

**Water Cycle Dynamics in a Changing Environment:
Advancing Hydrologic Science through Synthesis
Interim Report — August 2009**

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Executive Summary

Human activity in today's world is beginning to rival geologic-scale forces. Many freshwater services we have historically relied upon to protect our natural ecosystems and to provide for humans are becoming irretrievably degraded as a consequence of human activity and environmental change, including climate changes. Managing these environmental changes requires the ability to provide reliable predictions of the response of the water cycle to changing environmental conditions at a range of scales. How will the hydrologic system and associated subsystems respond to, and evolve under, natural and human induced changes in climate and the environment? We know that earth systems have co-evolved over geologic time scales and can expect that they will continue to evolve in the future with even greater speed due to human impacts. Predictions need to be made assuming transient conditions, or under new stationary conditions that may be established in future time periods. System evolution must be accepted as an integral part of system behavior – rather than the exception – and many system characteristics previously assumed to be stationary must now be seen as time-variant over periods relevant to water resource management, posing significant challenges for observing, prediction and management.

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. This calls for a broadening of foundations of hydrologic science to deal with change (Wagener et al., 2009), and the development of new modeling frameworks that can easily accommodate the propagation of the change through the cascade of elements that constitute the hydrologic system.

This interim report of the UIUC Synthesis Project presents progress we have made in the past 6-12 months in 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, and represents an addendum to the progress report submitted in May 2009. Much of the important progress has been made through work conducted as part of a 6-week long (June 22 to August 5, 2009) summer synthesis institute held at the University of British Columbia, Vancouver, Canada, where we brought together 10 graduate students, 8 faculty mentors, and a small number of support staff. The students carried out research under two major themes, both of which were already underpinned by common threads, especially a focus on "patterns", and which we hope to unify in subsequent planned synthesis activities. The research under both themes involved systematic data analysis and synthesis -- aided by parsimonious models to elucidate consistent patterns – and have helped to generate new insights into the dominant process controls on observed variability and changes, and have yielded valuable clues towards development of a new generation of models for future predictions.

The **first theme** involved analysis of inter-annual variability of water balance and vegetation response, expressed as the ratio, $H=E/W$, of annual evapotranspiration (E) to plant available water (W), named as the Horton Index (Troch et al., 2009). Under the **second theme**, we examine inter-annual variability in nutrient delivery ratio (NDR) as moderated by interactions between hydrologic and biogeochemical processes across the climate-hillslope-stream network continuum. In both cases, we explored emergence of inter-annual variability of spatio-temporally integrated outcomes (i.e., H-Index; NDR) resulting from both inter- and intra-annual variations in climate (e.g., rainfall, radiation), and land cover (e.g., vegetation). Even though the immediate focus on dissolved nutrients and contaminants, our long-term goal is to include both dissolved and particulate contaminants, and therefore we also started work on the prediction of sediment transport and export at watershed scale, and the transport of particulate contaminants.

Under the **first theme**, we analyzed statistical properties of the H-Index for over 400 MOPEX catchments across the U.S., and explored the climatic, landscape and vegetation controls on H. We found that the Horton-Index remains remarkably constant regardless of climatic variability (Troch et al., 2009), suggesting that vegetation has developed in such a way as to use a maximum climate-dependent fraction of plant available water. We also discovered that when catchments experience climatic drought, vegetation water use efficiency converges to that of semi-arid biomes, independent of any evolutionary traits. The between-catchment comparative hydrological analyses demonstrated that apart from mean climate, expressed as the humidity index, P/E_p , between-year variability of H-Index is governed, to first order, by within-year patterns of precipitation events, e.g., the pdfs of storm event depth and inter-arrival times.

Under the **second theme**, our work was motivated by consistent patterns seen in previously published water quality data in large watersheds across the entire Mississippi Basin, in fine-resolution data from two smaller watersheds (Little Vermillion River, IL; Goodwin Creek, MS), and outputs from a previous basin-scale modeling effort. Two interesting patterns emerged – “chemostatic” behavior of large watersheds, and a consistent pattern in the relationship between NDR and discharge across diverse watersheds ($\sim 50,000 \text{ km}^2$) in the Mississippi Basin. We developed simple hillslope-network models and explored the dominant drivers of these observed patterns with the overall goal of understanding the likely trajectory of these patterns in a changing environment.

Both themes 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). Work in this synthesis project has clearly demonstrated 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.

Given below are more detailed presentations of the work we have done recently, in particular under the aegis of a summer institute completed recently, and the research outcomes that have resulted from this work. More details will be presented in several journal articles that are in preparation.

Theme 1: Water balance partitioning at the catchment scale and its effects on ecological and biogeochemical processes (Peter Troch, Paul Brooks, Matej Durcik, Arizona; Murugesu Sivapalan, Ciaran Harman, UIUC; Ben Ruddell, Arizona State; Sally Thompson, Duke; Gavan McGrath, University of Western Australia)

The first part of the work under Theme 1 focused on developing a better understanding of hydrological partitioning at the catchment scale (from small experimental catchments up to larger MOPEX catchments) and how this partitioning can inform us about ecosystem response and biogeochemical processes. We used the Horton index as a simple but robust measure of hydrologic partitioning. The Horton index is defined as the ratio between catchment scale vaporization (the sum of evaporation and transpiration) and wetting (the amount of total precipitation that can be retained by the catchment and provides plant available water). Our work led to the following results.

1.1 Landscape/climate controls on space-time variability of the Horton index

Using data from 431 MOPEX catchments, three simple models of how the mean Horton Index and its inter-annual variability are linked to climate and landscape characteristics were constructed. The first model (called the Empirical model in Figure 1.1) is statistical in nature and explored several climate and landscape characteristics to predict the mean and variance of the Horton Index across the conterminous USA. It was found that the humidity index (ratio of mean annual precipitation and mean annual potential evapotranspiration) and the catchment-averaged topographic index (natural log transform of ratio between local drainage area and local terrain slope), and their interaction, can explain the observed spatial pattern of the Horton Index quite well ($R^2=0.77$). The same two catchment variables do not seem to capture the inter-annual variability of the Horton Index as well ($R^2=0.37$), which provided the motivation to look at within-year variabilities and interactions as the possible cause of the inability to predict this variability well.

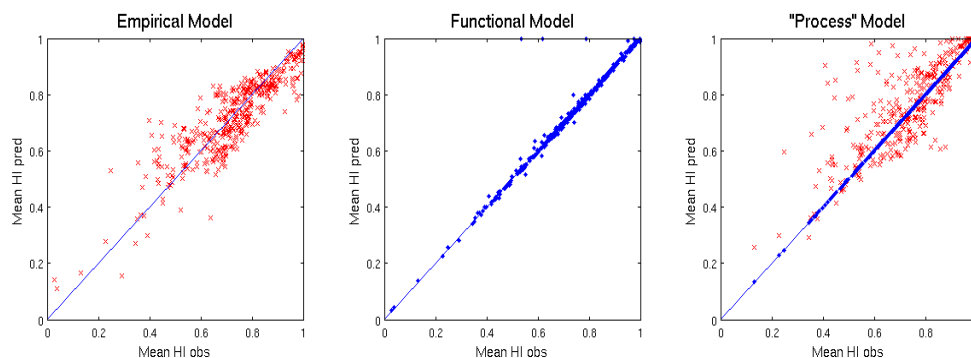


Figure 1.1: Predicted versus observed mean Horton indices for 431 MOPEX catchments and using three different models (see text for further explications).

The second model (the Functional model in Figure 1.1) was developed by Ponce and Shetty (1995) and is based on the conceptual model of the inter-annual variability of hydrologic partitioning of L'vovich (1979). The essence of the model is the realization that both surface runoff and baseflow can increase

unbounded as precipitation increases, but that the wetting and vaporization potential of a catchment is bounded. It also assumes that there are thresholds in the precipitation amount, below which no surface runoff or baseflow will take place. The 4 parameters were calibrated using 50 years of streamflow and precipitation data. The calibrated models show excellent agreement with observed mean Horton index, but systematically under-predict the variance of the Horton index. The parameters show interesting spatial patterns across the US that are related to climate and topography.

The third model (the Process model in Figure 1.1) builds upon earlier work by Botter et al. (2007) and uses a soil storage forced with stochastic rainfall events. The model has three climate-related parameters and one soil parameter. This simple process-based model can be used to derive analytically the probability density function of the Horton index of a given catchment. Assuming a fixed storage capacity of the soil for all 431 catchments, this model is capable of reproducing the observed mean Horton index (i.e., Figure 1.1) but again fails to explain its variance. Its performance can be greatly enhanced by calibrating storage capacity for each catchment, without significant improvements of the predictive capacity for the variance.

The links between the parameters of these three simple models were also explored. It was found that the storage capacity of the stochastic models is related to both catchment topography and the precipitation thresholds. Furthermore it was shown that the available energy limits the vaporization potential in the Ponce and Shetty model, and that catchments in different climates use the available storage capacity in different ways (wetter catchments show a larger range of storage capacities).

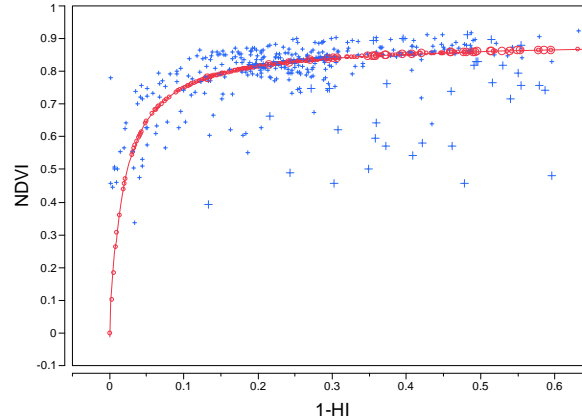


Figure 1.2: Observed and predicted annual maximum NDVI based on the Horton Index information (large blue +: data excluded from model due to low MODIS quality).

1.2. Hydrological partitioning and ecological/biogeochemical processes

Next we explored how knowledge about the Horton Index and its inter-annual variability can be used to understand ecosystem response and the retention/export of chemicals. Using 8 years of MODIS derived NDVI data for all 431 catchments, the relationship between the Horton Index and seasonal maximum NDVI (as a measure of greenness or ecosystems response to water availability) was investigated statistically. As shown in Figure 1.2, we were able to build a statistical model that uses the Horton Index

to explain 98% of the observed variance in maximum NDVI. This model excludes catchments with a mean topographic index above 5%, as it is well known that in steeper terrain the MODIS reflectances exhibit a smaller signal-to-noise ratio.

Data about the hydrology and biogeochemistry of 4 experimental catchments (HJ Andrews, Hubbard Brook, Loch Vale, and Fernow) were used to explore how the Horton Index inter-annual variability can inform us about nutrient retention and geochemical weathering products exports at (small) catchment scales. In these catchments, the Horton Index does not provide additional information (additional to annual precipitation or discharge) on nitrogen retention, and shows equally good fits (e.g. $R^2=0.68$ at HJ Andrews). Looking at intra-annual and inter-annual variability of Ca and NO₃ exports, 2 of the 4 catchments (Loch Vale and Fernow) show low variability in both elements, whereas in the other 2 catchments (HJ Andrews and Hubbard Brook), intra-annual nitrate export is much more variably between years than is Ca. This suggests a stronger biological control in these forested and snow-dominated systems.

1.3. Climate controls and vegetation buffering of intra-annual variability of hydrologic partitioning at the patch scale, and their manifestation at annual and catchment scales

The second part of the work under Theme 1 was focused on improving our understanding of water balance partitioning at the local (patch or ecosystem) scale, and understanding how the water fluxes from these systems vary at timescales ranging from a half-hour to a year. This work was especially motivated by our experience in not being able to satisfactorily model the variability of the Horton Index (as explained before) and the hypothesis that our difficulties in predicting the Horton Index are due to smaller intra-annual variability of the climate drivers (precipitation and radiation) and the active buffering of climate drivers by catchment vegetation (i.e. buffering mechanisms include phenology, root-soil water dynamics, and stomatal control of transpiration). In order to constrain and parameterize models of these mechanisms, FLUXNET towers representing a broad cross section of climatic, soil and ecological diversity across the US were used as a data source. Using flux and soil moisture data at these sites we evaluated not only evapotranspiration partitioning at annual scales (as measured by the Horton Index), but also considered seasonal trends in evapotranspiration, and their connections to flux dynamics at daily and hourly timescales. Our work involved the use of process models of increasing complexity developed to test hypotheses about the dominant controls on both inter- and intra-annual variability at individual sites, and we obtained the following results:

(a) Classical ecohydrological models fail to predict evapotranspiration (ET) fluxes at long timescales (seasonal-annual), in some catchment types.

The classical ecohydrological modeling approach assumes $ET = f(\theta, Rn, LAI, VPD, r)$, where θ is the soil moisture content, Rn the net incoming radiation, LAI the leaf area index of the vegetation, VPD the vapor pressure deficit, and r a measure of surface resistance. FLUXNET data, combined with MODIS LAI products, provide independent measures of all terms, with the exception of the resistance. We therefore used this data to interrogate the validity of the classical ecohydrological modeling approach. In sites with shallow soils, dry climates and strong seasonality in water availability, the classical model performed well. ET followed soil moisture strongly, and its dynamics were quite predictable (Figure 1.3).

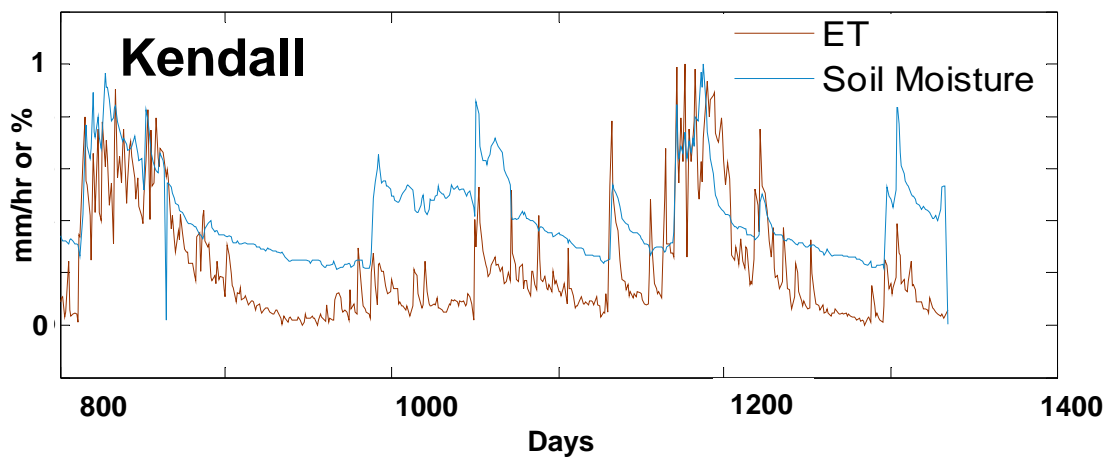


Figure 1.3: Soil moisture (% volume) and evapotranspiration fluxes (mm/hr) over a 600 day period at Kendall Grassland, a shallow rooted, water limited system.

In many sites, however, the classical model failed to capture observed ET patterns. For instance, in several sites it was evident that ET was not limited by soil moisture, indicating that plants accessed additional water sources such as deep groundwater or down-hillslope flow (Figure 1.4). These dynamics are not captured by the classical paradigm, so new approaches are needed to predict annual ET and its seasonal distribution.

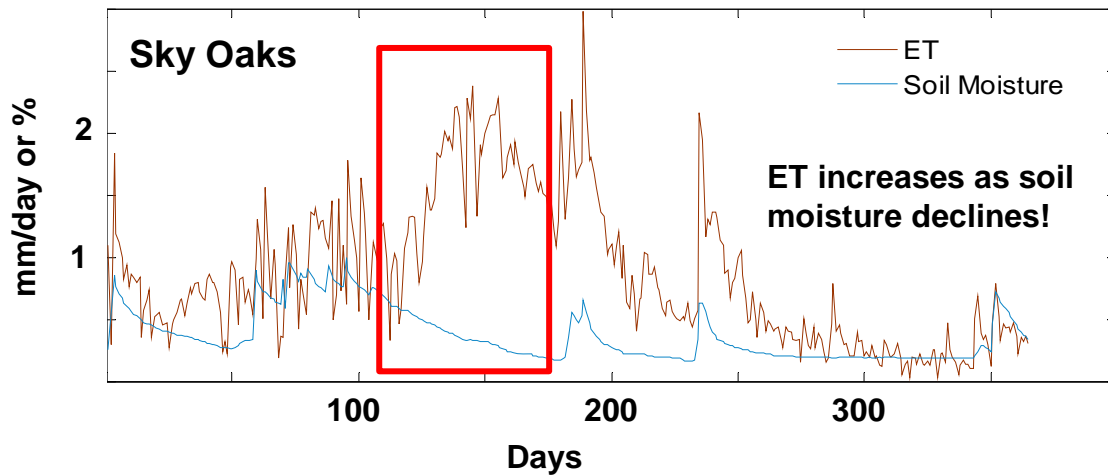


Figure 1.4: Soil moisture (% volume) and evapotranspiration fluxes (mm/hr) at Sky Oaks, a Californian chapparral. Although the soil is only 20cm deep, plants maintain high levels of ET year-round.

Furthermore, constraints on ET appeared to be imposed by vegetation activity not reflected in the Leaf Area Index. In many locations increases in ET are either decoupled from or lag changes in leaf area. This also leads to an apparent “hysteresis” in the surface energy balance, with radiation partitioned increasingly into latent heat exchanges as the growing season progresses (Figure 1.5). Again, new initiatives are needed to address this complexity.

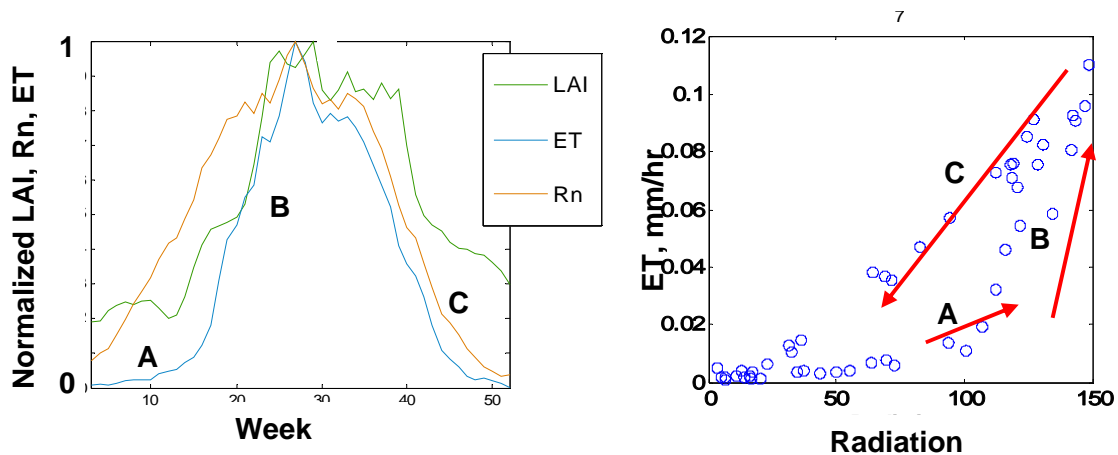


Figure 1.5: Apparent hysteresis in the annual ET-Radiation relationship explained by the lags between LAI and Rn, and ET and LAI at the beginning and end of the growing season.

(b) Improved ecohydrological models enhanced the prediction of ET fluxes at multiple timescales

Based on the finding that a very basic classical ecohydrological model was not sufficient to predict ET at all timescales at all sites, we developed an improved approach that accounted for the presence of groundwater. Adoption of this model significantly improved the model's fidelity to observed patterns in seasonal variability in ET (Figure 1.6).

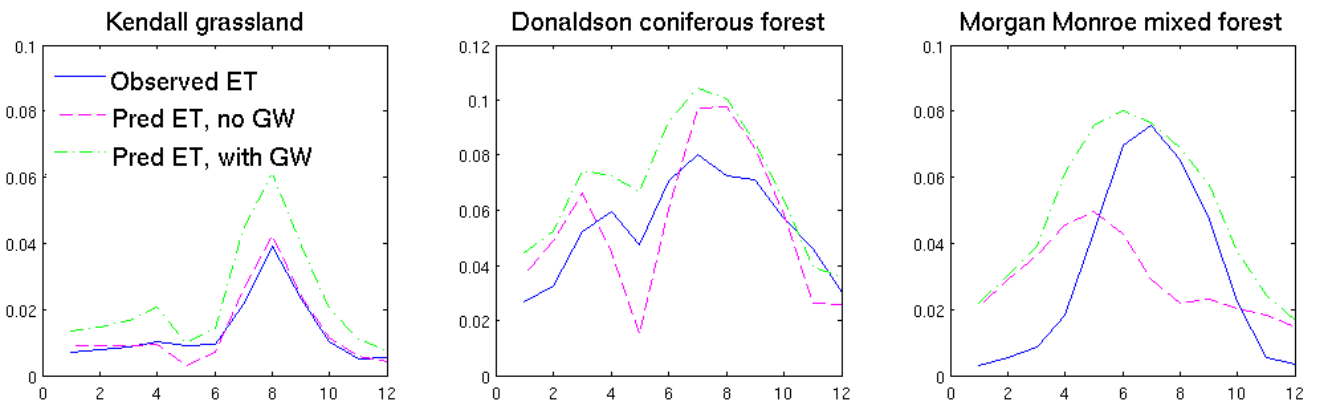


Figure 1.6: Prediction of the seasonal trend in ET by the basic "classical" model (no GW) and the improved model (with GW). Incorporation of a groundwater (GW) term improves the trend for the warm evergreen and temperate deciduous sites.

There is a strong indication that additional improvements can be made by incorporation of phenological drivers into ecohydrological modeling. For instance, at the beginning of the growing season, ET was found to correlate strongly with the cumulative growing-degree-days at a site.

Preliminary results based on the classical ecohydrological model indicate (a) non-trivial scaling behavior as rainfall variability at hourly and monthly scales propagates nonlinearly as a driver of inter-annual variability in ET and runoff, and (b) loss of sensitivity of ET to stomatal variation at a site at annual timescales. Future work will focus on revising these results using improved ecohydrological models of ET, and ultimately will consider spatial upscaling from patches to catchments. The improved models will be used to determine likely causes of the variance in water partitioning at inter-annual timescales, culminating in improved understanding of the physical relationships of the Horton Index to specific catchment and ecosystem properties.

Theme 2: Contaminant Dynamics across Scales – Landscapes as Cascading Non-linear Hydrologic and Biogeochemical Filters (Nandita Basu, Iowa; Suresh Rao, Purdue; Marwan Hassan, Simon Donner, British Columbia; Aaron Packman, Northwestern; Gavan McGrath, University of Western Australia)

Theme 2 of the Hydrologic Synthesis Summer Institute in Vancouver focused on understanding the scaling behavior of contaminant loads across large watersheds. The data analysis, supported by parsimonious models of various landscape components (hillslopes, river reach, river network etc.) generated new insights into the dominant process controls on observed variability and changes. Two interesting patterns emerged from the data --- an “apparent chemostatic” behavior of large watersheds, and a consistent pattern between the nutrient delivery ratio (NDR) and flow across diverse watersheds ($\sim 50,000 \text{ km}^2$) in the Mississippi Basin. We developed simple hillslope-network models and explored the dominant drivers of the observed patterns, with the overall goal of understanding the trajectory of the patterns in a changing environment.

Another major component of Theme 2 focused on understanding the temporal and spatial patterns of sediment dynamics across two watersheds: Goodwin Creek (Mississippi) and Isabena River (Spain). The two watersheds were selected because of data availability and their contrasting channel morphology, sediment supply regime, climate and land use. Our approach was to explore the temporal and spatial patterns through data analysis and then to develop a physically based model, whose objective is predicting sediment dynamics due to land use and climate changes. The focus of the model was on the watershed scale, because sediment transport rates and channel adjustment largely depends on sediment supply. Every watershed has a history (i.e. historical memory or legacy), and this legacy is likely to have dominant and persistent influences on sediment dynamics throughout the watershed. Other factors were also considered; those likely to influence sediment transport are runoff, disturbance (land use changes and climate shifts), vegetation, and geology. Through data analysis of the two watersheds, new insights were developed, based on the role of sediment supply. The spatial and temporal patterns of sediment dynamics were particularly considered, and these investigations led to new insights on how to develop a realistic, process-based model for sediment prediction, at a wide range of scales. Interesting patterns emerged from the data: (1) the role of sediment storage on sediment dynamics; (2) geomorphic connectivity of the landscape may or may not be related to the hydrologic regime; (3) the complex response of the landscape to land use; (4) the shifting patterns of sediment sources and sinks in the watershed. Finally, we developed a simple hillslope-channel hydrology and sediment transport model to explore the interaction between hillslopes and channels; we also constructed a reach-scale sediment model, and tested a basin scale sediment model.

The work completed under this theme was organized around the following five questions:

2.1 How do hillslopes act as non-linear hydrologic and biogeochemical filters that modify input signals (rainfall, chemical applications, etc.) to generate the apparent “chemostatic” behavior at annual time scales?

We were motivated by persistent patterns observed in data from three different sources: (1) water quality data across the entire Mississippi Basin for nitrate, phosphate, silica, pesticides, (2) whole-basin model (IBIS-HYDRA) simulations of nitrogen cycling, (3) fine-resolution (daily and smaller) data from Little Vermilion River (LVR) Basin, a 400 km² highly instrumented agricultural watershed in Illinois; and (4) suspended sediment load data from Goodwin Creek in Mississippi, and Isabena River (Spain).

Linear Load-Discharge (L-Q) relationships were observed in monitoring data for multiple dissolved constituents across a wide range of climates, spatial scales, and land uses. The slopes of these linear L-Q plots represent the flow-weighted annual average concentrations (C_f), and a linear L-Q relationship indicates an *apparent* “chemostatic” response of these large watersheds. Analysis of Mississippi River monitoring data and IBIS-HYDRA simulations revealed that C_f is a strong function of land-use (e.g., percent corn) that defines the chemical input function (see Figure 2.1 for nitrate). The scatter around the L-Q plots was small for endogenous solutes (e.g., silica) and maximum for exogenous solutes (e.g., nitrate and pesticides). Wavelet analysis of high resolution data at LVR watershed revealed that the cross correlation between concentration and discharge decreases with increase in scale (from the scale of a single tile to 400 km² watershed), leading to the *apparent* chemostatic behavior that is observed at larger scales.

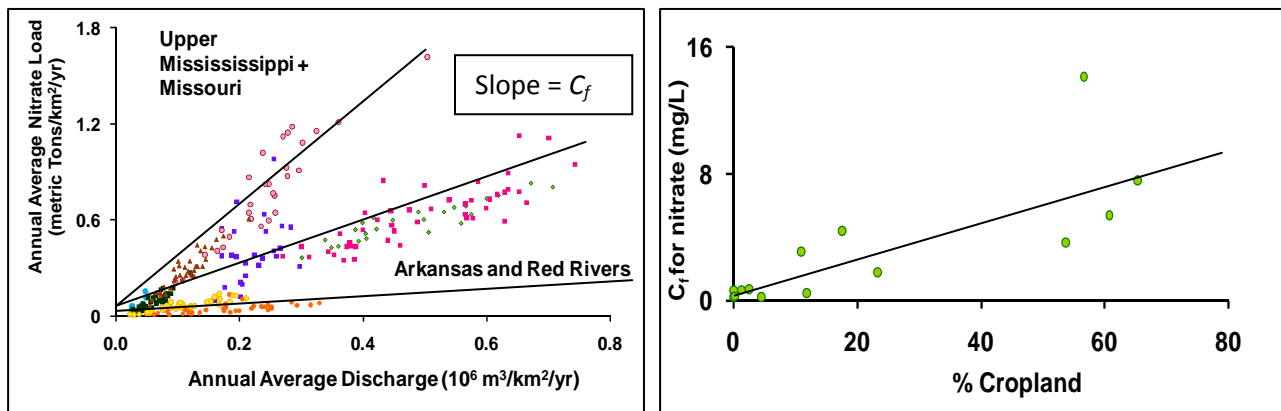


Figure 2.1: Plot on the left shows the grouping of the annual average inorganic nitrogen (nitrate + nitrite) loads versus annual discharge for several large sub-basins in the Mississippi River Basin (MRB). On right, plot shows the approximate linear relationship between the mean, flow-weighted concentration versus % cropland for several large watersheds in MRB.

Our overall premise is that these patterns are the result of filtering action of the landscape, which can be expressed as a function of the ratio of dimensionless time constants. Two different hillslope models were used to explore this filtering effect: (1) Mass Response Function (MRF) model, based on a stochastic representation of the hillslope residence time distributions at the catchment scale, which

determines the contact time available for mass-transfer between mobile-immobile zones; and (2) Hillslope Event Solute Transport (HEST), based on the episodic, advective, retarded transport of reactive solutes through the vadose zone in response to stochasticity of the rainfall forcing, and mobile-immobile mass transfer dynamics.

Through simulations using both of these models, we identified the following four time constants that explain the slope and scatter of the Load-Discharge relationships: (1) $1/\lambda$, the rainfall inter-arrival time; (2) $1/k_{res}$, the mean residence time in the catchment; (3) $1/\alpha$, the mean mass-transfer time for mobile-immobile exchange; and (4) $1/k_{deg}$, the solute degradation time constant. These, in turn, can be grouped into a single dimensionless constant, the Damkohler Number for the filtering, $D_a = [(\lambda/k_{res})(k_{deg}/\alpha)]$. Preliminary simulations using both models have supported these assertions, but thorough evaluations will be made with systematic simulations.

2.2 What is the spatial and temporal averaging that occurs in nutrient cycling in a stream network?

We examined the inter-annual variability in nutrient delivery ratio (NDR) as moderated by the links

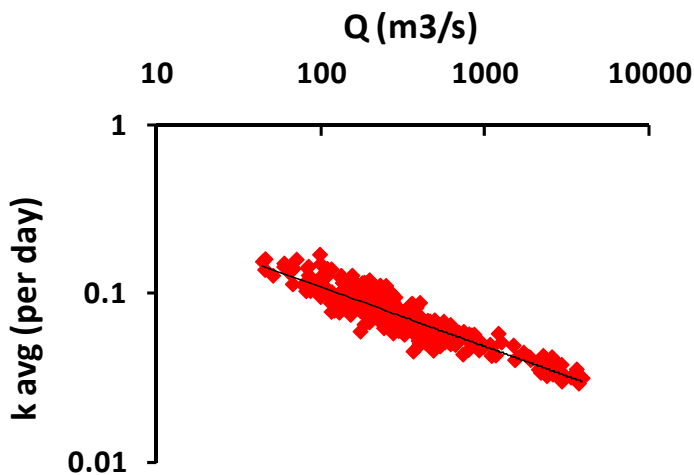


Figure 2.2: Spatio-temporally averaged, mean annual denitrification rate constant versus mean annual discharge shows fractal scaling in several large watersheds in the MRB. Plot based on reanalysis of IBIS-HYDRA model simulation results.

between hydrologic and biogeochemical processes across the climate-hillslope-stream network continuum. Analysis of reach-scale data suggested an inverse dependence of the biogeochemical cycling rate constant (k) on the stream stage (h). Similar inverse $k-h$ dependence was noted to emerge at much larger scales ($\sim 50,000 \text{ km}^2$) when IBIS-HYDRA simulations generated for several years in nine large sub-basins were reanalyzed. The spatio-temporally averaged reaction rate (k_{avg}) constant was observed to vary as a power function of the mean annual Q , indicative of fractal scaling behavior of in-stream biogeochemical processing.

Two parsimonious models were developed to scale up from the reach-scale to watershed scale, and explore the spatio-temporal averaging within the network under diverse climate forcing conditions. The first model was derived from THREW, and was enhanced by adding a two-compartment biogeochemical

reactions model. The second model used the inverse k - h dependence at the daily time scale, without invoking the two-compartment model, similar to that used in the basin-scale model, IBIS-HYDRA.

Preliminary numerical modeling analyses indicated that temporal averaging (over annual time scales) decreased the exponent of the k - h relationship at smaller spatial scales (e.g., first or second order watersheds); however, the relationship converged towards the reach scale dependence function at larger spatial scales. The reach scale k - h relationship thus acts as an attractor for the entire system, such that at larger spatial scales an effective k , derived solely from the mean stage at the outlet, has the ability to describe nutrient processing within the entire network. Further exploration of spatio-temporal averaging is required under different climatic forcing, network structures, stream morphology etc. Based on these preliminary results of numerical modeling, supported by analytical modeling for simpler cases, we propose that such averaging behavior is the expected outcome of fractal networks.

2.3 What are the controls on sediment mobilization on the watershed scale? How is the geomorphic magnitude and frequency (i.e. event sediment mobilization) related to the hydrological magnitude and frequency of floods?

This question was motivated by the temporal and spatial patterns of sediment mobilization observed in Goodwin Creek and the Isabena River. We hypothesized that sediment mobility is controlled by the supply and, to a lesser extent, the hydrology. In order to address this question we used suspended sediment transport data looking at multiple spatial scales: the basin scale (Isabena and Goodwin basins), small sub-basins (13 small basins in Goodwin), and reach scale (a three kilometer long reach in Goodwin).

At the basin scale, both data sets demonstrate significant hysteresis (inconsistencies in the relation between sediment concentration and discharge). The magnitude of these inconsistencies declines as the season progresses, and the relation becomes more linear. We relate this to the high sediment supply/storage early in the season and the depletion as the season progresses. To further explore the role of sediment supply/storage on sediment mobilization, we plotted the cumulative event sediment mobilization against event water volume. Due to large sediment storage early in the season, small events mobilized disproportionately large amounts of sediment, shown as a jump on the sediment flow cumulative plots. Later in the season, the relation becomes increasingly linear. Building on the modeling efforts in session two, and based on the analysis of sediment data, a simple model that accounts for sediment deposition, re-suspension and infiltration into the bed was developed. The observed pattern was very similar to that which is seen in the below figures. These are preliminary results, and further analysis and simulation is scheduled for the fall of 2009.

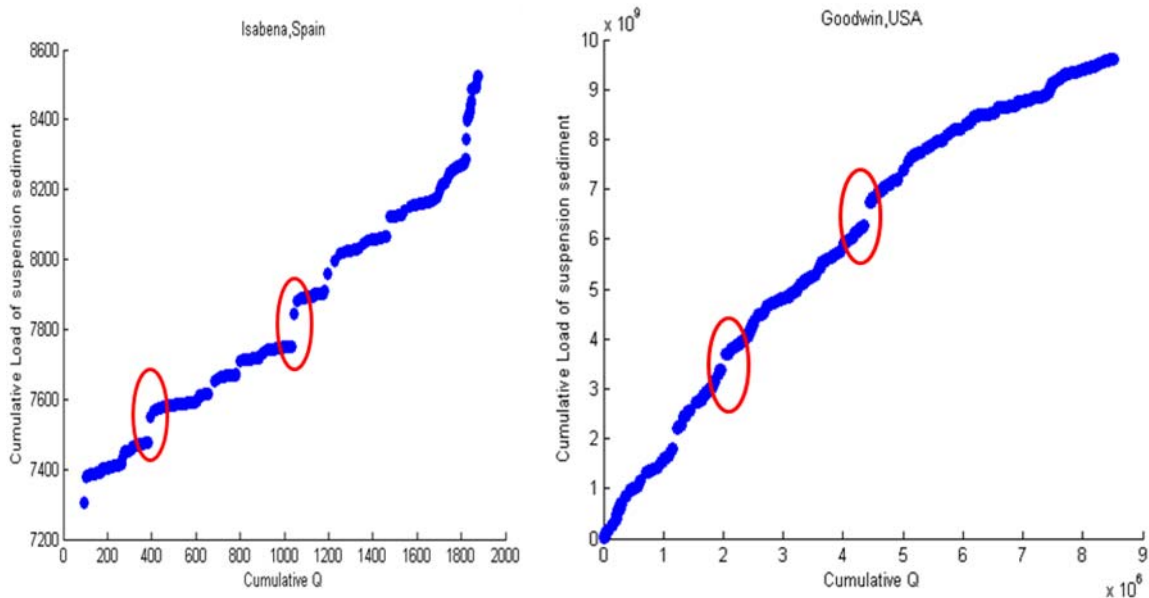


Figure 2.3: Measured cumulative loads of suspended sediments versus cumulative discharge for two watersheds: Isabena River (left) and Goodwin Creek (right). Red circles point to episodes of sudden jumps in sediment loads.

To further explore the control of supply/storage on sediment mobilization, we performed a reach-scaled sediment budget along one of the main reaches in Goodwin creek. The following data sets were used: 1) suspended data collected from five stations on the main stem and tributaries; 2) the bed load data set; 3) topographic cross-sectional data. This reach was selected because all inputs and outputs are accounted for. The sediment budget was conducted over a 20-year period, which includes 560 flood events, and was performed on different time scales, ranging from single floods, to annual patterns. Three patterns emerged from this analysis: 1) within the reach, sediment storage dominates the temporal patterns of sediment mobilization; 2) sediment is mobilized in wave form; 3) sediment storage is dominated by inputs from bank erosion. To our knowledge, this is the most comprehensive analysis completed on this topic. Preliminary results from a reach-based scale model yielded promising results; these will require further work in the near future.

2.4 How did streamflow and sediment respond to shifts in climate and land use?

This question was designed to explore the hydrological and geomorphological connectivity of the landscape, in response to changes in water discharge and sediment load. We tried to determine whether sediment load responded to changes in land use and climate variability. To address this, we performed long-term Hurtz analysis to explore trends in rainfall, flow, and sediment load. In addition, we constructed flow and sediment load duration curves. All 14 stations within Goodwin creek were included in these analyses. The results show that the flow and rainfall patterns are similar, indicating little change in rainfall and runoff, whereas the sediment load results suggested a different pattern. Given that the basin is small and homogenous in terms of lithology, we attributed the declining trend in

the sediment load to land use changes. To further explore these issues, we created a scaled sediment-yield map for the whole basin. The map illustrates spatial and temporal variation in the sediment sources and sinks. Prior to land use, the sediment yield was scale invariant, whereas an increasing trend was observed for the post-land use change period. The implication is that sediment mobilization from the landscape was reduced; however, this led to major bank erosion along the main river stem. Thus, one needs to take the whole basin into consideration.

2.5 How do fine sediments and sediment-bound contaminants get translated through the network?

Two previous questions explored the emerging patterns for dissolved constituents. Here process-coupling that controls sediment-bound contaminant transport load generation were explored. A parsimonious model was developed to describe event-specific re-suspension and re-deposition of contaminated sediment along a single reach. We divide the time series of flow in a reach into two classes: “base-flow” periods and “flood events”, with net-deposition being the dominant process during “base-flow” periods, and net re-suspension dominating during flood events. The model simulates the episodic translation of sediment loads downstream along the reach in response to some time series of flood events interrupting base-flow conditions. A specific cascade of flood events is required to generate a sudden “jump” (discontinuity) in cumulative sediment discharge observed at the reach outlet. Similar threshold-driven, episodic sediment discharge pattern were also noted from reanalysis of data from the Goodwin Creek.

Concluding Remarks

(1) Learning from patterns: benefits of the approach

The UIUC synthesis project aims to improve the predictability of water cycle dynamics in a changing environment, to address considerable concerns that exist about the effects of human-induced climatic and land use-land cover changes on both water quantity and quality.

The over-riding hypothesis in our research so far is that patterns of variability exhibited in nature, as seen in observed water quantity and quality data, can give us valuable insights, to first order, into how any human-induced future changes will propagate in time (e.g., inter-annual, inter-decadal changes in variability), and in space (e.g., down-slope, down-stream, down-wind etc.). This has been the rationale for our focus on observed patterns, and the use of a top-down modeling approach to the analysis and interpretation of and learning from these patterns.

One of the defining features of “patterns” chosen for study is that they required perspectives from hydrology, ecology, geomorphology and biogeochemistry to understand, interpret and implement for predictive purposes. In this way they have been excellent vehicles to help bring about inter-disciplinary synthesis, and are of considerable value beyond hydrology, as demonstrated in our work so far.

Because the approach is based on patterns, both in time and space, there was considerable between-catchment in both projects (Themes 1 and 2) and also between-site inter-comparisons (i.e., use of Fluxnet sites in the case of Theme 1). This makes it possible to produce generalizable insights and help advance theory development, and thus represents an important advance in comparative hydrology.

The approach based on data analysis and synthesis, with interpretation through the use of models of increasing complexity within a top-down framework, has been demonstrated to be ideally suited for use within a summer institute. Provided considerable preparatory work is done beforehand, the chances of producing not only publishable outcomes, but also potential breakthroughs are enhanced.

(2) Unifying theoretical/modeling framework based on landscapes as nonlinear filters

In spite of the apparent differences between the work carried out under Themes 1 and 2, they both had significant overlap in terms of the underlying theoretical framework. They both adopted the viewpoint of the landscape, and watersheds in particular, as consisting of a set of inter-connected nonlinear filters (in series and/or in parallel) representing different parts of the hillslope-network continuum. Such a formulation has enabled an explicit focus on the transformation of the natural variability inherent in the climatic drivers and on human interferences, as water and its constituents (sediments, nutrients etc.) cascade through the landscape getting transformed along the way through various transport, storage and reaction processes. In the immediate future, we intend to complete the development of this

theoretical framework through the inclusion of sediments and sediment-laden contaminants, and then extend it further to include ecological processes and their net impact on biodiversity and sustainability.

(3) Benefits of the summer institute model for achieving hydrologic synthesis

After trying out other modes of synthesis in the past 2 years (e.g., meetings, teleconferences, partnerships with other groups), this year we tried the summer institute model, which involved the use of graduate students to carry out focused and intensive research over a 6-week intensive summer period. Of course, this did involve considerable preparation beforehand by the PIs and a set of faculty mentors drawn from our overall synthesis team. The preparatory work mainly involved a priori assembly of data, preliminary data analysis, the development of a range of models, and some tutorial work in bringing all students up to speed with the research problem, the necessary skill sets, and training with respect to the use of some models. The summer institute itself was mostly devoted to data synthesis and the implementation of models to answer specific questions, so that the work will result in concrete outcomes that can be publishable within a short time afterward in peer-reviewed journals.

Graduate students who participated in the summer institute have appreciated the opportunity to learn through such intensive hands-on research training and skills development. They appreciate the fact that they have learned not only under the guidance of several faculty mentors drawn from many different disciplines, but have benefited immensely through interacting with fellow students. Participation in the summer institute is very highly likely to remain an important milestone in their research career. It is tempting to think that the summer institute format represents an alternative form of research training, to complement the usual model of learning through disciplinary coursework at their home institutions and the one-on-one interactions with their research advisors. In particular, the summer institute model could be highly effective for producing advances in inter-disciplinary research and synthesis.

Comments on and insights into the synthesis process that was seen in action at the Vancouver summer institute by Professor Suresh Rao, one of the project leaders and faculty mentors, can be found in Appendix A. These comments can be highly valuable for future improvements for the summer institute format.

Additionally, Jennifer Wilson, the project coordinator, is currently collecting informal and anecdotal responses to the summer institute experience (from students and mentors) as well as formally documenting changes to collaboration patterns and practices within the synthesis team (via CUAHSI-developed survey instrument). New results will be presented and compared with the initial process documentation completed in 2007.

(4) Inter-disciplinary research collaborations with institutional partners

One of the insights that our research has given us so far in terms of propagation of variability (and change) through the hydrologic system has been to demonstrate the ubiquity of the interactions of

relatively fast and slow processes, and the emergence of legacy (or memory) effects resulting from these interactions. These legacy effects are extremely clear and obvious in the case of sediment transport, and may not be as obvious and yet equally important in the case of nutrients and other chemical contaminants. The interactions of fast and slow processes often manifest in overall responses that exhibit heavy-tailed behavior, and to fully understand notions of hot spots (in space) and hot moments (in time). Discovery of these insights has been a major highlight of our work at the summer institute in Vancouver.

Our on-going collaboration with the STRESS group led jointly by Efi Foufoula-Georgiou (NCED, University of Minnesota) and Rina Schumer (DRI, Reno, Nevada) enable this aspect of hydrological response to be explored further with inputs from mathematicians, statisticians, geomorphologists and earth sciences specialists (see Appendix B for details of the STRESS effort). A 2007 joint STRESS workshop held in Lake Tahoe culminated in a special issue of *Journal of Geophysical Research (Surface Processes)*, and a second joint STRESS workshop is planned for November 4-6, 2009, where we expect to give considerable emphasis to the research carried out in the summer institute in Vancouver under Theme 2.

In the meantime, the work done on the Horton Index under Theme 1 has highlighted in many ways the critical role of co-evolution of climate, soils, vegetation and topography, the governing principles of which remain relatively unexplored, and yet remain crucial for predictions of the effects of change. In order to generate improved understanding of this co-evolution, over the past 2 years we have had an ongoing partnership with Biosphere 2 located at the University of Arizona. Together with them, we have helped design parameters of a 10-year artificial hillslope experiment that will be carried under the dome at Biosphere 2. This is a one of a kind research facility that will be available to the entire community for carrying out research experiments. Through a series of meetings and inter-disciplinary modeling studies (involving hydrology, geochemistry, ecology and geomorphology) a conceptual design of the artificial hillslopes to be constructed at Biosphere 2 has been completed; the engineering design is currently well under way. This work has resulted in 3 journal articles (currently in review), and a news article that has been published in *EOS* (Huxman et al., 2008). Details of our collaboration with Biosphere 2 are presented in Appendix C at the end of this interim report.

Appendix A: From Synthesis towards Consilience

P. S. C. Rao, School of Civil Engineering, Purdue University

The overall goal of the NSF-funded projects was to achieve hydrologic synthesis to improve predictive ability under rapidly evolving stressors. Selection of mentors and graduate students brought together at the Summer Institute was predicated on the need to represent diverse disciplines and a broad range of technical skills. Two carefully chosen project themes and a series of broad questions were used to challenge the students to explore possible solutions beyond their traditional disciplinary boundaries. This collaborative effort was designed as an innovative exercise in hydrologic synthesis.

Synthesis is usually defined as a process by which two or more pre-existing “elements” are combined to generate a new “element”; here, an “element” is taken to mean a unit of knowledge. In this sense, synthesis did occur, by combining ideas from hydrology, biogeochemistry, geomorphology etc. to build new, parsimonious models that recreated the patterns observed across scales and under varying forcing conditions. But, what emerged during the six-weeks of intensive and highly productive effort was much more than synthesis. We suggest that what emerged was the first glimpses of *consilience*; i.e., the concurrence and convergence of induction drawn from synthesis of different datasets and model simulations. Consilience can be described as the synthesis of synthesis, leading to unity of knowledge.

Here I use selected examples from the collaborative research conducted under two themes at the Summer Institute to illustrate consistency in the following ideas about emerging patterns and concepts.

- Landscapes, comprising of vegetated hillslopes and converging, fractal stream networks, act as *nonlinear hierarchical dynamic filters* to modulate the random, stochastic input signals (rainfall, chemical inputs, etc.) to produce consistent and persistent emergent spatio-temporal patterns.
- Despite the evident structural heterogeneity of the hillslopes, the emergent patterns suggest “*functional homogeneity*” of responses.
- The emergent patterns noted in stream networks appeared to be the “*mirror images*” of those observed for the hillslopes. This is the manifestation of the stream networks acting as the spatio-temporal integrators of the hillslope hydrologic processes, and their responses are likely to be reciprocals of those found for the hillslopes.
- The emergent patterns may be described as “*spiraling waves*” reflecting the coupled transport and attenuation processes in the hierarchical filters, and the episodic triggering required for overcoming the thresholds. Examples include hydrographs and chemographs in response to a sequence of rainfall events, multiple wetting and solute fronts propagating through the vadose zone, and contaminated sediment transport in stream reach or the entire network.
- These spiraling waves represent the spatio-temporal *legacy* of the forcing functions cascading through the hierarchical filters, and the “*spiraling distances*” are governed by the relative magnitudes of the retarded transport and exchange rates.

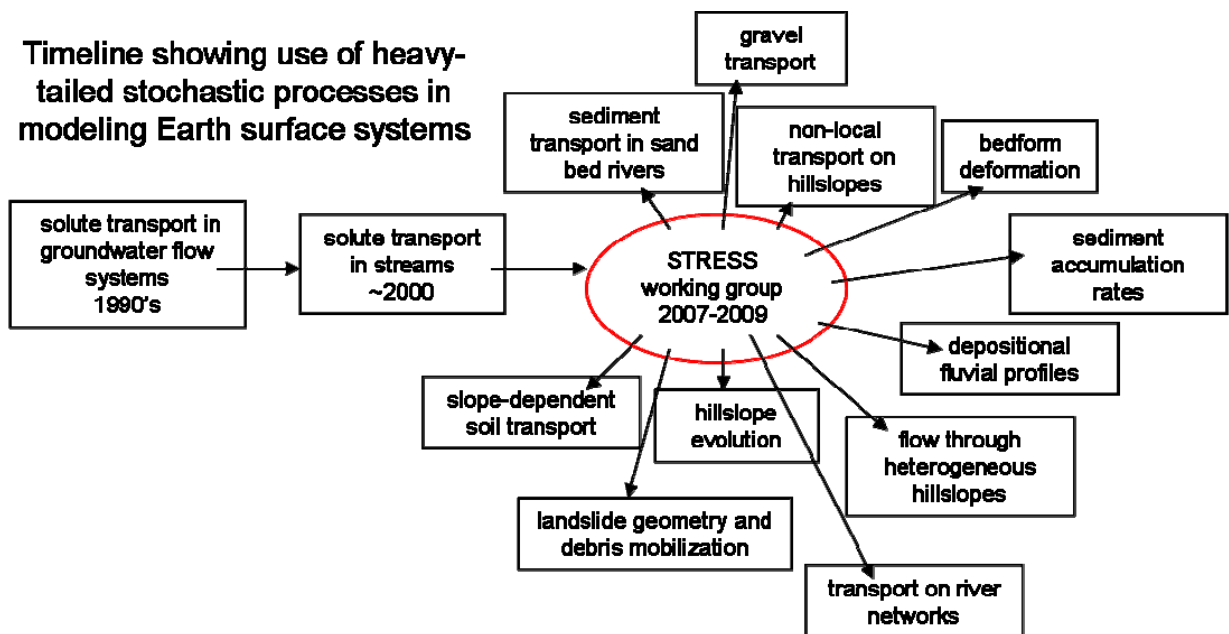
- Extreme-event outcomes arise not necessarily from extreme-event inputs, but rather from a *confluence* of the legacy events, attenuation in the filters, and crossing of some threshold.
- Spatio-temporal averaging of the filtering behavior generates patterns that converge towards a well-defined *attractor* that serves as a limiting response.

Appendix B. Stochastic Transport and Emergent Scaling at the Earth Surface (STRESS) Working Group: Example of Accelerated Learning through Synthesis (Dr Rina Schumer, Desert Research Institute, Reno, Nevada; Efi Foufoula-Georgiou, NCED, University of Minnesota))

The focus of the STRESS working group is exploration of heavy-tailed stochastic models for describing processes and transport laws that may lead to the power-laws and scaling frequently observed in Earth surface morphology. Specifically, we have begun and continue to identify

1. geomorphic and hydrologic transport laws to which existing heavy-tailed stochastic theories and fractional calculus tools can be immediately applied and
2. outstanding theory required for the development of novel scale-invariant models for Earth surface processes from the hillslope to the whole river network.

Synthesis began through sustained, intense interaction between mathematicians and scientists from a variety of environmental disciplines. Many had access to Earth surface measurement data while others had experience developing or applying novel analytical tools. During the following year, new theories and existing data were integrated to yield insight into Earth surface processes and to provide explanations of previously unquantified Earth surface patterns.



The diagram above demonstrates the way synthesis has accelerated the pace of research of Earth surface processes that are dominated by extremes in transport velocity or residence time. Although heavy-tailed stochastic processes were applied in statistical mechanics in the 1960s, 1970s and 1980s, they were not applied to environmental applications until the late 1990s. Following the use of fractals

to describe aquifer hydraulic conductivity fields, heavy tailed stochastic processes and associated fractional advection-dispersion equations were used to describe solute transport in groundwater flow systems by two research groups. The same groups extended applications to solute transport in streams a few years later. Frequent reference to seminal papers in the hydrology literature began in the mid 2000s. In contrast to the previous pace of conceptual advances, the 2007 STRESS workshop sparked the proliferation of this type of mathematical technique to explain a variety of Earth surface processes. All of the research relied upon existing data, either collected during previous PI laboratory and field research or obtained from published manuscripts.

The success of this synthesis project has received widespread attention in the hydrologic community. A second STRESS workshop will be held in November 2009. Increased interest in application of heavy tailed stochastic processes to describe landscape patterns and evolution will result in a synthesis meeting double the size of the original.

Selected scientific results

Characterizing the collective behavior of particle transport on the Earth surface is a key ingredient for describing landscape evolution. Alternatives to local, diffusive transport laws are sought because these classical models do not always capture essential features of transport on hillslopes, valleys, river channels, or river networks. A variety of field and theoretical studies suggest super-diffusive non-locality in transport of tracers at the Earth surface. For example, re-analysis of tracer studies in sand and gravel-bed streams revealed hop length distributions with heavy tails (Bradley et al. 2009). Hill et al. (2009) suggest the source of power law hop lengths in bedload transport. They present and review experimental data to justify an exponential step length for particles of a given size. Since mean step length varies with particle size, the overall step length for all particles is a mixture of those exponential distributions. Using standard models [e.g., Gamma distribution] for the pdf of grain size leads to an overall step length pdf with a heavy power law tail. Even though neither the grain size distribution nor the step length pdf for grains of a given diameter are heavy tailed, the mixture distribution turns out to have a heavy tail. This result shows that a fractional Exner equation (Ganti et al. 2009a) is applicable to bedload transport. It also highlights the need for additional experiments and analysis to improve estimates of grain size distribution, step length for moving particles, as well as entrainment rate for particles of varying size.

Stark et al.(2009) use a fractionally integrated flux term to capture non-local effects in a model of bedrock channel evolution that includes the effect of hillslope sediment production on channel bed sediment buffering and bedrock erosion. Foufoula-Georgiou et al. (2009) argue that transport on hillslopes is non-local and that sediment flux must be calculated using not just the local gradient, but also that of upslope topography. Tucker and Bradley (2009) describe how this non-locality may be represented in particle-based hillslope models .

Stochastic models that incorporate non-local effects in time can reproduce power-law residence times and loss to immobile zones that arise because tracer particles spend more time at rest than in motion at the Earth surface. Evidence for heavy-tailed waiting times in transport is captured in the depositional

record through the frequent observation of power-law decay in sediment accumulation rates with measurement interval (Schumer and Jerolmack 2009). Ganti et al. (2009b) use a novel non-local model to improve description of sediment transport in laboratory flumes while Harman et al. (2009) use temporal non-locality to reproduce relevant features of anomalous flow through hillslopes.

Appendix C: The Hills Are Alive: Earth Science in a Controlled Environment

(Peter Troch, Paul Brooks, Travis Huxman, Jon Chorover, Jon Pelletier, University of Arizona)

The structure of Earth's critical zone, which is the interface between the solid Earth and its fluid envelopes and involves the co-evolution of biota, soils, and landforms, is governed by processes important to hydrology, geology, biology, and atmospheric science. Earth surface scientists have long recognized that temperature, chemical, and gravitational gradients drive energy and water fluxes, thus controlling systems evolution, but understanding the critical zone have been tackled primarily from disciplinary perspectives. Interdisciplinary research is needed, and many such efforts, such as the U.S. National Science Foundation's recent watershed-scale Critical Zone Observatories and the National Ecological Observatory Network, are in formative stages. By and large, these facilities focus on utilizing land surface complexity to elucidate process knowledge. Unfortunately, incorporating such complexity occurs at the expense of the control that characterizes true experimentation.

At the University of Arizona, a science program is being built to bridge the gap between laboratory- and field-scale studies by utilizing the unique infrastructure of the Biosphere 2 project. Biosphere 2 is a large-scale Earth science facility near Tucson that encompasses about 3.15 acres of land and houses five natural biomes. Sealed off to the outside world, Biosphere 2 allows scientists to exert precise climate and mass balance control at large scales. The facility's name stems from the Earth's biosphere (biosphere 1); the goal of Biosphere 2 is to be a microcosm of the interaction between life and landscape seen on Earth, such that critical zone interactions can be studied at large spatial scales.

B2 EARTHSCIENCE



To facilitate this study, scientists from the University of Arizona will construct experimental landscape units—hillslopes—within Biosphere 2. They will also build corresponding system models that couple critical zone hydrology, geochemistry, geomorphology, and biology. This program and facility provides a new opportunity to advance understanding of critical zone processes through controlled large-scale experimentation.

Scientists working on this project are specifically pursuing an interdisciplinary approach to experimental design through cultivating a collaborative group that includes representation from hydrology, geomorphology, soil geochemistry, atmospheric science, ecology, and genomics. Several planning workshops have already occurred (jointly supported by the Hydrological Synthesis Center; <http://cwaces.geog.uiuc.edu/synthesis/index.html>), and others are scheduled for the near future. A key focus to date has been on understanding spatial variability, temporal dynamics, and interactions (including abiotic-biotic couplings) within hillslopes using modeling assessments.

Three 33-meter × 18-meter environmentally controlled bays will be available to scientists who would like to propose projects for experimentation. The long-term goal is to improve our understanding of the processes that lead to surface and subsurface structure of the critical zone. Workshops have guided design parameters, such as hillslope geometry (slope angle, planar or complex shape), soil composition (mineral assemblage and texture), vegetation type (herbaceous, woody plants), and key details of climate forcing. Focused numerical modeling was also used to inform decision making on design parameters. For example, groups from the University of Arizona, Oregon State University, University of Québec, University of Illinois at Urbana-Champaign, University of California, Riverside, and University of Michigan worked together to investigate hydrological partitioning and chemical weathering rates for different mineral assemblages, surface areas, hillslope configurations, and climate regimes. Hydrological models were used to estimate subsurface saturation and water residence time as a function of soil and geometry.

To relate the project to other existing research infrastructure, scientists sought a design that offered the greatest spatial and temporal soil moisture variability in a climate that contains wet-dry transitions in both warm and cool seasons. These criteria were met with a loamy sand soil distributed within a basin shape that does not vary with time. This basin will be 30 meters long and 12 meters wide with soil 1.0 meter deep (*Hopp et al.*, 2009). The soil will be constructed from granular basalt with loamy sand hydraulic properties, but with sufficient small (clay) particle fraction to enhance chemical weathering and water-holding capacity. The average bedrock slope will be of the order of 8°–12° to enable subsurface throughflow but minimize overland flow and erosion. Soil erosion modeling indicated that these characteristics also will minimize effects of surface runoff on soil loss and rill formation. Detailed hydrogeochemical modeling predicted that within 3 years of treatment, the basalt parent material will develop significant changes in subsurface structure, including pore size and particle size distributions that could potentially affect hydrologic flow paths (*Dontsova et al.*, 2009). Accelerated structural evolution is expected following introduction of vascular plants.

A main goal of the experiments conducted on these hills will be to address effectively the topics that integrate physical and biological processes. These include (1) understanding how the environment in general and the water cycle in particular affect assembly of biological communities; (2) determining whether simple versus diverse communities arise as a consequence of differing climate regimes; and (3) assessing if different communities affect ecosystem function (e.g., the cycling of water through ecosystems) differently. A classic example of these problems in ecosystem ecology is the “two-layer” vegetation community in which shallow-rooted herbaceous plants stably coexist with more deeply rooted woody plants. By accessing different resource pools, this functionally diverse community is both ecologically robust and hydrologically important, using the water resource much more effectively than the simpler single-layer community.

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