere small scale process descriptions to fully capture these essential and universal functions. This is because they arise as emergent behaviors from the natural organization of the catchment structure, linked by interactions and feedbacks to other land forming and life sustaining processes occurring within the ecosystem (e.g. Lin and Chen, 2006; Sidle and Onda, 2004; Paola et al., 2006; Kumar, 2007), including the role of humans (Fig. 1b).

This complex interplay between biotic and abiotic processes shapes the constantly evolving landscape; whatever properties it has today are the legacy effects of the history of its evolution. The structure of the landscape (e.g. vegetation patterns, river networks, soil catena) suggests that these interactions of climatic, geomorphic, pedological, biological and hydrologic processes is not unorganized but indeed leads to specific, identifiable patterns (e.g. Rietkerk and van de Koppel, 2008). The mechanisms underlying the observed patterns and functions of catchments and associated ecosystems and their connection across time, space and scale are the subject of intense research (e.g. Levin, 1992; Rodriguez-Iturbe et al., 1992b; Thomas, 2001; Gisiger, 2001; Sivapalan, 2005), and a range of models that reproduce observed patterns and feedbacks are available (see e.g. Borgogno et al., 2009; Rodriguez-Iturbe et al., 2007). Saco et al. (2006), for example, present a model that, in water-limited ecosystems, reproduces observed patterns of vegetation, runoff, erosion and their redistribution, and the evolution of micro-topography. Conversely, it is reasonable to expect that observable patterns of vegetation and micro-topography contain valuable information and may provide insights into the interactions and feedbacks between the water flow and evolutionary land forming and ecological processes that they emerge from (e.g. Grimm et al., 2005).

### 2.3 Using organizing principles to constrain models

From this perspective, it is tempting to think that the organized patterns that we see in the landscape could be translated into certain principles that may underpin these emergent patterns and encapsulate the nature of system evolution, in the future as well as in the past.

In the words of Rinaldo et al. (2006), ”nature works through imperfect searches for dynamically accessible optimal configurations". If we can discover and summarize the underlying principles in terms of rules or governing laws (Paik and Kumar, 2010), we could mimic this search in our models and identify plausible (future) system states respecting these principles as well as any other boundary conditions or constraints that may apply. We call these governing laws "organizing principles" (a term that is becoming increasingly popular in the literature, e.g. McDonnell et al., 2007; Wagener et al., 2010), and the plausible states "behavioral" - in analogy to the usage of this term in systems theory, where "behavioral" designates a subset of all theoretically possible dynamic system outcomes that is actually observed. Polderman and Willems (1998) give the example of planetary orbits to illustrate this concept. Since the time of Kepler we know that they are elliptic. The general equation describing the movement of two bodies mutually attracted by gravitation would also allow hyperbolic paths but they would not be "behavioral", and are eliminated. A hydrological example can be found in (Ridolfi et al., 2006): they describe a riparian water table - vegetation feedback system that theoretically has two stable states, complete vegetation cover or complete absence of vegetation, but the non-vegetated state is rarely observed in nature, i.e. therefore it is not behavioral.

As mentioned earlier, the evolution of a catchment ecosystem could, in theory, be predicted by modeling all relevant process interactions with suitably complex models. However the uncertainty in the model structure and parameters limits our ability to make reliable predictions with such models. An infinite number of trajectories of system evolution may be possible in the future, and there is a clear need to discriminate amongst these and choose only those that are plausible. If we adopt a priori the organizing principle that encapsulates or drives some of these interactions, we can then account directly for their joint effect on the overall system behavior by adjusting the model structure and parameters so as to respect this organizing principle.

## 3 Identifying organizing principles

An organizing principle may be seen as the answer to the question: "In a landscape where every component is permanently changing, is there some principle that nevertheless persists and continues to manifest itself in the evolving features of this dynamic system?" This general definition is indeed very broad and leaves space for a large range of potential organizing principles that either reflect the causes of evolution or the resulting signatures (for a short discussion of these points of view, see Paik and Kumar, 2010).

The use of organizing principles is predicated on the idea that there are certain configurations of the system that are more likely to occur than others. These 'stable states' should not be confused with the notion of equilibrium or steady-state. Environmental systems are non-equilibrium systems by definition, and moreover are almost never observed in a 'steady-state'.

Two broad classes of organizing principles can already be found in the hydrologic literature: optimality principles and empirical patterns.

### 3.1 Optimality principles

*Optimality modeling* is a technique which first became popular in behavioral ecology to predict the behavior of animals given all factors and constraints facing them (see, e.g. Krebs and Davies, 1993). A recent example is the prediction of bird migration routes on the basis of optimal trade-offs between travel time and energy-use (Vrugt et al., 2007).

A special issue of Philosophical Transactions of the Royal Society, B-Biological Sciences, edited by Kleidon et al. (2010), provides overviews of physical concepts underpinning optimality, such as maximum entropy production (Kleidon et al., 2006; Kleidon and Schymanski, 2008; Ozawa et al., 2003), minimum energy expenditure (Rodriguez-Iturbe et al., 1992a; Rinaldo et al., 1992) or Helmholtz free energy dissipation (Zehe et al., 2010). Paik and Kumar (2010) discuss a range of optimality principles that can be used to interpret observed landscape patterns or to predict land forming processes and the resulting patterns.

In the case of biotic systems, optimality principles can be formulated on the basis of established biological laws, such as Darwin's theory of evolution. A listing of evolutionary organizing principles in plant sciences can be found in the review by Schymanski et al. (2009a). The most well known example in hydrology is the use of ecological optimality principles by Eagleson (Eagleson, 1982; Eagleson and Tellers, 1982; Eagleson, 1978) who focused on net primary production. In more recent ecohydrological studies, we have seen the introduction of several other alternative organizing principles such as the maximization of water use, the minimization of water or oxygen stress (e.g. Brolsma and Bierkens, 2007; Marani et al., 2006b; Porporato et al., 2001; Rodriguez-Iturbe et al., 1999; Caylor et al., 2009), and the maximization of net carbon profit: Schymanski et al. (2007, 2009b) simulated the most probable vegetation cover in catchment ecosystems as the one that maximizes the long-term net carbon profit for a given climate, subject to local constraints. They obtained good correspondence between transpiration fluxes observed under the given climate and the corresponding simulated flux for the most probable vegetation cover (see Fig. 2).

### 3.2 Empirical patterns

The above optimality-based organizing principles result from a priori knowledge and assumptions about the underlying physical and ecological principles. However, we can also formulate organizing principles that are empirical, i.e. based on the patterns of the behavior of natural systems observed at many places, scales or moments. Such empirical principles or laws can be used for predictions only after they have been extensively shown to be time-invariant and valid at many places and scales.

A good example of such an empirical organizing principle in hydrology is the Budyko curve (Budyko, 1984), which is a widely known and accepted universal pattern related to the climate dependence of the annual water balance. In the Budyko diagram (Fig. 3), in theory, the ratio of annual evapotranspiration to precipitation can take on any value below the straight line envelopes, and yet values near the empirical Budyko curve are deemed the most probable, or in other words behavioral. In this sense, the Budyko curve is a potentially useful concept to discriminate between likely and unlikely catchment annual water balance responses. For example, Li (2010) used the Budyko curve to discriminate between unlikely and likely parameter combinations (climate, soils and topography) for a physically-based, high resolution, spatially distributed hydrological model.

Hydraulic geometry relations can be seen as a widely-used form of a behavioral model. An early example is Lacey (1930) who found a simple equation relating the width of a natural channel at bank-full discharge to the square root of flow. As pointed out by Savenije (2003), many authors have confirmed this simple formula without being able to give a physical (causal) explanation. Savenije suggested that Lacey's formula emerges from the "bed-shaping flow velocity that has just sufficient power to lift the bottom material to the natural levee". The existence of such relationships implies that there may indeed be organizing principles that are useful for making predictions about whole system behavior at ecosystem level, which have not yet been shown to reflect a classical (i.e., physical or biological) law or related optimality principle.

### 3.3 Use of modeling to develop organizing principles

As the evolution of natural systems is often very slow, we can rarely observe it. Therefore, a promising approach is to translate the observed behavior into a model and to let the model shed light on the evolution and on potential stable states. An example can be found in (Wong, 2008): Analyzing the effect of overland flow regime on detention storage, Wong found that the dominant flow regime in nature is the one that provides maximum flood attenuation. Another example is the work of Ridolfi et al. (2006) (see also Sec. 2.3): They formulated a simple model of water table - vegetation dynamics in riparian zones and identified several theoretical stable states depending upon the initial water table depth. They argued that one of the stable states (corresponding to absence of vegetation) is rarely observed in nature and discuss how to make use of their results to quantify ecosystem resilience.

Such ecosystem resilience could itself be used as an organizing principle to build predictive models. In fact, resilience is a classical landscape sensitivity concept that designates the likelihood of a change, which is widely used in geomorphology and in ecology (e.g. Usher, 2001). In ecology, the sensitivity concept takes on different forms, such as elasticity, extinction risk, persistence, population viability, resilience, resistance, or turnover time (Miles et al., 2001). These results point towards potentially new experimental and modelling approaches that can be adopted for discovering new organizing principles, as articulated by Kleinhans et al. (2010).

## 4 Behavioral modeling in practice

### 4.1 How do we build behavioral models?

Building a hydrologic prediction model within the behavioral modeling framework involves the following steps: i) understand current or potential stable system states resulting from the co-evolution of interacting processes; ii) summarize this understanding in some time-invariant organizing principle useful for hydrologic prediction at many places, scales and times; iii) build a model to simulate a range of different system behaviors; iv) use the organizing principle to identify the most probable system behavior, i.e. to identify the most appropriate model parameterization for a given case study; v) validate or falsify the model.

Understanding and identifying stable system states and organizing principles, from models or from observed data, requires of course, much further research. As we will illustrate in the next section, steps (iii) to (v) can be completed at least partly with existing models and model identification techniques (see, e.g. Gupta et al., 2005).

The validation and model falsification steps are an essential component of the behavioral modeling framework. Potentially available observed data about system structure and response is not used to calibrate or constrain the hydrological model, but rather used to falsify the assumed organizing principle, which offers new perspectives for the development of specific model validation techniques.

Going back to the examples of Schymanski et al. (2008, 2009b), the authors postulated that vegetation at the landscape scale maximizes net carbon profit. Accordingly, they developed a water balance model that included a conceptualization of all key processes involved in terms of plant physiological behavior and their carbon costs and benefits and thereafter optimized the model parameters so as to maximize net carbon profit. Therefore, the resulting model parameters were obtained thanks directly to the organizing principle without calibration to match observed evaporation or other fluxes. The comparison of the fluxes predicted by this optimal model against observations then becomes an exercise in falsification of the hypothesis that plants maximize net carbon profit.

### 4.2 Relation to existing modeling approaches

Traditional prediction models in catchment hydrology are developed using either a bottom-up or a top-down approach (Sivapalan, 2005, see also Fig. 4a). As illustrated in Fig. 4b, the behavioral modeling framework can be seen as an extension of this traditional framework, where the organizing principle is used to identify the most appropriate model (structure). Because a model of hydrologic change must account for structure forming and life sustaining processes in the landscape, one would normally expect them to be more complex and multi-dimensional than traditional hydrological models. The use of organizing principles, however, contributes to model parsimony: as Marani et al. (2006a) state in the context of developing a coupled, predictive model of vegetation and geomorphology for tidal ecosystems, the key is the ”identification of simplified formulations of the relevant biophysical interactions, yet retaining their essential dynamics". The organizing principle, in turn, would have been previously identified based on theory and data. For example, the Budyko curve, as an empirical organizing principle, results from theory (envelop lines), as well as from observed data. As in a traditional modeling framework, the model predictions are compared to theory and to observed data to validate the modeling assumptions.

On the basis of the above discussion, one may be tempted to think that the development of behavioral models is way too far into the future. In reality, though, many behavioral models are already in place although they are not yet called that. As example, we would like to present the results of a modeling study (representing the bottom-up approach) that, in our view, is just a small step away from using organizing principles for hydrologic predictions.

Hwang et al. (2009) use a complex physically-based model (the RHESSys model Band et al., 1993; Tague and Band, 2004) to investigate whether the observed ecosystem patterns in a fully forested catchment of the southern Appalachian Mountains correspond to some optimal configuration under the local climate and soil conditions. They asked the question whether the catenary sequence of ecosystem patches maximizes a catchment scale vegetation property such as Net Primary Production (NPP). Hwang et al. (2009) first calibrated the hydrological model parameters to yield maximum correspondence between observed and simulated daily runoff. They then varied the average rooting depth and the spatial arrangement of rooting depths (i.e., from increasing in hillslope direction to uniform and then to decreasing in the hillslope direction) to yield maximum correspondence between observed and simulated above ground vegetation (in terms of leaf area index). Subsequently, they showed that the same rooting depth distribution parameters that led to an optimal correspondence between simulated and observed runoff also maximizes catchment scale NPP (compare Fig. 9b and Fig. 11a of Hwang et al., 2009). In the discussion of their results the authors argue that the observed vegetation gradients do correspond to some optimal state of system-wide carbon uptake (Hwang et al., 2009, Section 5.1). From a behavioral modeling perspective, we understand this to mean that they have found evidence that maximization of NPP can be used as an organizing principle to make predictions about spatial vegetation patterns and coupled ecohydrologic response. In other words, their results suggest that they could calibrate their detailed process model by simply maximizing NPP, i.e. to ensure that the model satisfies the identified organizing principle. Then, the simulated and observed patterns could be used to validate or falsify the assumptions in the model. This offers some new perspectives for change predictions too: for example, if they were to investigate system behavior under changed climate, they could directly infer the future vegetation patterns along with the future hydrologic regime through invoking the organizing principle alone, assuming that it is both universal and time invariant. This, in our view, would represent a considerable advance over scenario-based predictions, i.e., simply feeding assumed climate change scenarios into a present-day hydrological model.

### 4.2.1 Relation to other ”behavioral model” concepts

Hydrological modeling has a long tradition of parameter estimation and model identification. In this context, Beven and Binley (1992) shaped the usage of the term ”behavioral parameter sets” for sets that, within a chosen model structure, give acceptable reproductions of the observed behavior. This usage goes back to Hornberger and Spear (1980) who suggested ”(..) that the result of any simulation using a model can (..) be classified as exhibiting either ”the behavior” or ”not the behavior” (of the system)” (Hornberger and Spear, 1980, p.30) and led to the expression ”behavioral model” (Beven, 2006). Just as in our proposed framework, Beven’s use of the concept ”behavioral” designates, in the traditional model development context, a subset of all possible models that is plausible given the historical behavior of the studied system. There is, however, a fundamental difference of how behavioral models are obtained. The traditional approach compares the simulated variable (e.g. discharge) to observed values (time series) of the target variable to select behavioral parameter sets or model structures. This selection is based on a performance measure that can be either a classical sum-of-squared error measure or any other distance measure (see, e.g. Schaefli and Zehe, 2009). The retained models are, thus, the ones that best mimic historical records of the variable to be predicted.

Behavioral modeling uses a priori knowledge and historical behavior to propose an organizing principle to identify behavioral models. The method of identification depends on the type of organizing principle. In the case of optimality principles, a behavioral model simply maximizes the corresponding system output. The fundamental difference to Beven’s concept lies in the fact that in behavioral modeling, the identification of behavioral models involves deeper insights into the system dynamics and explicitly excludes comparing the target variable (which we want to predict) to observations of this variable - this as a prerequisite to use such observations to validate or falsify the model, i.e. to hypothesis testing.

## 5 Potential of the new approach

The behavioral modeling approach is based on explicit hypotheses about the functioning and directionality of evolution of whole ecosystems. Therefore, we believe it has great potential for the prediction of hydrologic change and much of the present paper argues along this line. Hereafter, we would like to discuss some additional promising aspects.

The proposed modeling framework represents a major step towards the building of models based on understanding rather than on calibration to detailed local observations. This goes to the heart of the philosophy adopted by the predictions in ungauged basins (PUB) initiative (Sivapalan, 2003). In this context, the organizing principles represent the crystallization of our understanding of how nature works and offer a new way to transfer knowledge of ecosystem functioning from one place to another.

Organizing principles encapsulate how small scale process interactions are related to the system evolution and response at some higher scales. They thus provide a link between the scale of prediction (e.g. the catchment scale) and the scale at which the relevant processes interact. As example, we can cite here the organizing principle proposed by Zehe et al. (2010). They propose maximum energy dissipation as a connection between worm burrow density and rapid water flow at the hillslope scale. In this sense, we can see that the investigation of organizing principles through virtual and real-world experiments, including controlled field or laboratory experiments, offers new perspectives towards mapping of relevant structures across scales.

The use of organizing principles also presents a new way of including more process understanding into hydrological models and for transferring understanding across different types of models. We can, for example, gain knowledge about the sensitivity of riparian ecosystems to water table depth from a simple physical model (see Ridolfi et al., 2006), translate it into an organizing principle (e.g. ”maximization of resilience”) and then use it to parameterize the vegetation cover (i.e. to identify the most likely vegetation state) in a more complicated hydrologic prediction model. Nicotina et al. (Submitted 2010) use the principle of minimum energy expenditure, combined with a physical model, to identify equilibrium soil depths to be used in a rainfall-runoff model. In this sense, behavioral modeling has the potential to help unify (data-based) conceptual and physically-based modeling approaches.

Finally, a behavioral model can be viewed as a hypothesis about how a catchment ecosystem works. Since it provides quantitative predictions, the validity of the hypothesis can be tested by comparing the predictions against observed system responses (discharge, evaporation etc.). Our understanding advances, even if, and especially when, an organizing principle is proven to be false. This offers an important advantage over traditional models where the observed system response is used for model calibration and is difficult to use for further hypothesis testing, i.e., there is usually no generalizable hypothesis to test.

## 6 Conclusions

This paper has presented the rationale for a new behavioral modeling framework for hydrologic prediction that makes use of universal and time-invariant organizing principles to at least partially replace calibration to observed response data as in traditional models. Our hope is that this modeling framework will contribute to the development of a new generation of models that can be extrapolated in time and in space, and that open new perspectives for hypothesis testing and for unifying traditional conceptual and physically-based modeling approaches. It is a small step towards a new vision for hydrology: one in which there are less black-box parameters, where models are driven both by information about particular places and by fundamental understanding encapsulated in universal principles. It therefore heralds a new future for hydrology where hydrologic models are capable of more confidently predicting the response of a catchment to conditions that have not been experienced in the past, such as under climate or land-use change.

The key to this framework is to postulate that we can use organizing principles to identify the most probable behavior of a catchment ecosystem and the related most appropriate model structure and response. The proposed framework can be viewed as a generalization of optimality modeling, as the time-invariant organizing principles can either be derived from fundamental physical or biological laws (as in the case of several optimality hypotheses currently being explored), or from empirical laws that have extensively been shown to be time-invariant and to hold at many places and scales. The proposed framework aims at overcoming the need of observed data for model calibration and can be used as hypothesis testing tool when used in conjunction with available data.

There are, of course, an enormous number of open questions and to make progress in this direction, much further research is required: What types of organizing principles are useful for hydrologic prediction? Are they transferable, i.e. are they useful for predictive model development in many places? Can we classify catchments with the help of organizing principles? How can we know whether an ecosystem is in a stable state? How can we know how long it takes before a system reaches a new stable state?

Behavioral modeling should be viewed as a modeling technique, as a way of formulating modeling hypotheses and translating them into mathematical models (rather than as a ”literal transcription” of what nature actually does). Unlike traditional approaches to modeling, where calibration rules the day, model building and model validation in the behavioral framework is really, in one way or the other, a hypothesis test. When a model constrained by an organizing principle fails to reproduce real-world observations, this in itself represents scientific progress as it helps eliminate inappropriate assumtions or model structures. Or, in other words, as Kull (2002) formulates it, ”poor results (..) are not proof that optimality fails; they merely imply that the function to be maximized in a natural community remains undiscovered.”

Building hydrologic models thus becomes a process of formulating hypotheses about the organization and structure of the landscape - hypotheses that will need to be tested by new observations and new field experiments. It will thus require an interdisciplinary research effort that brings together specialists from many different fields related to catchment and ecosystem functioning, motivated by both the desire to discover and test widely applicable organizing principles and by the need to make hydrologic predictions in specific places about future conditions.

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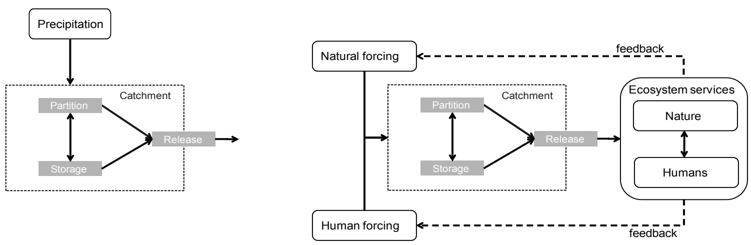


**Fig. 1.** a), left: The catchment and its function, viewed as a system with fixed structure and precipitation as exogenous forcing (adapted from Wagener et al., 2007, with the permission of the authors); b), right: the catchment as part of an evolving ecosystem, which provides services and feeds back on the human and natural forcing.

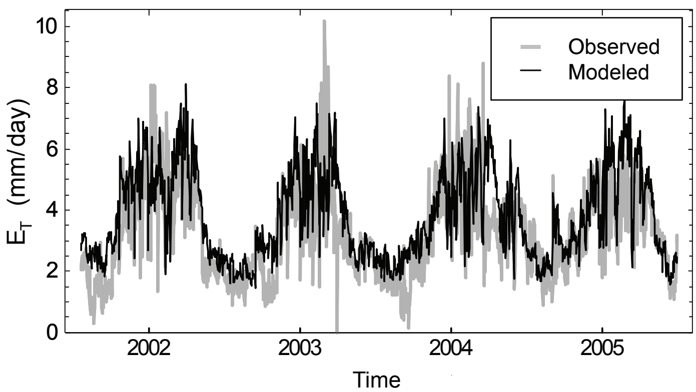


**Fig. 2.** Result of an optimality based modeling framework (from Schymanski et al., 2009b): observed and modeled daily evapotranspiration rates. The model simulates the vegetation that optimizes the net carbon profit given an observed semi-arid climate in Australia.

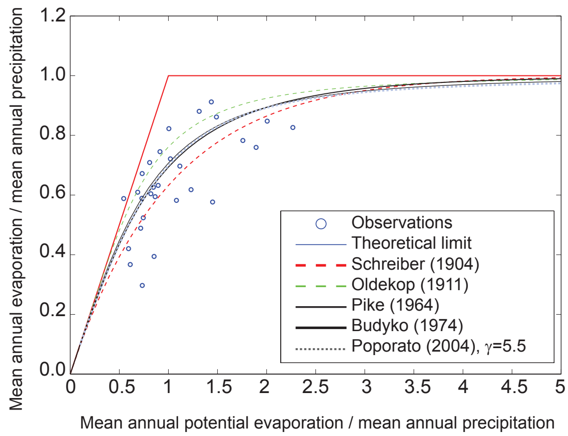


**Fig. 3.** From (Gerrits et al., 2009), reproduced with the permission of the authors: different representations of the Budyko curves and some observations. The 1:1 limit expresses the limitation by available energy, and the horizontal limit expresses the limitation by available water.

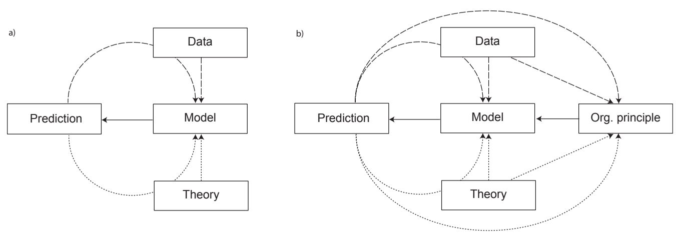


**Fig. 4.** a) classical bottom-up (dotted lines) and top-down (dashed lines) model development approach (inspired from Sivapalan, 2005); b) new behavioral framework.

Appendix G

**Water Resource Projections over Decades to Centuries at River Basin to Regional Scales: A Vibrant Research Agenda for Systems in Transition**

**Executive Summary**

The problems of water scarcity, environmental degradation and water-related natural hazards arising from the expansion of the human imprint on Earth pose enormous challenges to the way we conduct hydrologic science (Wagener et al., 2010). However, they also provide an unprecedented opportunity to utilize technological and theoretical advances in measurement, modeling, and visualization of both variability and change in our world, these being prerequisites for detecting, interpreting, predicting, and managing evolving hydrologic systems. By addressing these challenges and capitalizing on the opportunities, we can help to bring about a paradigm shift in hydrologic science, fundamentally revising and advancing the concepts, theories and methodologies that underpin our science. The required scientific revolution can best be achieved by a community-wide effort that focuses on regional implications of change (in climate, land cover, land use and population), providing the catalyst needed to bring about the changes we believe are required.

Through teleconferences and in-person meetings in 2010 (so far Bozeman, MT, March 2010; Durham, NC, October 2010) the synthesis team is in the process of preparing the outlines of a long-term, sustained and vibrant research agenda focused on *water resource projections over decades to centuries at river basin to regional scale*. It is hoped that the quest to achieve better regional scale (spatial) and decades to century scale (temporal) predictions will help to uncover deficiencies in our quantitative understanding and in our ability to provide information at the scales most relevant for decision-making.

1. The first step in the development of the research agenda was the work (through a series of teleconferences during 2009) that led to the publication of a paper in *Water Resources Research* (Wagener *et al.,* 2010, attached), which articulated the need for a paradigm shift in the science of hydrology to deal with a changing world with an expanding human footprint. The paper also presented the key elements of the needed paradigm shift, and argued that it will only be through a cross-disciplinary long-term community effort (involving hydrology and other Earth as well as the biological and social sciences), with a unified focus on the regional implications of environmental change, that the required fundamental transformation of our science can be achieved.
2. The second step along these lines was an in-person meeting of a synthesis team that assembled at Bozeman, MT, where the focus was the development of a broad conceptual framework that will underpin the details of the proposed research agenda, and the outlines of the research report that will eventually submitted to NSF and published in appropriate scientific forums (see box). A summary of the deliberations at Bozeman, and early drafts of the report arising from these deliberations and subsequent contributions by various writing teams are attached herewith as an appendix.

**Conceptual Framework for Research Agenda and Outline of Final Report**

1. SWOT analysis – where we are and where we want to get to
2. Framework for addressing problems – how we will get there?
   a. How will we know we got there? (evaluate implementation, relevance)
3. Vision statement
   a. How to changing drivers propagate and/or translate to ecosystem state (dynamics?) and water availability and what are the higher order feedbacks?
      i. Human behavior and management
      ii. Vegetation and land surface change
      iii. Morphology and storage
      iv. Driver characteristics – frequency, order, intensity, magnitude
4. Cycles of learning/knowing – observations/models/theories
5. Research agenda for change prediction & management
   a. Theory of observations/experimentation
   b. System evolution subject to basic governing principles
   c. New modeling paradigm for interdisciplinary problems
   d. Predictability of change
   e. Discovering institutions for resilience
6. How do we implement the agenda, a vision for the future

3. The third step will be a follow-up 3-day meeting at the University of North Carolina in October 20-22, 2010. During the meeting a more detailed research agenda will be developed around the broad conceptual framework agreed upon in Bozeman, including experimental, monitoring, modeling and theoretical that will be needed to advance the proposed new research agenda.
4. The final step in this process will be the compilation of the final report by a small writing team, which will be made available to the entire synthesis team for internal review. Upon completion of the final draft, we propose to invite a small team of external reviewers to join the writing team to help improve the report through a process of consultation, critical reviews and editing. We hope to submit the final report to NSF by May 31, 2011.

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**Water Resource Projections over Decades to Centuries at River Basin to Regional Scales: A Vibrant Research Agenda for Systems in Transition**

## 1. Introduction

The problems of water scarcity, environmental degradation and water-related natural hazards arising from the expansion of the human imprint on Earth pose enormous challenges to the way we conduct hydrologic science. However, they also provide an unprecedented opportunity to utilize technological and theoretical advances in measurement, modeling, and visualization of both variability and change in our world, these being prerequisites for detecting, interpreting, predicting, and managing evolving hydrologic systems. By addressing these challenges, we can help to bring about a paradigm shift in hydrologic science, by fundamentally revising and advancing the concepts, theories and methodologies that underpin our science.

| Current | Future |
|---|---|
| Humans are external to the hydrologic system | Humans are intrinsic to the hydrologic system, both as agents of change and as beneficiaries of ecosystem services |
| Assumption of stationarity: past is a guide to the future | Nonstationary world: past is no longer a sufficient guide to the future, expected variability could be outside the range of observed variability |
| Predicting response, assuming fixed system characteristics: boundary value problem with prescribed fixed topography, soils, vegetation, climate | Both system and response evolve: no longer a boundary value problem, boundary conditions and interfaces themselves evolve and are coupled. Becomes a complex adaptive system |
| Learning from studying individual places (often pristine experimental catchments) to extrapolate or upscale to other places | Comparative hydrology: learning from individual places embedded along gradients (e.g. changing climate, human imprint) and across spatial scales |
| Hydrologists as analysts of individual processes *or* features at small scales (akin to a microscope) or as synthesists of whole system behavior at large scales (akin to a telescope) | Hydrologists as both analysts *and* synthesists (akin to the *macroscope*) studying the coupled system across a range of time and space scales |
| Observations to characterize input-output behavior in individual (mostly) pristine places | Observations to track the evolution of both structure and response in coupled systems and subsystems |

| | |
|---|---|
| Observe and analyze pristine places and extrapolate to make predictions of human impacts | Observe and analyze real places where humans live and interact with the hydrologic system at range of scales |
| Model predictions derive credibility by reproducing historical observations | Model predictions derive credibility via more in-depth diagnostic evaluation of model consistency with underlying system and testing of behavior outside of observed range |
| Observation, prediction (modeling) and management are separate exercises (without feedbacks!) | Real-time learning: observations (sensing, including participatory human sensing), modeling and management are interactive exercises with feedbacks and updating |
| Strong separation between engineering and science approaches to hydrology education | Integration of qualitative and quantitative aspects into a holistic teaching of hydrology |
| Focus on teaching established solutions to current problems | Focus on teaching of evolving skill sets with a strong scientific basis that can be adapted to solving new problems and to understanding new phenomena |

**Table 1**. Elements of the paradigm shift in hydrologic science. See Wagener *et al.* (2010), which is provided as an attachment to this interim report.

How do we, as a community, facilitate this paradigm shift? What are some of the actions we can undertake to help evolve our science? We believe that the required scientific revolution can best be achieved by a community-wide research agenda that focuses on the regional implications of change (in climate, land cover, land use and population), thereby providing the catalyst needed to bring about the change we believe is required. The quest to achieve better regional scale predictions will help to uncover deficiencies in our quantitative understanding and in our ability to provide information at the scales most relevant for decision-making. We believe that it will only be through a cross-disciplinary long-term community effort (involving hydrology, other earth as well as the biological and social sciences), with a unified focus on the regional implications of environmental change, that the required fundamental transformation of our science can be achieved.

The recent Predictions in Ungauged Basins (PUB) decadal initiative of the International Association of Hydrological Sciences (IAHS) launched in 2002 (Sivapalan et al., 2003a) quickly went far beyond a dependence of predictive models on calibration, and highlighted limitations in theory, in the ability to observe and predict, and ultimately in our capacity to assess the hydrologic implications of environmental change (Sivapalan, 2003; Blöschl, 2006; Kirchner, 2006; Wagener, 2007; Troch et al., 2008). By elevating the profile on the fundamental question of how to transfer information from one location to another and from gauged to ungauged catchments, PUB led to a sharper focus in research, energized the hydrologic community, enhanced integration across disciplines and sub-disciplines, and is bringing about significant advancements and greater coherence in our understanding of catchment responses and our ability to predict them. Driven by the increasing speed of environmental change, the proposed new initiative must shift the focus from extrapolating in space, to extrapolating in time (using space for time proxies as appropriate), by creating a particular emphasis on the regional implications of global and local change. This will help provide guidance for adaptation efforts, as it is at the regional scale that human decision-making and environmental stresses intersect (Barron, 2009).

**Research Agenda for Predictions of Systems in Transition**

The water management challenges posed by global change dictate that we embark on developing a vibrant research agenda for dealing with predictions of water cycle dynamics, with implications for how we observe, predict and manage water resources at large time and space scales, guided by new questions and methodologies that are geared towards addressing change, nonstationarity and adaptations by both humans and nature (Sivapalan, 2009; Blöschl and Montanari, 2010; Wagener *et al.,* 2010).

Prediction in a (rapidly) changing environment means prediction of transient behavior that may be radically different from what has been observed at a given place. The traditional stationary view will not be sufficient for some of the emerging problems that we face. Variables we normally assume as fixed, e.g., soils, topography/morphology, vegetation, land cover etc. are themselves changing but at different rates (Wagener *et al.,* 2010). Their own 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 adaptive processes. Water plays an important role in this evolution.

## 2. SWOT Analysis of Hydrological Science

SWOT (Strengths, Weaknesses, Opportunities and Threats) is a brainstorming tool to collect the information necessary to analyze an organization's or a group's goals or programs. Here we use it to analyze the current state of hydrology.

### Internal Strengths

- CUAHSI (as an example) and generally the increasing willingness to and recognition of the value of working together as a community.
- Availability of long-term experimental watersheds and hence observational records.
- The inclusion of estimating uncertainty is becoming more and more standard in hydrology.

- The very high societal relevance of our science.

**Internal Weaknesses**

- Long-term focus on small-scale analysis and on the analysis of individual (and often unique) places.
- Engineering hydrology (in support of solving many societal problems) has focused on simplistic recipe type solutions, which solve the problem at hand, but have little physical basis. Hence they cannot be used to address the issue of change.
- Over-reliance on data (historical observations) to derive predictive power – a problem in a nonstationary world.
- Extensive focus on pristine headwater catchments (with minimum human impact) and on spatial units that do not allow for generalization of results (e.g. hillslopes).
- Separation between engineering and science education of hydrologists.

**External Opportunities**

- The issue of global change forces an advancement of the hydrological sciences since it demands a revision of tools, methods and strategies, and therefore of our theory.
- The incredible advancement of computer resources available is enabling us to model the hydrological cycle at previously impossible scales (global scale, incredible resolutions etc.).
- Increasing relevance of urban hydrology will demand hydrologists to move into this topical area.

**External Threats**

- Decreasing funding for continued monitoring of environmental variables at a time where global change impacts are accelerating.
- Other sciences, such as climate science, integrated assessment, economics etc. are moving quickly into areas previously dominated by hydrological research (e.g. climate change impact assessment). Water is the connection between many global change drivers and societal impacts. Others are realizing that we need to understand water at the decision-making scale to solve many problems.

## 3. Framework: An adaptive integrated view of evolving systems

Humans like other life forms cannot exist without water. Despite, in pragmatic sense, our interest in quantifying the amount of fresh water resources have traditionally involved various engineering calculations—relating precipitation with land surface conditions to estimate runoff amounts, or using stationary probability theory for floods and droughts—under global change (climate, human impact, land use) understanding the water dynamics would require a holistic approach examining the water exchange and cycle within the biotic and abiotic components of the Earth system. As such, we are not only challenged by predicting the dynamics of the system that impact hydrology under changing boundary conditions, but also to understand how those boundary conditions might change over time for reliable projections of future water and ecological resources. The urgency of a holistic approach is echoed by many catastrophes we have faced globally in the last several decades, not only due to the severity of the stressors of the nature, but largely as a result of the infrastructure failures. Clearly, for the sustainability of human welfare throughout the world, this holistic understanding cannot remain an academic interest, but should be rapidly communicated to engineers in practice, water and land management agencies, and policy makers at various levels of literacy.

The pressing need for the community is to identify a strategy and a unifying perspective of predictive models across disciplinary boundaries. Developing the future directions first will require examining the status quo of predictive models used in water resources and hydrology and identifying their limitations in relation to the natural dynamics of the hydrological systems.

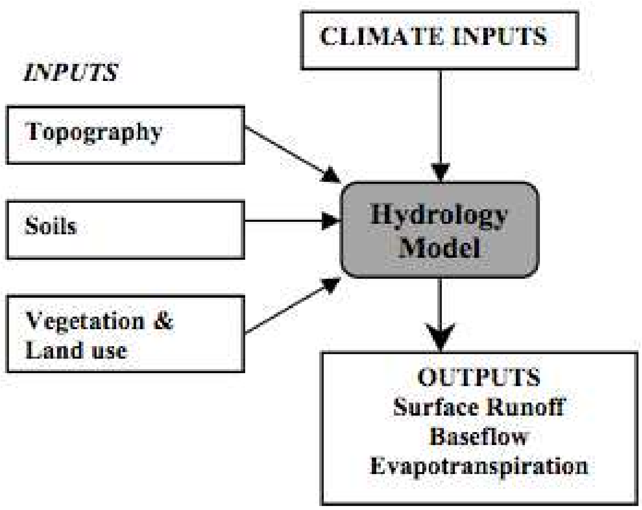


**Figure 1.** Flowchart of a conventional hydrology model: an example of “linear thinking” that dominates applied hydrology.

### 3.1 Hydrological modeling: The conventional wisdom

From most simplistic lumped and empirical, to complex spatially-explicit and physics-based representations, hydrological models are typically based on a “one-way” linear thinking of input-output logic in which the model transfers precipitation inputs to runoff output, conditioned on inputs for watershed characteristics (Figure 1). The watershed characteristics required by models vary, but usually include certain level of land use classification, vegetation, soil, and topographic properties, which are typically assumed static through time. Only in some limited research applications seasonality of vegetation is introduced by satellite-derived vegetation properties or prescribed time-varying functions. Hydrology models are first calibrated using historical observations of streamflow, and then used for predictions in numerous modeling applications. These include streamflow forecasts, analysis of floods and droughts, planning and engineering design of water infrastructure, and managing water resources, land use, and ecological resources. It is critical to note here that many of these applications require realistic predictions about the future behavior, states, and the risks associated with the hydrological systems in 10, 25, 50, or 100 years.

The conventional modeling methodology remains valid so long as human impact and land use change in the watershed are not too severe [Sivapalan *et al.,* 2003a], the climate can be considered stationary, and vegetation distribution remains unchanged in the basin [Milly *et al.,* 2008]. In human-impacted regions, however, where the parts or the whole basin undergoes changes, this conventional methodology can no longer be applicable as the system behavior changes to a previously unobserved regime. Human-induced changes in the system may include urbanization, agricultural development, climate change, increased vegetation disturbances due to fires and outbreaks and other related effects. In the hydrological system with state variables that are related to one another through coupled biological and physical processes, and the two-way interactions with the regional climate, predicting the impacts of "change" would require a thorough understanding and representing of the whole-system behavior in models for improved predictability into the future. Here we identify some of the challenges, and develop strategies for the future directions of predictive models in hydrology.

### 3.2 Beyond Status Quo: The need for a whole-system approach

Significant conceptual, observational, and modeling research challenges lie ahead for predicting the human-impact and assessing the human footprint on the hydrological system. These challenges in the order of their complexity include understanding:

#### ***1) The natural system without humans:***

The human footprint on the natural system arguably has different characteristics in different climates, vegetation cover, geology, and topography. For example farming and irrigation in highly erodible, poorly developed soils in semiarid climates would potentially lead to more severe environmental consequences than those regions with deep fertile soils and humid climates. Land use change with urbanization and agriculture will also have a different response in the hydrology of floods whether the climate is dominated by snow or rain or if there is significant seasonality in precipitation.

In order to improve the predictions of human impact on the natural system and for a sustainable management of our natural resources, we need to understand the coupled processes of the physical and biological systems in particular with respect to the exchange of water, nutrient, and sediment fluxes and identify the dominant controls of the system that lead to a range of system behavior in different climates and geographies. Figure 2 illustrates some of the key processes and variables of the coupled natural system effecting hydrology. We know little about the full system interactions that impact the hydrological dynamics, even in the absence of human impact. Significant research will be needed for the classification of basins with respect to the dominant controls of the hydrological response.

***2) Human impact on the natural system (natural system w/ humans):***

The result of the cumulative activities of humans (agriculture, forestry, industry) all trying to improve their socio-economic well being, leads to the degradation of natural resources. The processes of resource degradation not only involve the water cycle, but also could lead to serious environmental consequences over time involving nutrient and sediment fluxes. We need to examine the ways humans interact with, impact, and modify the natural system, and understand how the human impact propagates into and alters the state variables of the natural system. Modeling of the propagation of the human impact and the human footprint in the natural state variables will require a fully coupled, whole-system approach. To quantify such hydrologic propagations, a modeling framework is needed that explicitly couples water, nutrient and sediment fluxes and allows the cascade of local perturbations through the entire river basin and the region. In an attempt to develop a conceptual framework, in Figure 2 we postulate that humans impact the landscape template through building infrastructure and urbanization; directly alter the local state variables of the system, and could change the climate through green house gasses.

Many practical issues relevant to the public can be examined with this new, coupled perspective. These include water resources and non-point source management, land use and land cover change, and floodplain management. These issues have long been addressed using the standard linear models and data analysis. However for improved predictions, the new modeling paradigm should be based on the understanding of the system behavior under change, not only through sensitivity analysis of an input-output flow model. Some generic research questions can be listed as:

- Does the form of human impact (e.g., urbanization, agricultural, timber harvest), its spatial and temporal scale (frequency, duration) have different consequences depending on the climate, topography, geology, soils, and vegetation?
- How does the human impact propagate to the various states of the system across spatial and temporal scales, perhaps in changing forms of influence? Can the nature amplify the impact or dampen it or change its location and form?
- Are there any natural thresholds that can be crossed by human impact and what are those thresholds and the level of human influence to cross them? For example it is believed that erosion in the Loess Plateau, China has started centuries ago with vegetation disturbances but has continued ever since.

How predictable are those thresholds as human impact progresses over time on the landscape?

- How do we change the predictability of the system and associated uncertainties?

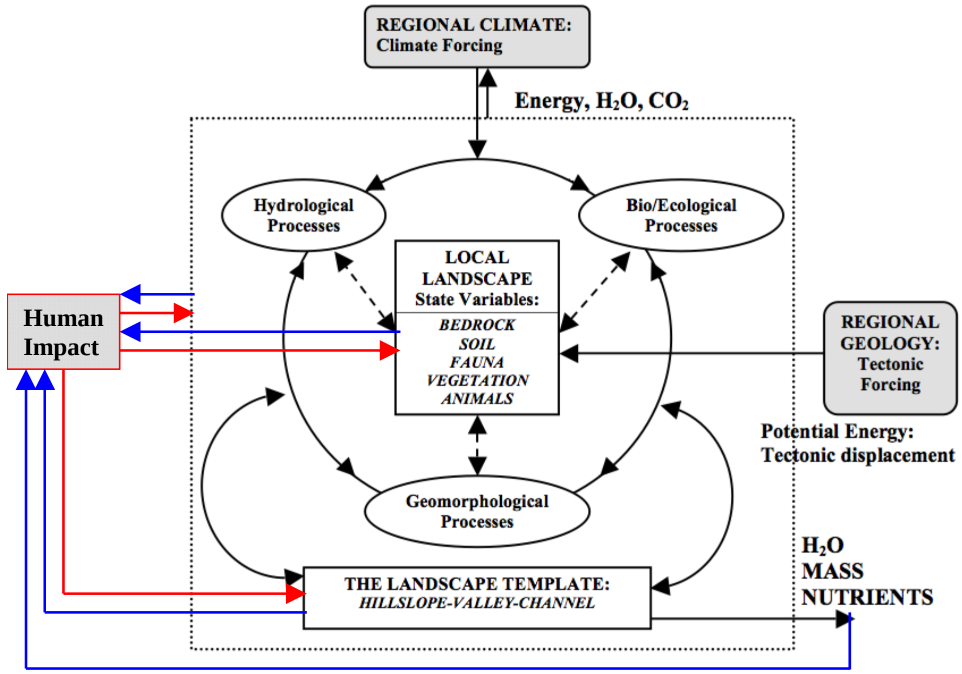


**Figure 2.** Coupled hydrological system, illustrating the processes interactions among the components of the natural system and the potential influence of humans impacting the system state variables (denoted by red arrows), whereby propagating into the system state variables which in turn could lead to feedbacks on the human behavior leading to changes in the human decisions.

### *3) Humans as part of the complex-adaptive natural system:*

Humans have a tendency to maximize utility while institutions minimize their use particularly in regions where resources are limited. In this new modeling paradigm we need to understand how humans, trying to maximize their benefits, react to changes, make decisions, and adapt with and without the influence of institutions. For the sustainability of the human civilization, we will need to understand how humans react to natural stressors (e.g., floods, draughts) and adapt to alleviate their consequences, and develop ways to manage the human-impact by adapting (or coupling with) the nature itself to sustain the production of renewable resources. In Figure 2, the blue arrows illustrate the feedback from the natural system to human decisions. When long-term water and environmental planning is considered, human adaptation to natural response would be a critical link to understand and model.

The first step toward this coupled human-nature modeling paradigm will be to quantify the human and institution response in different environments and climates. Finally the new model paradigm should aid the planning of water and natural resources and managing risks with climate change in 10, 20, 50, 100 year periods but treating humans a part of the dynamic state variables that adapt over time based on some principles of organization.

### 3.3 Propagation of Human Impacts:

**Example 1: Reservoirs and Streamflow Regulation**

The construction of dams over the past century on major rivers of the world has greatly benefited the society by providing hydropower, secure water supply, flood control, and recreation. However, it also caused large disturbances on the natural riverine systems. Almost instantaneously, it changed the river flow regimes by reducing the magnitude and irregularity in seasonality and interannual variability, upon which many aquatic ecosystems depend (ref on importance of irregularity). By trapping sediments behind the dams, it deprives sediments flux into the coastal ocean, causing imbalance between sedimentation and erosion and the loss of coastal wetlands (ref on Mississippi delta wetland loss). (There are other consequences of impoundment not mentioned here. If no one already has it at the finger tips, I can dig out these cases).

In these cases, the benefits of reservoirs are local, but the hydrologic, ecologic, and geomorphic consequences propagate downstream as far as the coastal ocean. To quantify such hydrologic propagations, a modeling framework is needed that explicitly couples water, nutrient and sediment fluxes and allows the cascade of local perturbation through the entire river basin and the region.

**Example 2: Large-scale Irrigation**

Irrigation constitutes 70% of consumptive water use worldwide, be it from surface or groundwater. This represents a huge water transfer from rivers and aquifers into atmospheric vapor through enhanced evapotranspiration (ET). In the US High Plains, the bread basket of the nation, groundwater pumping for irrigation accelerated after WW-II due to the invention of central pivot irrigation system. As a consequence of decades-long groundwater pumping, the regional water table has declined more than 40 m in large areas (Figure 3). However, this not only caused stream flow depletion from the High Plains itself, but also caused changes far downwind. The enhanced ET flux lies on the path of the High Plains Low Level Jet with wind speed peaking in July, the peak of the irrigation season. The increased downwind vapor transport has been linked to a statistically significant increase in July precipitation over the Midwest of the US (DeAngelis et al., 2010). This further translates into a significant increase in July-August-September streamflow where increased precipitation is received (Kustu et al., in prep).

In this case, the hydrologic perturbation occurred at the High Plains, but its impact may have propagated downwind, far away from the region of perturbation, through the atmospheric pathways which span continental scales. As shown by van der Ent et al (2010), continental ET contribution to precipitation increases along vapor transport pathways so that in the eastern US over 40% of its precipitation is derived from ET upwind. The ratio of continental recycling is even greater in the large continent of Eurasia and over the high ET of the Amazon. It points out the efficiency and the large spatial scales of atmospheric vapor transport in propagating hydrology signals across regional to continental distances.

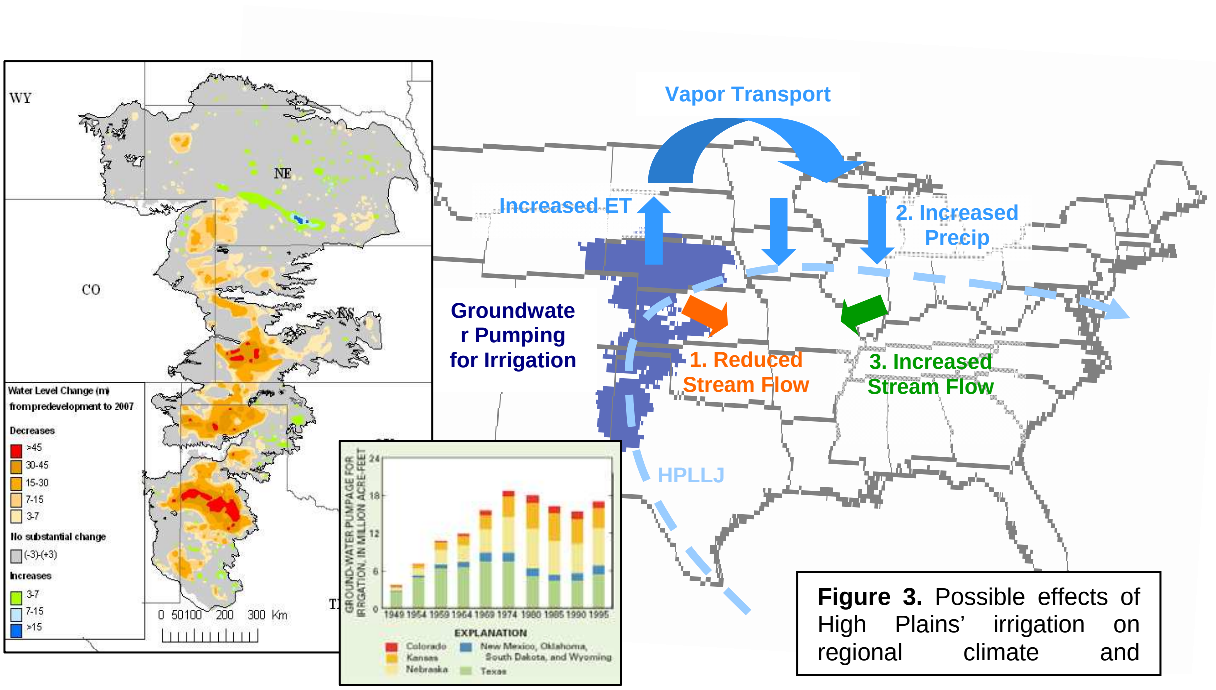


**Figure 3.** Possible effects of High Plains' irrigation on regional climate and

## 3.4 Path Forward

The above examples illustrate the connections among the various terrestrial water stores, among physical, geochemical, and biological processes, and between the natural and human systems. In order to fully understand and predict the results of these interactions, our modeling framework must explicitly include all the vital components, as discussed below.

### *The need to couple climate and hydrologic processes*

The standard approach for projecting future changes in water resources is downscaling GCM future projections (e.g., IPCC) using a regional climate model (RCM) to a spatial resolution meaningful for water resources planning. Although these RCMs can better represent many processes that improve the simulated precipitation over GCMs (Leung and Qian, 1003; Han and Roads, 2004; Liang et al., 2006), there are two basic problems that make this approach less useful. First, state-of-art RCMs do not include the aquifers (model soil ~2m deep). Groundwater is a major resource in itself, and it buffers soil moisture and river flow in dry seasons and droughts. Any meaningful water resource downscaling must include the groundwater reservoir and its exchange with the surface water stores.

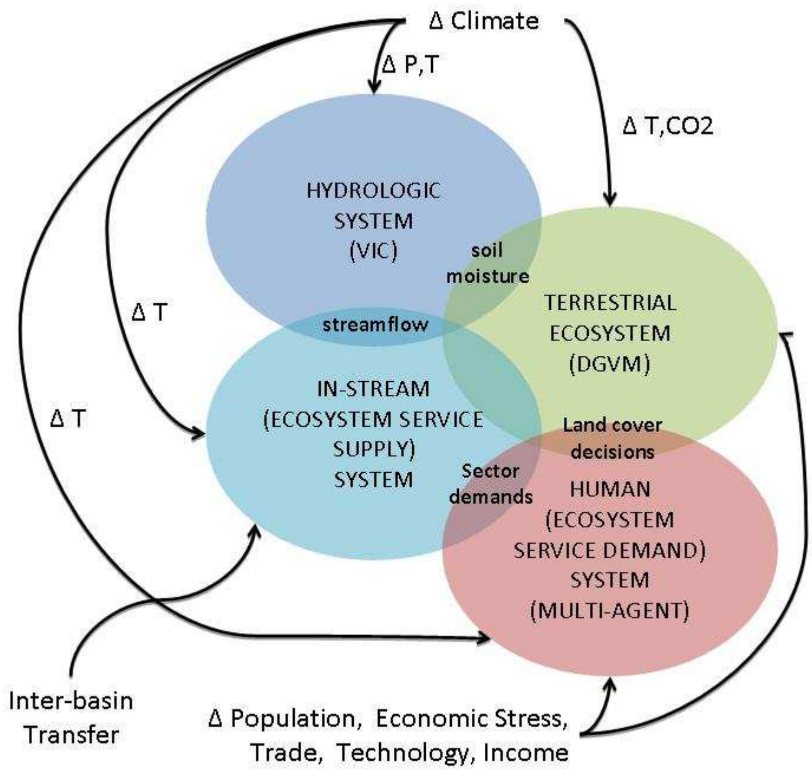


**Figure 4.** Characterization and promotion of sustainable water resources requires an enhanced understanding of cascading scales of alternative drivers of variability and change throughout hydrologic, ecologic and human systems and recognition of the central role of ecosystem services in tracking the trajectory of environmental changes

### *The need to include humans as agents of change and solutions to problems*

The second problem with the standard climate downscaling approach is that the RCMs do not have two-way interactions with human systems. With regard to changing the hydrologic landscapes, humans are arguably more efficient and powerful, and humans may provide the ultimate solutions to the problems we face if proper actions are taken (see Figure 3).

### *The need to couple physical, geochemical, and biological processes*

Water quality and the fate of ecosystems are determined by biogeochemical states and fluxes associated with the water cycle….

## 4. Overarching Vision

a. How do changing drivers propagate and/or translate to ecosystem state (dynamics?) and water availability and what are the higher order feedbacks?
   i. Human behavior and management
   ii. Vegetation and land surface change
   iii. Morphology and storage
   iv. Driver characteristics – frequency, order, intensity, magnitude

## 5. Cycles of Learning and Knowing: a Conceptual Framework for Hydrologic Observations, Models and Theories

The classic water research paradigm recognizes three main elements: field work, experimentation, and modeling (e.g. Weiler and McDonnell, 2004). Hydrologic field work is concerned with observing and recording aspects of hydrologic and water resources systems, generally without manipulation. Data from this type of study may be considered as close as possible to reality (Kleinhans et al., 2009) but is stymied by issues such as data incompleteness due to lack of accessibility of the process of interest.

Water resources modeling aims to develop computational or perceptual frameworks that summarize perceived system behavior (Savenije, 2009). Models may then be tested or assessed for their validity under different conditions or across sites. Water resources and hydrologic experimentation is gaining increasing importance (e.g. Kleinhans et al., 2009) but is hampered by the non-controllable nature of many hydrologic characteristics and difficulties in appropriately scaling processes that may occur over large temporal or spatial extents (Hooper, 2001). As hydrologic science expands its traditional disciplinary boundaries we seek a unifying philosophy that recognizes these learning processes but inspires new standards in water resources management, modeling, and observation. This concept aspires to move beyond traditional physical hydrology research to recognize inherent interactions between social, hydrological and ecological systems, feedbacks and non-stationarities of these systems and their characteristic responses.

Many researchers seek to integrate modeling/observational research tools to iteratively develop and test new hypotheses about hydrologic system behavior under existing or proposed scenarios. It has long been known that the uncertainty and ambiguity in this process can be great (e.g., Klemes, 1988). Ignoring this uncertainty would be detrimental to the scientific process and preclude us from using the reduction in uncertainty as a means to quantify our learning and appraise our data (Beven, 2007).

Significant advantages in testing and rejecting watershed hypotheses can be achieved if (1) our observational, experimental and modeling approaches are well integrated (e.g. Vaché and McDonnell, 2006) while recognizing uncertainty, and (2) if hypotheses/models are considered dynamic and iteratively updated through the research process (e.g. Dunn et al., 2008). We therefore aim to turn our existing observation/modeling tools into an iterative learning framework. This allows us to continuously refine our system representation while also providing insight into the value of the observations that we make and motivating new hypotheses about hydrologic systems. Such a learning framework is implicit in many of the philosophies of scientific scholarship. The scientific method is based on the formulation and testing of hypotheses; it has a necessary iterative nature to refine system understanding and generate new theories (Hooper, 2001). Three classical tenets of scientific inference (induction, abduction, deduction) have long been applied to hydrologic research although they may not be identified as such nor faultlessly apply (Kleinhans et al., 2009).

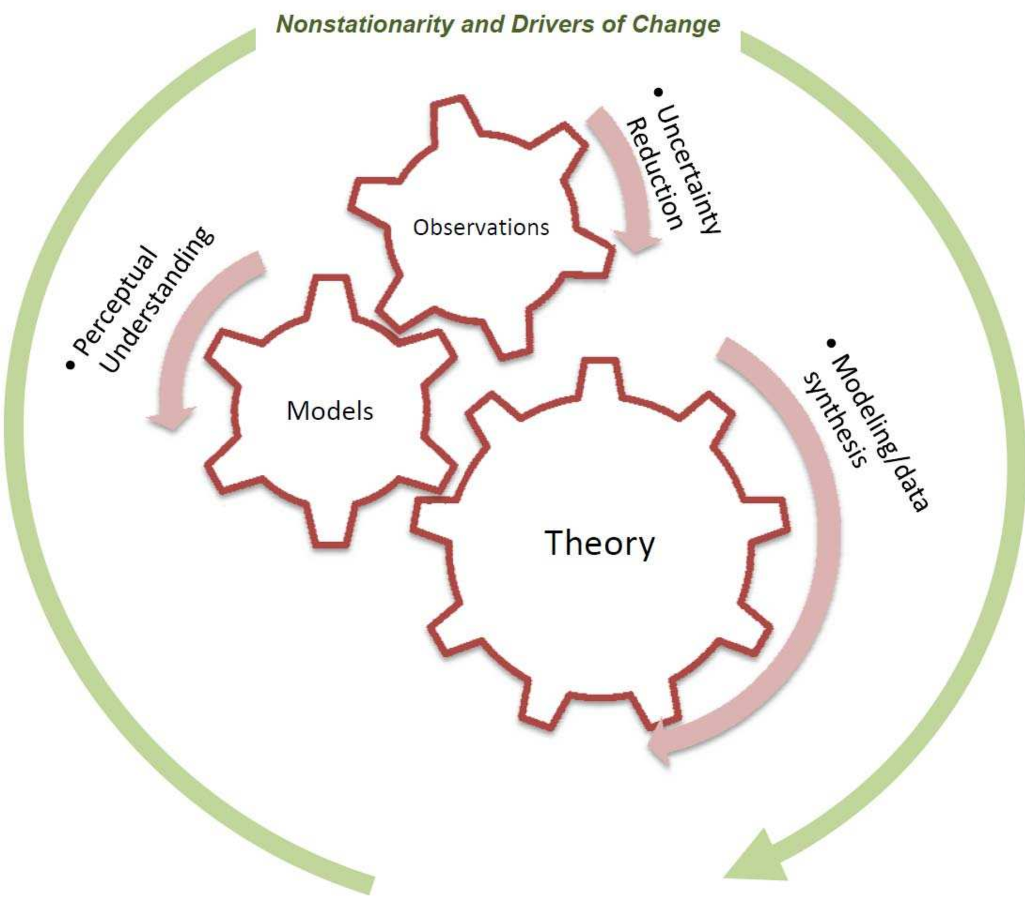


**Figure 5**: A hydrologic cycle of learning and knowing

Induction, whereby generalizations are formed based on analysis of data and observations, has issues due to inherent uncertainties in water resources data and subsequent concerns about the validity of conclusion formed. Nonetheless, the development of new technologies giving rise to massive amounts of data suggests that such correlative inference may lead to new investigative methods alongside hypothesis driven science (Nature Methods, 2009). Abduction, where final system conditions are combined with physical theories to generate potential hypotheses, provides a formal procedure for the hydrologists "perceptual" model (Beven, 2001) which can then be tested via modeling (e.g. the downward approach, Sivapalan *et al.,* 2003b), experiments, or data analysis. Deduction, where system drivers are combined with laws of nature/physics to predict effects, is clearly illustrated by the development and testing of physically based models (e.g. Freeze and Harlan, 1969). However such an approach is affected by difficulties in expressing these physical laws mathematically, in observing system drivers accurately, and in simplifications that are often made to address issues of scale.

Direct application of traditional scientific philosophies such as these is further complicated by confounding hydrologic characteristics: the near infinite complexities of natural systems, our inability to observe necessary variables adequately in space and time, and difficulties in quantifying non-linear hydrologic processes. Traditional learning mechanisms in hydrology and water resources are also significantly impacted by interactions between human-natural hydrologic systems and the difficulty in controlling or separating any one aspect of the system. Overall, there is a clear need to recognize learning feedbacks in hydrologic research and the impacts of external system drivers. While this cyclical approach may be well recognized (Dunn et al., 2008), it is not intuitive to all aspects of hydrologic science where catchment models tend to follow linear paths emphasizing inputs-processes-outputs and where feedbacks are less regularly included. Recognizing feedbacks in hydrologic research becomes critical when we consider the variability and interaction between other relevant systems (social, economic, ecological, climatic) and so requires a learning framework that is cyclical and iterative. Such a cycle for hydrologic learning and knowing may be illustrated by **Figure 5**. The cycle may be initiated by a perceptual understanding of the system of interest, prompting a model to make this understanding explicit. The model sets a framework for hypothesis testing and motivates new observational data or experiments to address uncertainties. As hypotheses are tested via observation/model synthesis, new theories are developed about system behavior. Results from data analysis and/or modeling may encourage new questions to be addressed in the next iteration. Overall such a cycle is affected by change induced by interactions between (say) ecological, engineered, or social system drivers. Non-stationarity and drivers of change then stimulate a need for new models, observations, and theories.

## 6. Hydrologic Change: Observational Science Challenge

Population growth, changing land-use, and climate change place water resources at the center of focus for a broad range of interdependent science, engineering, and policy problems and reflect consequent research needs [*National Science and Technology Council Committee on Environment and Natural Resources*, 2007; *Advisory Committee for Environmental Research and Education*, 2009; *Advisory Committee for Geosciences*, 2009]. These visions contend that the accelerating rate of environmental change makes it critically important to advance our understanding and prediction of the interdependencies and feedbacks between the natural, built, and social systems that define our water resources. The *complex systems* focus of these calls to research (as exemplified in their use of terms such as complexity, emergence, dependency, thresholds, etc.) represents a growing consensus that the significant uncertainties and severe prediction challenges posed by water resources systems' nonstationary and nonlinear dynamics is a credible challenge to our ability to sustainably manage them [*Milly et al.*, 2008; *Rockstrom et al.*, 2009].

Hydrologic systems can be classified as having *organized complexity* [*Weinberg*, 1975; *Dooge*, 1986]. Consequently as noted by Dooge [1986], hydrologic systems pose a severe observation and prediction challenge where the value of hydrologic models can vary significantly and our ability to clarify this issue with observations is strongly constrained [*Langbein*, 1979; *Moss*, 1979b; *Neuman*, 2002; *Beven*, 2006]. These issues provide a strong justification for Bayesian frameworks that acknowledge the biases, errors, and uncertainties in our data and models while simultaneously seeking to extract the useful information they may provide [e.g., *Haimes*, 1979; *McLaughlin*, 2002; *Drécourt et al.*, 2006; *Gupta et al.*, 2008; *Kollat and Reed*, 2008]. Advancing our use of Bayesian frameworks is particularly relevant to the growing ambitions of our field's suggested research agendas [*Advisory Committee for Environmental Research and Education*, 2009], which place a strong emphasis on observing, predicting, and managing critical "transitions" and "tipping points". In hydrological and environmental contexts, these terms are a reference to highly nonlinear systems where critical thresholds lead to a loss of resilience and a sustained change in their observable dynamics [*Folke et al.*, 2004; *Folke*, 2006].

Our detection, prediction and management of environmental gradients is dependent on our ability to design and manage observation networks. As noted by Reed et al. [2006], environmental change necessitates a shift from myopic, non-adaptive long-term observation strategies towards adaptive design frameworks that link our observations and predictions of evolving human—natural systems. Key to this challenge of fusing models and measurements is properly posing and analyzing the question: *what environmental observations are necessary to detect, predict, and manage the risks posed by environmental change?* Although a more holistic assessment is justified, at present our national, regional, and local observation strategies are largely ad-hoc, non-adaptive, and generally disconnected from evolving water resources policy and management needs, a condition that has long been recognized [*Davis et al.*, 1979; *Langbein*, 1979; *Moss*, 1979a; *United States Geological Survey*, 1999].

Thirty years ago Marshall Moss [1979a] acknowledged these challenges and framed the need for future observation network design strategies to use a "…more integrated measure of information…[that] results from a complex interaction of both the hydrologic knowledge and the procedures that are used to incorporate the knowledge into…decisions" (p. 1673). Moss's recommendation represents a major departure from the more commonly employed statistical information measures [e.g., *Shanon*, 1948; *Kiefer*, 1959] by seeking to understand the value of observables for advancing knowledge while simultaneously characterizing their value to the procedures used to make decisions. This postmodern view acknowledges knowledge feedbacks and the potential for the observer to be responsive to breakthroughs and create policy. A clear illustration of the importance and difficulty of more directly linking observation to policy decisions can be drawn from the water quality markets literature [*Horan*, 2001; *Horan et al.*, 2002; *Stephenson et al.*, 2005].

In brief, water quality markets research seeks to identify more cost-effective policies for pollution control using pollution credit trading between point sources (PS) and non-point sources (NPS). Although successes attained in cap-and-trade air pollution are the dominant motivating factors for interest in water pollution credit trading, the organized complexity of water resources systems creates a fundamentally different observation and prediction problem [*Stephenson et al.*, 2005]. Air quality markets are able to exploit the assumption that pollutants are well-mixed in the atmosphere and that the spatial location of emitters does not control the effectiveness of pollution control. This is not true in hydrologic systems and consequently key observation—policy dependencies emerge in two dominant issues: (1) our present inability to observe NPS pollution introduces uncertainty and risk when it is traded with well characterized PS effluents and (2) confirming the performance of pollution credit trading entails significant "transaction costs" associated with monitoring, which can strongly degrade the markets' efficiency and effectiveness in pollution control [*Stephenson et al.*, 2005].

Although water quality markets are a specific example, detecting, predicting, and managing critical environmental gradients given finite resources requires that our observation network design frameworks strike a balance between their evolving scientific and management objectives.

## Bridging Legacies and Modern Ambitions

The water resources and meteorological literature shows that the formalized evaluation of observation networks has a long history. Innovations by Kolmogorov [1939] and Wiener [1949] remain dominant influences on reasoned or systematic observation network design. Crawford [1979] highlights that one of the earliest attempts at formalized spatial network design was the meteorological precipitation network analysis of Drozdov and Sepelevskij [1946] using stochastic spatial interpolation. This work foreshadowed the pioneering theoretical work of Matheron [1971] in geostatistics which has had a lasting impact on spatial network design in hydrology and meteorology [*Jones et al.*, 1979; *Villeneuve et al.*, 1979; *Olea*, 1984; *Rouhani*, 1985; *Loaiciga et al.*, 1992; *Reed and Minsker*, 2004; *Karamouz et al.*, 2008; *Mishra and Coulibaly*, 2009]. These approaches often focus strongly on the Kriging interpolation scheme's estimation variance to provide some *a priori* measure of the spatial uncertainties that would benefit from additional observations.

Early advancements beyond spatial methods towards spatiotemporal network design drew on Kalman filtering theory [*Wiener*, 1949; *Kalman and Bucy*, 1961] to enhance forecasting under uncertainty by statistically conditioning (or assimilating) physical model predictions with uncertain observations. Arnold and Dey's review [1986] highlights that filtering (or data assimilation) innovations have strongly impacted the meteorological community and served to shape the modern concept of *observation system simulation experiments (OSSEs).* Since the early 1950's OSSEs have been used to simulate how observation innovations can improve weather prediction benchmarks. The OSSE framework represents a major innovation in the history of observation networks that has strongly benefited meteorology as a field. A key to OSSE's success is the early acknowledgement of the importance of the systematic errors and uncertainties in predictive weather models, which consequently motivated a more rigorous definition of what constitutes a simulation system as being "…a complete assimilation/forecast system consisting of an analysis method, initialization technique, and numerical prediction model" [*Arnold and Dey*, 1986].

The terms "forecast" and "analysis" refer to the 2-stages of prediction using data assimilation techniques: (i) the forecast beyond the present observations and (ii) the statistical analysis or blending of new observations to innovate/improve predictions. Although a full review of data assimilation is beyond the scope of this paper. Interested readers can briefly sample this topic within the following references [*Kalman*, 1960; *Lettenmaier*, 1979; *Lewis and Derber*, 1985; *Evensen*, 1997; *Eigbe et al.*, 1998; *McLaughlin*, 2002; *Drecourt*, 2003; *Evensen*, 2003; *Caya et al.*, 2005]. The use of data assimilation in observation networks has largely been motivated by the methods' abilities to forecast in space-and-time the impacts of new observations on the mean and potentially the variance of the predicted states of a system (precipitation, streamflow, concentrations, etc.). The exploitation of OSSE's in meteorology has been framed with community-level benchmarks for judging predictive skill (i.e., how can weather forecasting skill be enhanced with new observations?). The use of OSSE's has provided a direct observation—prediction feedback that has served to promote major advances in meteorological observation, numerical weather prediction and weather related risk management. In fact, objective evaluations [e.g., see *Shanteau*, 1992] of how experts across a range of fields impact the systems they manage has rated weather forecasters as being highly skillful because of their discipline's focus on prediction and effective exploitation of observation-based knowledge gains.

The OSSE approach and community-level benchmarking has not been consistently used within the water resources field's observation, prediction, and management efforts. Although water resources researchers in 1960's and 1970's recognized and explored the value of data assimilation methods [e.g., see the early literature review within *Lettenmaier*, 1979], the field's methodological divisions (operational—scientific, surface—subsurface, quantity—quality, etc.) have yielded very different network design approaches across its sub-disciplines, which are strongly influenced by their scales of focus, their distinct network foci and fundamental differences in their preferred modeling paradigms [*Fiering*, 1965; *Haimes*, 1979; *Langford and Kapinos*, 1979; *Lettenmaier*, 1979; *Liebetrau*, 1979; *Moss*, 1979b; *Loaiciga et al.*, 1992; *Mishra and Coulibaly*, 2009]. An early and lasting consensus view is that the promise posed by geostatistics or data assimilation in assessing the value of observables in space and/or time is ultimately limited by our ability to capture observation networks' evolving uses and objectives [e.g., see the discussions by *Langbein*, 1979; *Moss*, 1979a; *Loaiciga et al.*, 1992; *Advisory Committee on Water Information and National Water Quality Monitoring Council*, 2006; *Subcommittee on Ground Water*, 2009]. The historical water resources literature [e.g., see *Haimes*, 1979] clearly highlights the dynamic and multiobjective nature of the water resources data worth problem. Thirty years ago Haimes correctly predicted that the long-term "social pressure" on water resources will make the observation—management nexus a pivotal issue.

At present, the water resources community has not evolved in a manner such that the value of existing or proposed observations is systematically evaluated in forecasts prior to events of interest. Alternatively, the traditional decision analyses and multi-criterion decision making approaches [*de Neufville*, 1990; *Haimes*, 1998; *Loucks and van Beek*, 2005] for judging the value of information (1) fail to fully account for the incommensurate network objectives, (2) are limited by our lack of an *a priori* understanding of the how to define the preferences/constraints for incommensurate network objectives, and (3) ignore the complex dependencies between our observation and management decisions that emerge from hydrologic systems' socio-physical organization. Moreover, a vast majority of our science and policy is based on post-event, regressive explanatory modeling with very little treatment or acknowledgement of systematic biases and uncertainties. Consequently, these approaches have strong limitations for addressing environmental change [*Wagener*, 2007]. As noted by Beven [2006] even something as basic as a using observations and predictions to close a watershed's mass balance can be viewed as a "*holy grail*" ambition.

There is a growing incongruence between water resources prediction needs and their support from existing observation networks as noted in the recent national reports proposing new observation infrastructure for the U.S. [*Advisory Committee on Water Information and National Water Quality Monitoring Council*, 2006; *Subcommittee on Ground Water*, 2009]. The spatial, temporal, and focal complexity of the proposed monitoring systems have motivated recommendations for managing and expanding an emergent *network-of-networks* to deal with water quality and quantity challenges. Although this ambition should be lauded, the network design recommendations used in the national reports largely focus on concepts (e.g., random, stratified sampling across regions) that originate from the statistical design-of-experiments work of Kiefer [1959]. The key technical issue here is that the design of experiments methodology is appropriate for well defined closed systems with a limited variation in their states and a very modest number of experimental options (laboratories or manufacturing control processes). In contrast water resources network design occurs in the context of open systems (i.e., poorly defined boundaries and states) with severe variation and exponential growth rates for experimental options. If we are to attain some understanding of the value of information within an emerging *network-of-networks*, it will be vital to better approximate their evolving tradeoffs and dependencies. The water resources field needs to innovate the defining concepts and use of OSSE frameworks to address environmental change.

## 7. System evolution subject to basic governing principles

*What governs the structure and co-evolution of vegetation, soils, and landforms that control hydrologic response within drainage basins?* Coupled earth surface systems of vegetation, regolith and groundwater are essential to sustaining life on the planet. The function of catchments to partition, store and release water, energy and carbon fluxes is the result of complex interactions among physical, chemical and biological processes. Understanding these interactions remains a major challenge to earth system sciences (Rasmussen et al., 2010). For example, soil horizons develop in response to radiant, geochemical, and elevational gradients. These horizons, in turn, modify system hydrology and ecology in ways that earth scientists have not been able to fully predict. Addressing the complexity of these interactions is central to answering the question of what controls catchment evolution and improving our understanding of fundamental earth surface processes such as terrestrial carbon and nutrient cycling, mineral-microbe interactions, and the geologic and atmospheric controls of landscape evolution (NRC, 2001). We currently lack a quantitative, cross-disciplinary and integrated framework for taking on this challenge. Catchments may be conceptualized as an integrated group of systems or structures that act to move energy and matter down gradients. Gradient-driven energy and matter fluxes result in physical transport and chemical transformation processes that create the physical and chemical organization observed in catchments, e.g., soil horizons, catenas, stream networks, vegetative structure, etc. Classic early work of Lotka (1922), Jenny (1941), Lindeman (1942) and Hutchinson (1957) on ecosystems and the initial development of ecosystem theory have been broadly applied across earth science disciplines for modeling processes such as: the transfer of heat in the earth's climate system (Kleidon & Lorenz 2005b); the development of stream channel networks (Rinaldo et al. 1998); the complexity and organization of biological systems (Morowitz 1968; Odum 1988); and the rate and degree of soil formation (Smeck et al. 1983; Volobuyev 1983). These concepts can be integrated within an "open system thermodynamic" framework that characterizes gradient-driven energy flow and mass transfer (Bejan, 2006). Rasmussen et al. (2010) developed an integrated framework based on thermodynamic theory to quantify process interactions that characterize catchments as systems open to energy and matter fluxes that are forced by radiant, geochemical, and elevational gradients. They derived a coupled energy and mass flux statement that demonstrates the relative importance of solar radiation, water, carbon, and physical/chemical denudation mass fluxes to the catchment energy balance. Within this framework they used rates of *effective energy and mass transfer* [*EEMT*; W $m^{-2}$] to quantify the relevant flux-gradient relations. Synthesis of catchment data in this context demonstrates that energy and mass transfer associated with primary production and effective precipitation dominate the majority of earth surface systems and explain substantial variance in catchment structure and function. Furthermore, synthesis data indicate a threshold in critical zone processes at the transition to systems dominated by primary production energetic fluxes. Their analysis suggests that the proposed framework provides a first order approximation of non-linearity in catchment processes that may be coupled with physical and numerical models to constrain catchment evolution.

## 8. New Modeling Paradigm for Hydrologic Change Predictions: Behavioral Modeling

Most hydrological models are valid at most only in a few places and cannot be reasonably transferred to other places or to far distant time periods. Transfer in space is difficult because the models are conditioned on past observations at particular places to define parameter values and unobservable processes that are needed to fully characterize the structure and functioning of the landscape. Transfer in time has to deal with the likely temporal changes to both parameters and processes under future changed conditions. This remains an important obstacle to addressing some of the most urgent prediction questions in hydrology, such as prediction in ungauged basins and prediction under global change.

We propose a new approach to catchment hydrological modeling, based on universal principles that do not change in time and that remain valid across many places. The key to this framework, which we call behavioral modeling, is to assume that these universal and time-invariant organizing principles can be used to identify the most appropriate model structure (including parameter values) and responses for a given ecosystem at a given moment in time. The organizing principles may be derived from fundamental physical or biological laws, or from empirical laws that have been demonstrated to be time-invariant and to hold at many places and scales. Much fundamental research remains to be undertaken to help discover these organizing principles on the basis of exploration of observed patterns of landscape structure and hydrological behavior and their interpretation as legacy effects of past co-evolution of climate, soils, topography, vegetation and humans. Our hope is that the new behavioral modeling framework will be a step forward towards a new vision for hydrology where models are capable of more confidently predicting the behavior of catchments beyond what has been observed or experienced before.

More details about the proposed Behavioral Modeling framework can be found in Schaefli *et al.* (2010), which is attached to this interim report.

## 9. Theory of Change: Predictability of Hydrological Change

It would be very useful to establish the basis for a theory of hydrological change and, in our specific case, a theory of predictability of hydrological change. Indeed, there have been many attempts to try to predict the effects of changes in the hydrological cycle. The vast majority of these contributions have focused on land use change (for instance, Brath et al. (2006) and references therein) and climate change (see, for instance, Arnell, 1998). Usually, the simulation approach has been adopted, meaning that different meteorological/climatic scenario were used to feed an assigned local/global scale hydrological model that has been previously calibrated and validated by referring to a baseline scenario, which usually refers to the current asset of a given catchment. Uncertainty of the simulations has been quantified in a few cases. Up to our knowledge, there have been no attempts so far to formalize a theory underlying the above approach and the related uncertainty assessment. As a matter of fact, different modeling, calibration and validation approaches were used, by often focusing on a few catchments only. The results are different and do not permits us to obtain any general conclusion, notwithstanding the numerous contributions and research efforts dedicated to the problem.

A scientific theory is made up by assertions about the reality underlying observations. It should be described in such a way that any scientist in the field is in a position to understand, and challenge it. A scientific theory generally comes with or generates potential applications in the real world, allowing solutions that were not previously possible. A theory of predictability of hydrological change should be composed of

1) Definitions (change, variability, non-stationarity, etc etc).
2) Axioms (or postulates. Underlying relevant disciplines and processes, etc
3) Basic principles and propositions (fundamental laws, conservation laws, Newton laws, physics, chemistry, sister theories, etc).
4) Aim of the theory (change analysis, change attribution, change propagation, prediction, and design).
5) Models.
6) Hypothesis testing (how to verify the results, tests etc).
7) Ethic principles (presentation of the results, peer review, data sharing etc)

In our opinion, axioms and basic principles are a significant and challenging issue. What are the axioms and basic principles that should drive the predictability of change? Is stationarity of (at least) some of the involved processes a reasonable assumption (for instance: the simulation approach described above usually assumes that model structure and parameters do not depend on the scenario)? What are the basic principles for model selection, calibration and validation? Are future hydrological conditions predictable and to what extent? We believe we can provide useful hints here.

In our view, we should:

1) identify the fundamental laws that we believe apply in the presence of change: conservation of mass, conservation of energy, Newton laws, ..;
2) recognize the intrinsic limit to predictability of hydrological processes (impossibility to define the geometry of control volumes, to monitor processes at fine spatial scale, ..);

3) recognize, as a consequence, the intrinsic presence of uncertainty. Promote the recognition of uncertainty in a positive way. Uncertainty is not limiting our capability of understanding the physics. It is just limiting our ability to predict in a deterministic way and opens to door to statistical prediction;
4) recognize the value of combining the deterministic and statistical (or possibilistic, or fuzzy) prediction. Deterministic prediction takes advantage from physical knowledge and predictability, while statistics can be used to model uncertainty;
5) identify modeling solutions, including calibration and validation procedure. Concepts for model validation (a agreed protocol) are strongly needed;
6) identify with scientific approach those processes which we assume do not significantly change in future conditions (for instance: flow routing, energy exchanges (?), ..);
7) put in evidence emerging concept, like space-time transferability, and identify their links with the fundamental laws above.

The final concept that we would like to stress is that uncertainty is unavoidable, and therefore we should explicitly recognize our inability to provide a deterministic prediction. Therefore, the deterministic approach (understanding) should always be coupled with uncertainty assessment (statistics, for instance; understanding and modeling what cannot be fully understood/described). Within this respect, we need to shape a consistent representation of natural processes, in which predictability (suggested by deterministic laws) and unpredictability (randomness) coexist and are not separable or additive components. Deciding which of the two dominates is simply a matter of specifying the time horizon and scale of the prediction. Long horizons of prediction are inevitably associated with high uncertainty, whose quantification relies on the long-term properties of the processes (Koutsoyiannis, 2010).

## 10. Implementation of the research agenda: vision for the future

### (i) Drivers of Variability and Change: Detection and Attribution

Detection and attribution of changes in temperature, $CO_2$ concentrations and rainfall space-time patterns, land cover and land use changes, population changes and demographics, demand for food and biofuel, and water quality and ecosystem health.

- Impacts on large scale or regional climate and weather patterns, including precipitation, snowfall/snowpack
- Impacts on hydrologic cycle variability
- Impacts on water demand
- Impacts on water resource quality and quantity

### (ii) Propagation of Variability and Change

Landscapes as nonlinear filters: propagation of variability and change through the hydrologic system: climate, soil and vegetation and topography interactions that impact on how the variability and change propagate through the system

- Propagation downslope (hillslope scale)
- Propagation downstream (watershed scale, through the river network)
- Propagation downwind (regional scale, through land-atmosphere interactions)
- Focus on dominant parts of the filter: partitioning, storage, transport, dispersion, reaction
- Long memory effects: buffering by long-memory processes such as storage in soil moisture and in local and regional groundwater aquifers
- Changes to flow regimes, soil moisture, groundwater table dynamics
- Tele-connections: linkages between regional flow regimes and large scale atmospheric and oceanic circulation patterns
- Scale effects on changing hydrological cycle dynamics: differential impacts, including directionality of changes, process controls and regime shifts, with changing scales
- Signatures of variability at long time scales and large space scales: flow duration curves, scaling behavior of flood peaks, contaminant delivery ratios, load-discharge relationships

### (iii) Ecosystem Responses and Adaptations

Interactions between hydrological processes and biogeochemical, erosional and ecological processes that contribute to changes in landscape structure, vegetation response and adaptations, river morphology, in-stream ecology, aquatic habitat and biodiversity.

- Impacts on the fate and transport of material fluxes (e.g., sediments, nutrients, heavy metals, pathogens, pesticides, pharmaceuticals)
- Impact on weathering and biogeochemical changes
- Impact on ecological processes/aquatic habitat/movement along the river corridor
- Impacts on downstream uses by humans and riverine and riparian ecosystems
- Vegetation adaptations: diurnal adjustments of stomatal conductance, longer term adjustments to available soil water, seasonal adjustments in plant growth and phenology
- Inter-annual plant responses to disturbance and competition for resources
- Decadal adjustments to soil carbon and nitrogen, and longer term changes in soil and landform development
- Regional shifts in vegetation patterns in response to global change, their impacts on regional water cycle

### (iv) Human-Nature Interactions and Adaptations

Interactions and feedbacks between hydrological processes and human/social processes in the landscape

- Effects of land use and land cover changes on the hydrologic cycle at a range of scales
- Downstream and downwind impacts of human impacts on nature and the environment, and on humans
- Ecosystem services and disservices due to human impacts, and their assessment on the basis of characteristic signatures of hydrologic variability at a range of scales
- Valuation and trading of ecosystem services and disservices, and approaches to sustainable watershed management
- Monitoring and modeling of human-nature system evolution in urban and agricultural landscapes
- New complex systems approaches to the modeling of human-impacted landscapes, and implications for water resources management

**(v) Impacts on Extremes: Floods and Droughts**

Changes to the frequency and severity (magnitude, duration) of water-related hazards such as floods and droughts in the context of an intensifying hydrologic regime

- Changes due to intensification of precipitation patterns (intensity, duration, sequencing, seasonality)
- Changes due to reduction/increase of the thresholds that cause floods/droughts
- Changes due to changes in antecedent soil moisture
- Changes due to destruction of connectivity thresholds at large scales
- Changes due to removal of riparian vegetation and other natural/man-made flood control structures
- Catastrophic flooding due to confluence of factors: rainfall, antecedent conditions, transmission capacity
- Scale effects: which geographic regions are most vulnerable to floods and droughts, and how will these change as a result of global change

**(vi) Tipping Points and System Resilience**

Potential for catastrophic changes: landscapes/ecosystems disturbed beyond their capacity (tipping points) to restore their ecosystem functions

- New framework to assess the functioning of ecosystems, and the balancing of disturbance and restoration
- Critical processes that hold ecosystems together – positive and negative feedbacks – and keep them sustained and resilient to change
- Confluence of factors that contribute to extremes and tipping points
- Learning from nature's experiments: need to think outside the box, outside of the data experience, outside the process theories that we are familiar with

**(vii) Predictions: A New Predictive Framework**

We need a new generation of simulation models that can predict the entire hydrological cycle over long time periods, e.g., annual to multi-annual and multi-decadal, and at large river basin scales that is specifically targeted to predict propagation of and adaptations to global change.

- Learn from nature: the seeds of changes are already present in nature or recorded in data: new modeling approaches that combine traditional process models and appropriate data analysis and data mining techniques
- Analysis of vegetation dynamics at the boundaries between different ecosystems, such as forested wetland and upland forest transitions
- Models that include the co-evolution of the biotic and abiotic components of the hydrologic system, including all of the essential feedbacks and couplings
- Explicit inclusion of the human component, including human-nature interactions
- Approaches to deal with non-stationarity and non-linearity (models that do not depend on matching to past observations)
- Need more general and not just site-specific approaches: comparative hydrology (space for time, nearest neighbor)

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**APPENDIX: Bozeman Meeting Deliberations**

**CONTEXT**

- The purpose of this workgroup and meeting
  - NSF-funded conceptual discussions with key players
  - Produce a major report (different to Blue Book)
  - The challenge
    - Develop a concrete research agenda
    - Develop a theory of water resources change

- Benefits of the effort
  - More investment in research
  - More coherence within and between disciplines are they relate to water

- How the effort is unique
  - More action-oriented and targeted than other efforts
  - Not claiming to represent the entire community
  - Offering of the best we can without constraints or bias

- Expected long-term outcomes from meeting and beyond
  - Meeting will produce
    - Collective ownership of concepts/ideas/approach
    - Detailed outline of report
    - Identify leaders and contributors for sections
    - Agree on a timeline
  - Why it will work
    - People support what they help create
    - We are all valuable

- How this group will function
  - Must find balance between technical specifics and a holistic vision
  - Details allow inter-disciplinary group to speak the same language
    - Use problems as examples
  - Broad discussions help unify themes and ideas
  - Blind Men and the Elephant analogy – must make a real elephant

- The problem: predictions on regional and decadal scales
  - Idea of change & water cycle
  - Water management crisis
  - Predictions problem

**PROPOSED REPORT OUTLINE**

- The Research Agenda
  - Synthesis and revolution are not the same
  - What do we do when old tools are insufficient?
  - Template of data-model-theory
  - Is it the research or the agenda that requires transformation?
      - How do we build comprehensive tools & theories in a more scientific way?

- SWOT analysis – where we are and where we want to get to (Thorsten Wagener)
  - Can help balance perspectives & explore systems
  - Change is the driver of this investigation
  - Takes the normal research agenda a level deeper (usually only highlights opportunities)
  - Will identify needs

- Framework for addressing problems – how we will get there? How will we know we got there? (evaluate implementation, relevance) (Erkan Istanbulluoglu, Geoff Poole, Larry Band, Greg Characklis, Ying Fan)
  - "New" paradigm of the complex adaptive system
    - Not truly new, acknowledgement is new
    - Bringing complexity to problems is new
    - What are the rules for co-evolution?
    - If the rules are unknown, how can they be managed?

- Vision statement (Brian McGlynn)
  - How to changing drivers propagate and/or translate to ecosystem state (dynamics?) and water availability and what are the higher order feedbacks?
    - Human behavior and management
    - Vegetation and land surface change
    - Morphology and storage
    - Driver characteristics – frequency, order, intensity, magnitude

- Cycles of learning/knowing – observations/models/theories (Lucy Marshall)
  - How do the ways of learning (deduction, induction, abduction) interact with change to organize a larger view?

- Research agenda for change prediction & management
  - Theory of observations/experimentation (Pat Reed Paul Stoy, Lucy Marshall, Brian McGlynn)
    - Challenge of experimental design in human-nature systems
    - Would be transformative to conduct a cross-cutting experiment

    - Information lacks a cost structure
    - Need to place value statements on the information – will inform the experimental design
    - Few rigorous connections between economics and natural sciences – legitimate benefits exist
    - Tendency to study pristine catchments and compare to human-impacted – but this is not straightforward
    - If you want to understand system as a whole with humans as a component, as it is being managed, you are observing and modeling in real time
    - Benefits of a very large quantity of inaccurate information
    - Data assimilation, model-data fusion
    - What is insufficient with the status quo?
  - System evolution subject to basic governing principles (Peter Troch, Jack Brookshire, Brian McGlynn, Erkan Istanbulluoglu, Dominique Bachelet)
    - Diagnostics to determine endogenous vs. exogenous
    - Evolution conditioned by initial state and time, how it processes information
    - Rules of how that works are what we need to discover
    - Undisturbed systems evolve by processing energy and mass fluxes
    - Fundamental principles that will re-organize energy and mass – but how does human system fundamentally change propagation of signals and even drivers (feedbacks)
    - Where does this fall apart? We cannot predict subsurface structure – must create new models, new modeling paradigm to address this
    - Lots of work in soil science to address this – hydropedology
    - Processes are not on the scale of interest? Maybe/maybe not
    - Emergent patterns on the landscape as a result of co-evolution – study with the idea of understanding what is behind them
    - Interrelated systems, accuracy is not currently sufficient for engineering applications
    - Ecosystem resilience to altered/disturbed regimes
    - Climate-vegetation feedbacks
    - Infrastructure
    - At a certain point, will not exhibit emergent properties (threshold)
  - New modeling paradigm for interdisciplinary problems (M. Sivapalan, Chris Castro, LeRoy Poff, Ying Fan)
    - Incorporates how the information is used
    - Types of patterns, observations and methods of incorporation
    - Hierarchical models (in ESS,e.g. EM, circ., LSP), downward methods, uncertainty characteristics, reduction
    - Focus on interfaces
    - Explicitly coupling of hydrologic and process-based ecosystem models
    - Interactions go beyond exchange of variable

- Cannot just stick models together – outputs into inputs
- Limitations of "supermodels" – designed to answer specific questions
- How do we move on from here? Start from scratch? What do we mean by a new paradigm?
- New paradigm would allow changes in sub-components of coupled system driven by other sub-components
- How do you include system changes on one parameter that effects movement of water?
- Does a compromise exist? Is there a way to re-organize the modeling landscape?
- If we just say this doesn't work, that is not offering anything new?
- Replicability of events – need to innovate the mechanisms of group modeling, facilitate the new approaches (diversity is approach to robustness)
- How do you assess value-added from a new paradigm? How do you evaluate/compare with old paradigm? Use observations
- Improved feedback between modeling and observations – must emphasize that we are not going to observe and the predict
- What is the scale at which observations are necessary?

- Predictability of change. Model credibility for future projections – How do we establish a model's credibility to predict change? How to establish the credibility of model predictions (for change)? (Günter Bloschl, Alberto Montanari, Chris Castro, Thorsten Wagener, Geoff Poole, Chris Forest, LeRoy Poff)
  - New paradigm for testing models
  - Problem: what you want to predict is not something you can test first? What can you use as a proxy?
  - Use model's ability to represent physical mechanisms
  - Best prediction does not matter, not relevant – what is the best representation we can expect?
  - Use transitional environment – if you can get a model to predict the various states – doing well (+ feedback to experimental design)
  - No longer predicting hydrology, but predicting the other things that impact (not just outcome of black box)
- Discovering institutions for resilience (Jim Shortle, Greg Characklis, Jack Brookshire, Ashwini Chhatre, Saket Pande)
  - What are the information needs (amounts, types) to support institutional innovation?
  - What are the scales at which innovation is required?

- How do we implement the agenda, a vision for the future (Larry Band, M. Sivapalan)