Watershed Hydrology & Biogeosciences

From the Field to Forecasts

Observing, interpreting, and quantifying emergent catchment hydrology behavior

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Watershed Sciences at Montana State University

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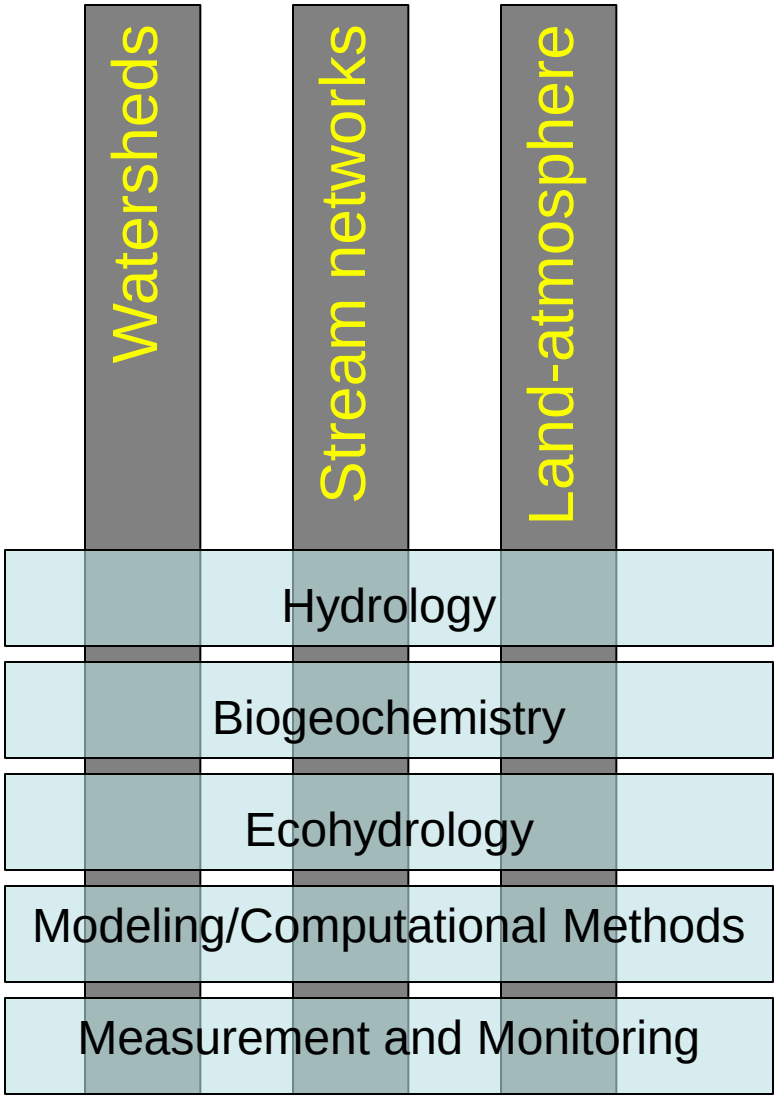
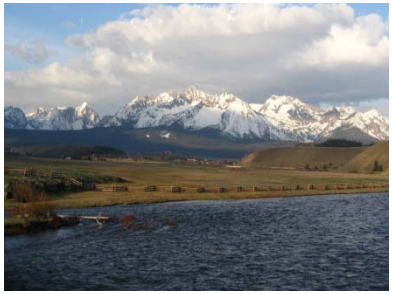


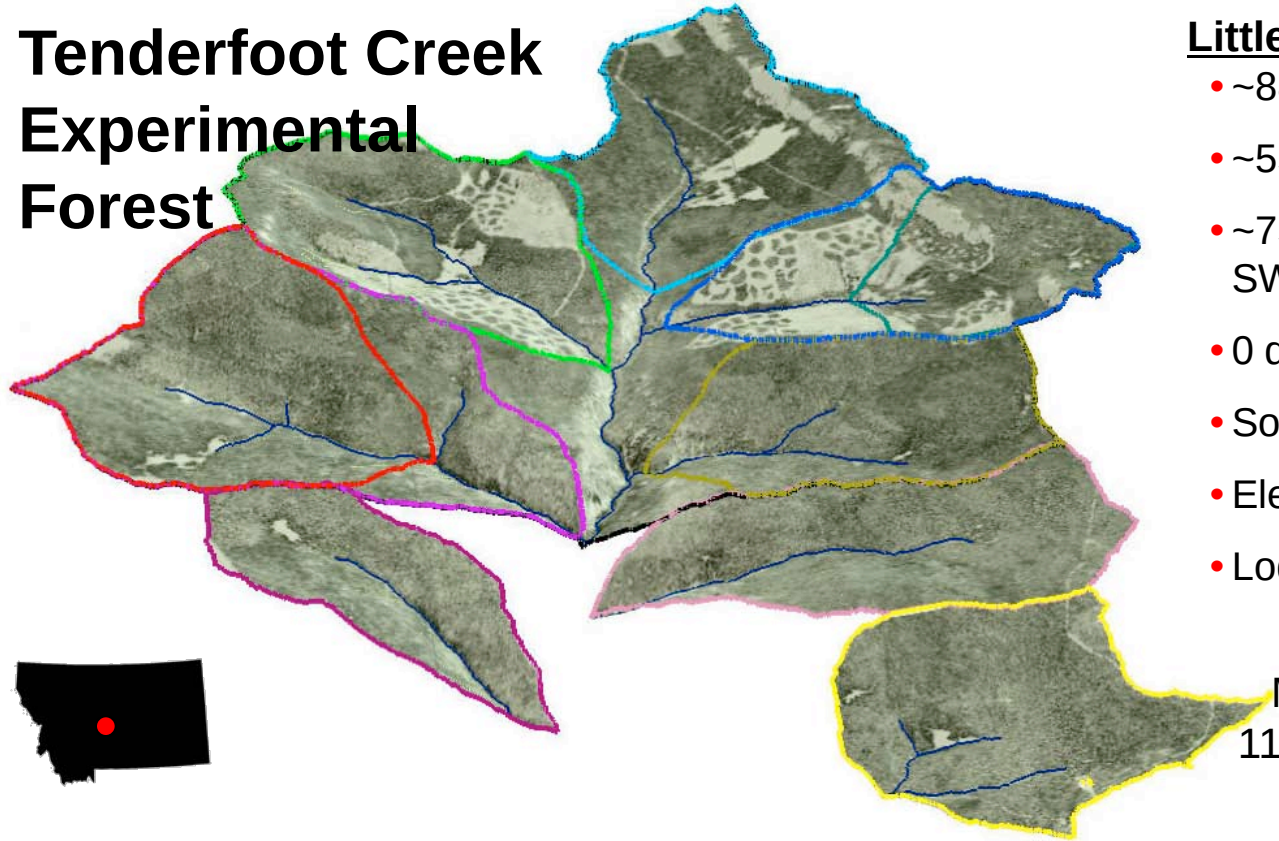


Research Questions

Observing and conceptualizing watershed processes

1. What is the role of landscape structure (shape) in headwater catchment hydrologic response and source water contributions?
2. Can we develop new quantifications (models) of watershed behavior based on hypotheses about the role of landscape structure in watershed response?
3. How do field observations help infer specific model structures and parameters, and constrain predictive uncertainty?

Tenderfoot Creek Experimental Forest

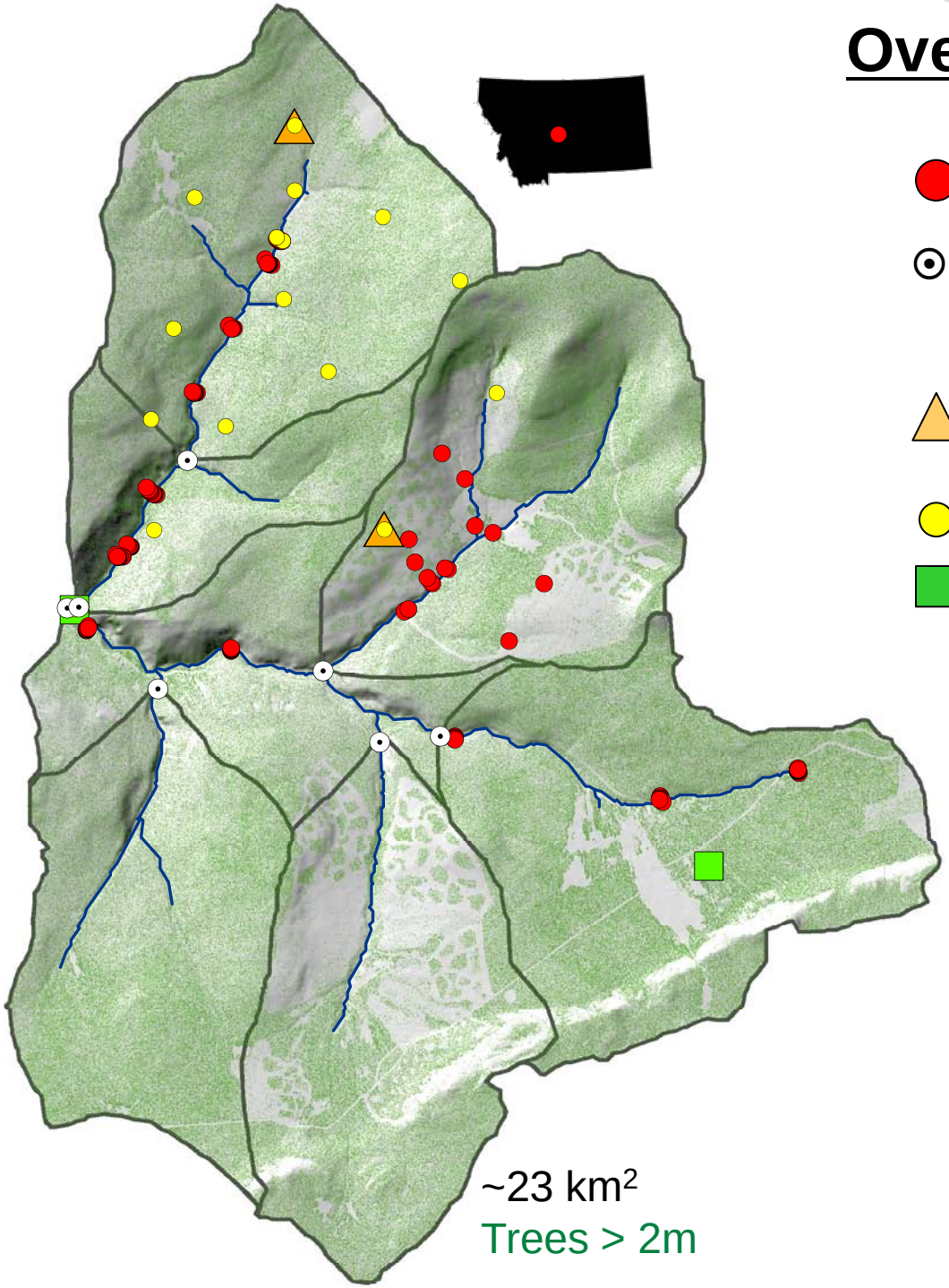


Little Belt Mountains, Montana

- ~880 mm precipitation
- ~550 mm evapotranspiration [ET]
- ~75% as snow and 500-600 mm SWE
- 0 degrees C average temperature
- Soil depths 1-2 meters
- Elevation range ~500m from 2300m
- Lodgepole pine forest

Map area ~ 32 km^2
11 gauged watersheds

Overview of instrumentation



162 recording GW wells along 29 transects (12 with specific conductance SC)

11 gauged catchments - flumes with real time specific conductance (SC), temperature, and stage

3 H_2O/CO_2 eddy-covariance towers w/ full energy budget instrumentation

15 snowmelt lysimeters / courses

2 SNOTEL sites

Frequent stream and GW sampling with a focus on solutes, ^{18}O, D, SC, N, and DOC

LiDAR 1m topography and veg data

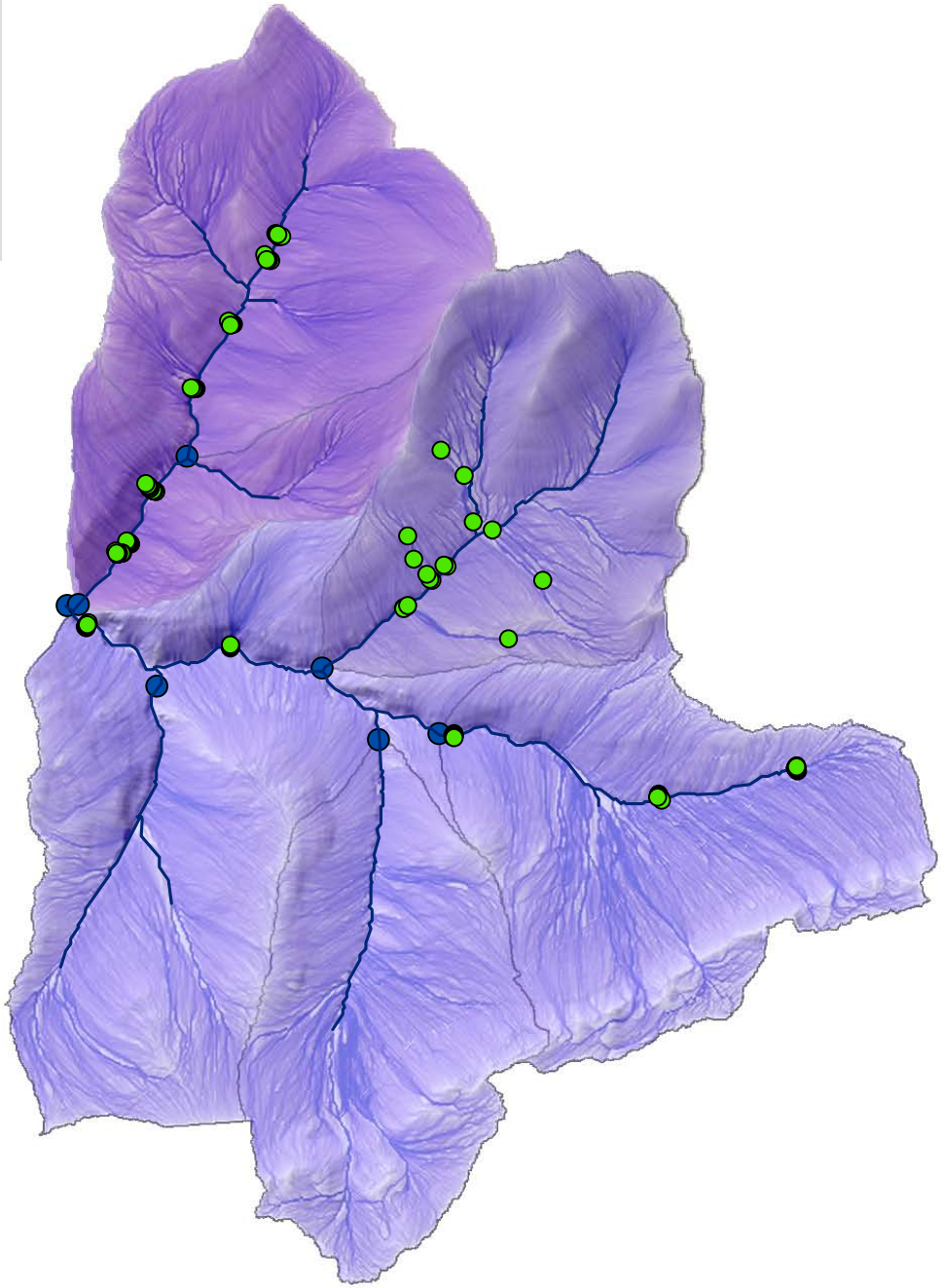
Repeat QUICKBIRD remote sensing

13 water content probe nests across riparian hillslope transitions

>8 rain gauges

600 m^2 plot w/ intense water content (64 TDR probes) soil and snow temperature (80)

63 soil CO_2 and soil CO_2 efflux sampling locations with 3 depth co-located soil gas wells, WC, temp, etc



156 shallow GW wells across 29 transects and 7 watersheds

Topographically-driven lateral redistribution of water

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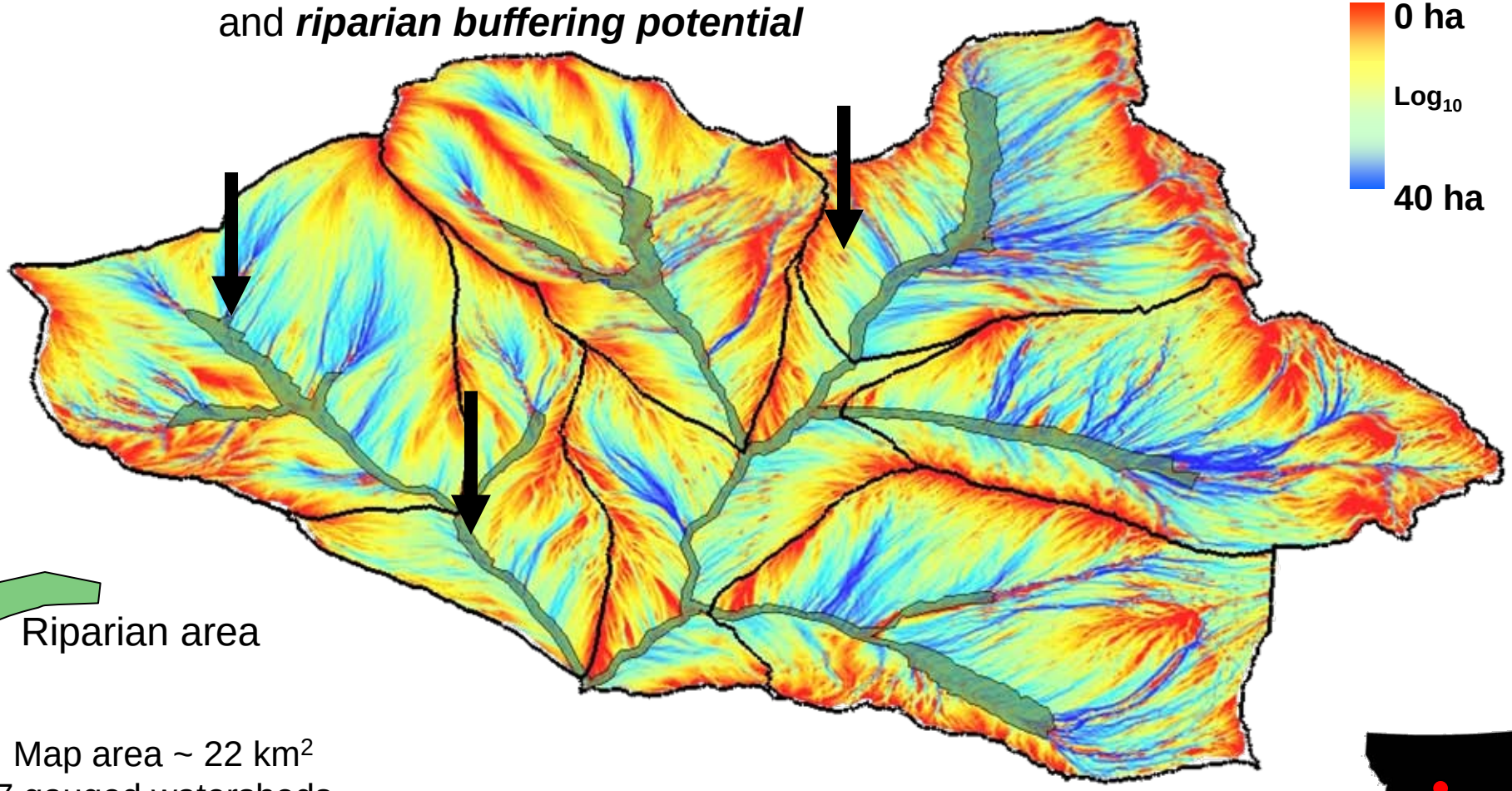
3 of 24 experimental transect locations for examining ***hillslope-riparian-stream hydrologic connectivity*** and ***riparian buffering potential***



Riparian area

Map area ~ 22 km^2
7 gauged watersheds

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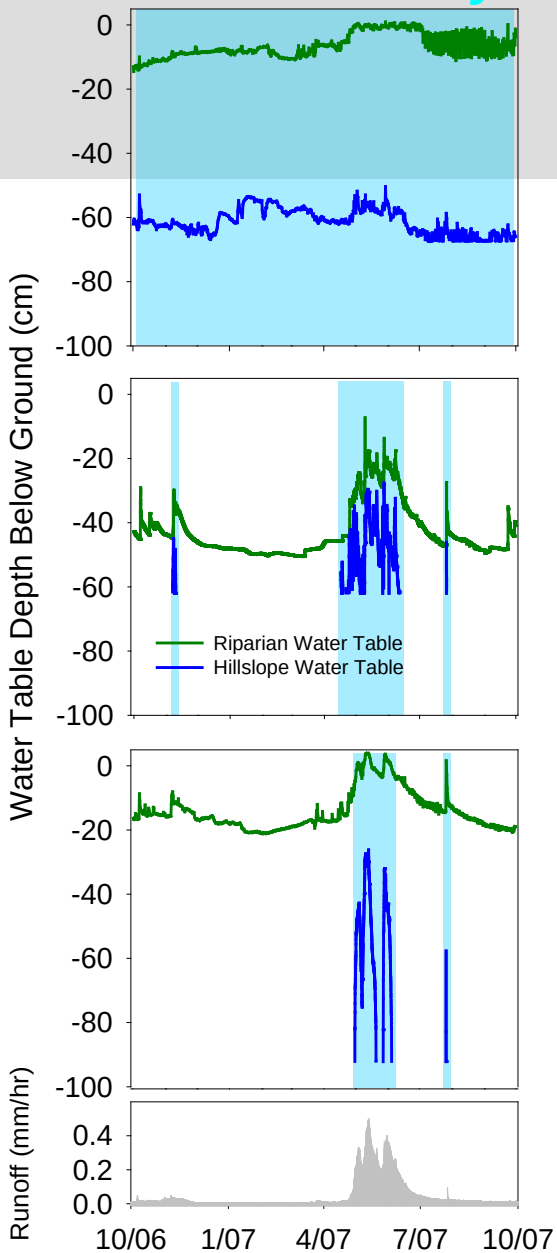
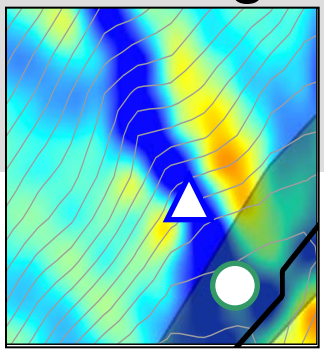
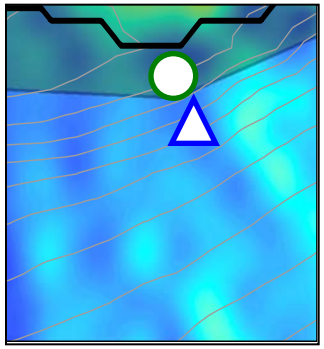
Connectivity

Setting

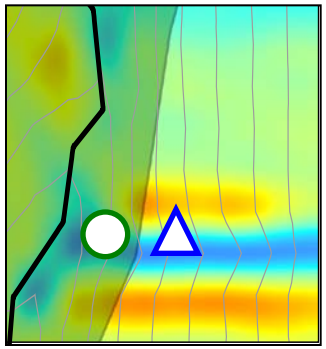




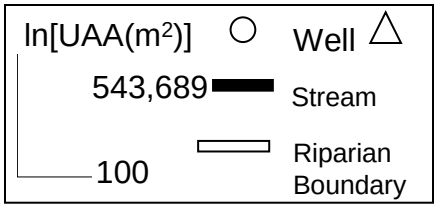
UAA 45,000 m^2



UAA 20,000 m2



UAA 9,000 m^2



Binary measure of hydrologic connectivity

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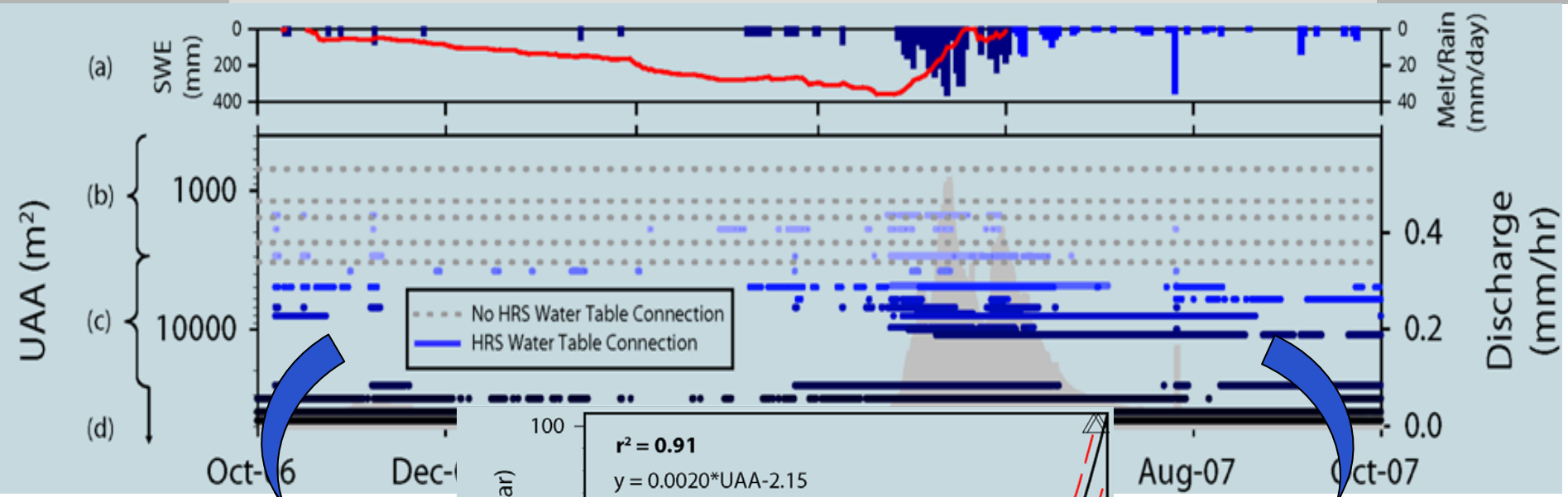

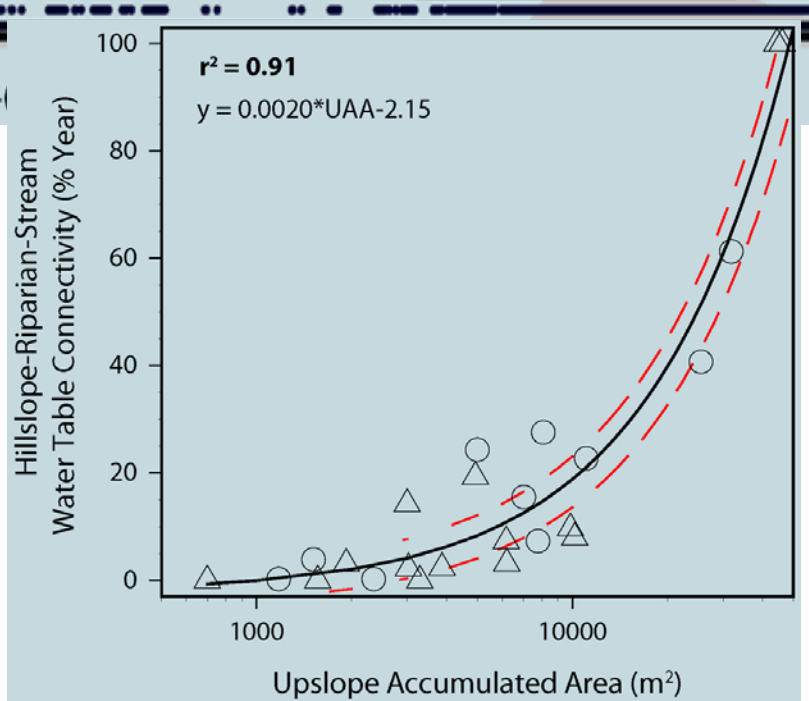

How does upland connectivity relate to streamflow magnitude?

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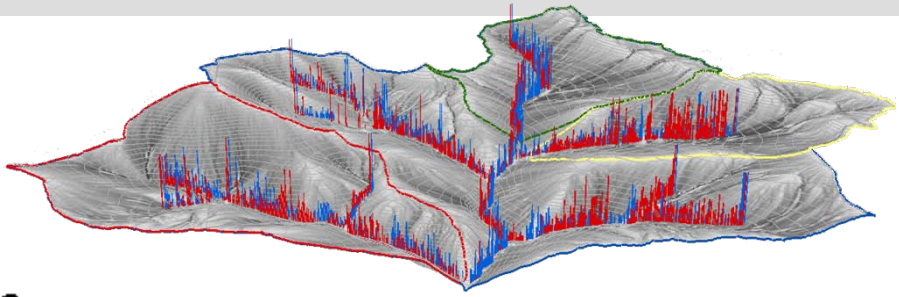
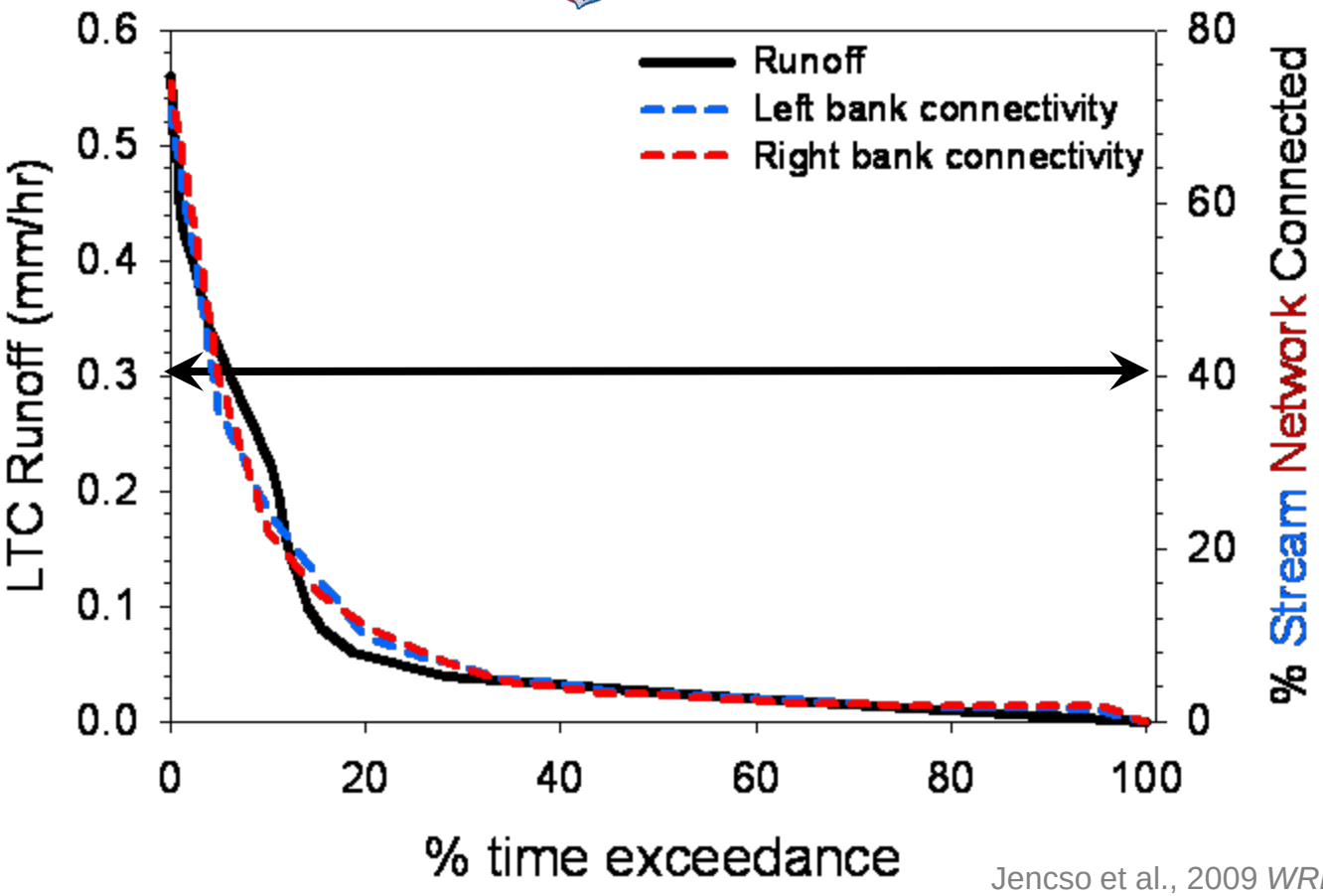




> 0.3 mm runoff
> 40 % network connected
< 5 % of the year (~18 days)

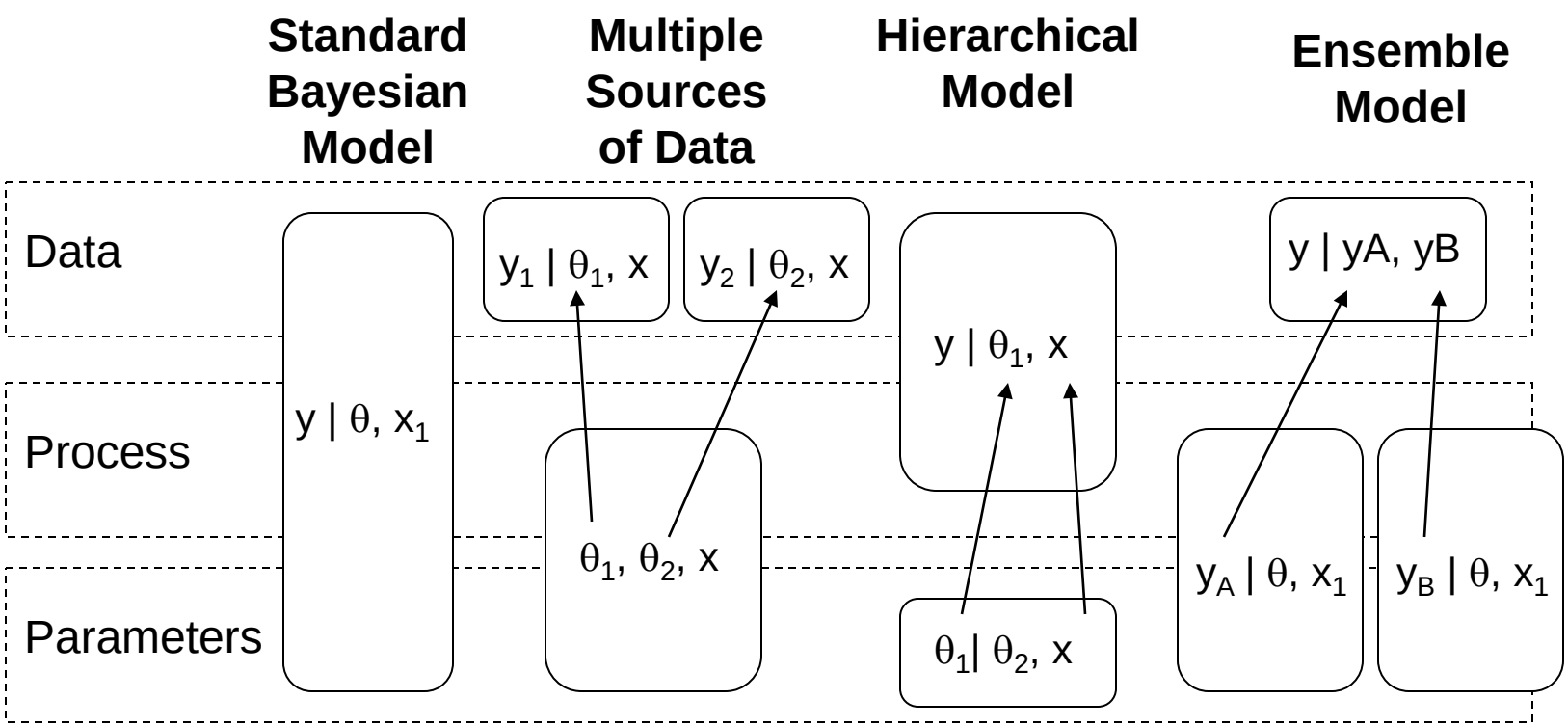
Jencso et al., 2009 *WRR*

Hydrologic connectivity summary

- Topographically driven lateral redistribution of water drives transient upland-stream connectivity and runoff generation

- It is the frequency of connections that controls watershed discharge rather than the magnitude at the connections

An uncertainty framework – ways of modeling hydrologic complexity



y ~ variable of interest
x ~ input data, climatological variables
θ ~ parameters

Adapted after Clark, Ecology Letters, 2005.

Hydrologic model assessment

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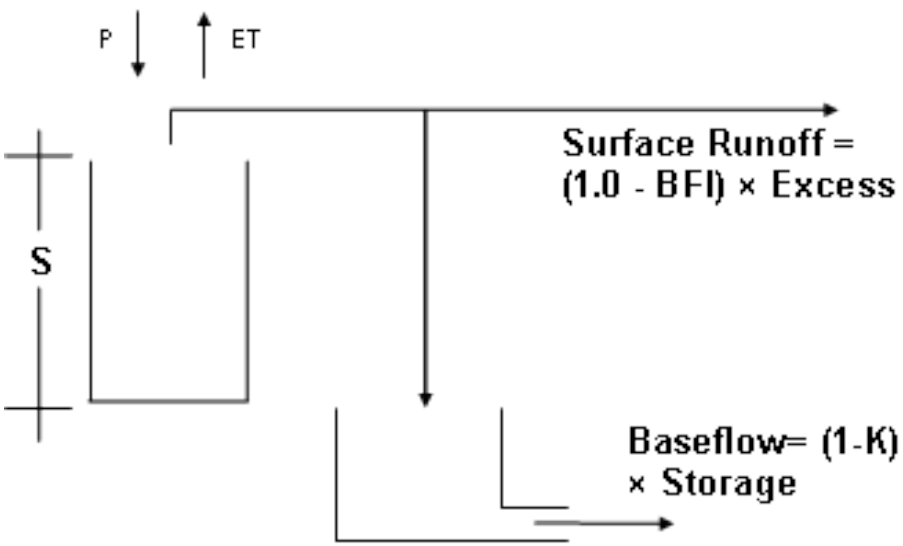
- Structural
- Parameter

- Complexity v. Efficiency
- Streamflow Fit
  - Calibration Period
  - Validation Period

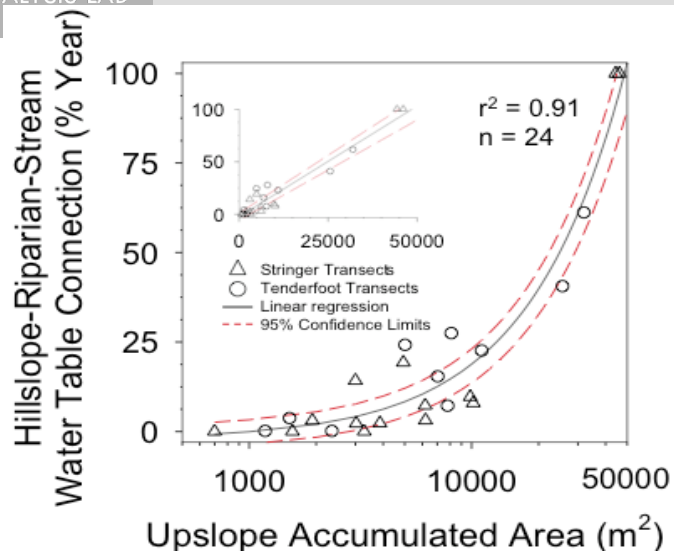
- SWE Simulation Consistency

How could a basic conceptual model be “realistic”?



- Simple daily conceptual model
- 3 parameters
- Water budget based
- Are the parameters physically interpretable?
- If not- how is this model useful over pure empirical models?

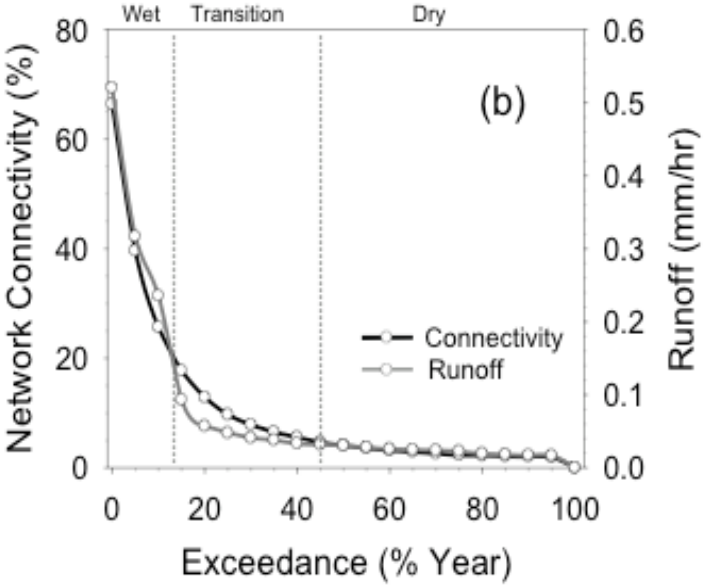
How can we improve our model structural uncertainty?



We observe strong correlations between watershed form (UAA) and function (connectivity)

Jencso et al., 2009

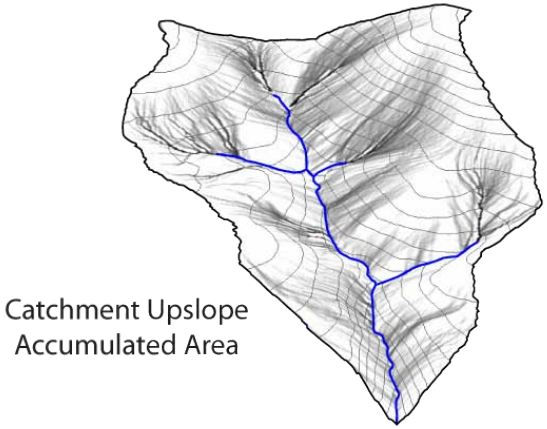
Hydrologic connectivity may be a good predictor of watershed runoff

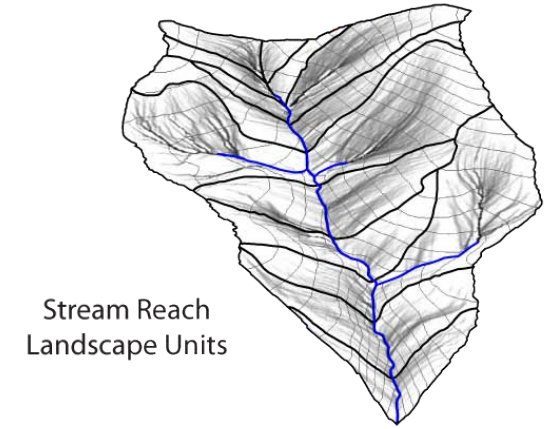


How it works…

1. Watershed is semi-distributed into landscape units (LU) based on UAA

- chose 50 LU's to balance resolution with computational demand (model is essentially applied 50 times per time step)
- note that the LU's membership is *not* contiguous (despite this figure – members can come from any location within watershed)

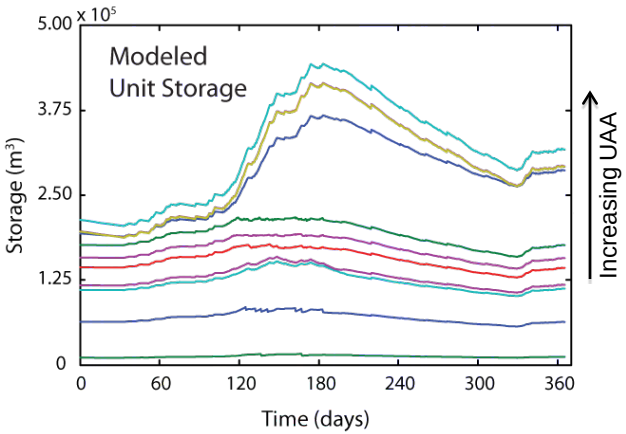




How it works…

2. LU's are treated as individual, mini "watersheds" within the model structure

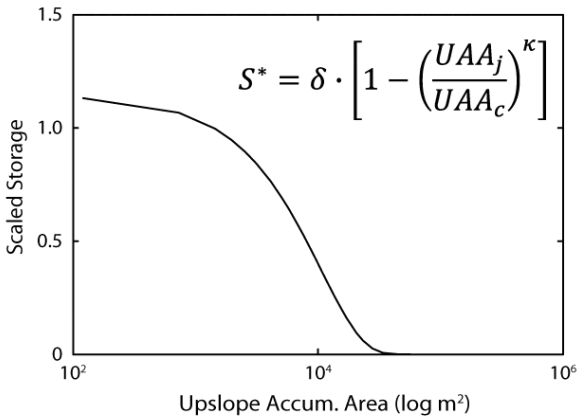
- each LU has a modeled storage, outflow, connectivity duration, etc.

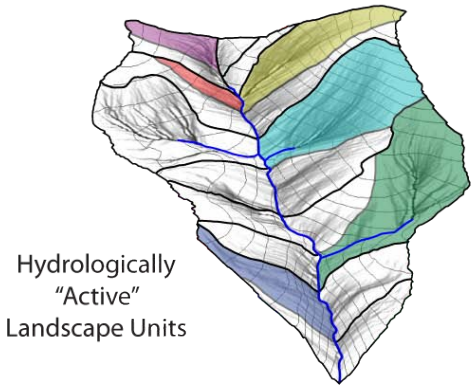


How it works…

3. LU's interact with each other based on a "switching" function

- enforces logic from empirical results
- larger UAA's connected most of the year and smaller UAA's becoming connected during wet-ups
- forces a sequential switching where an LU with a smaller UAA size can only become "*hydrologically active*" if the LU one size larger is also active during that time step

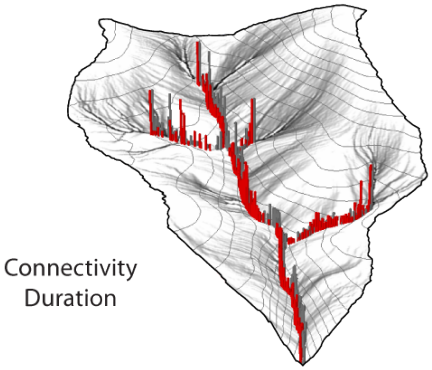


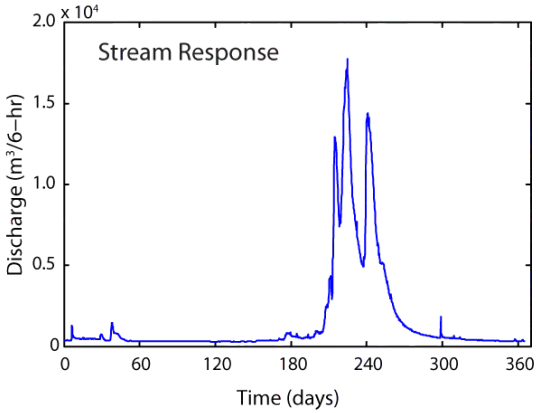


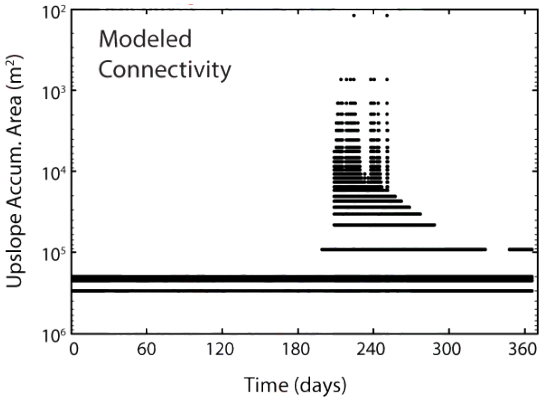
How it works…

4. Sum of outflows from each LU equal the total outflow at the watershed outlet

- each LU has the same outflow rate during hydrologic connection
- duration/frequency of connections drives total outflow volume
- larger UAA LU's are connected a greater % of the year and thus contribute more of the total volume of water





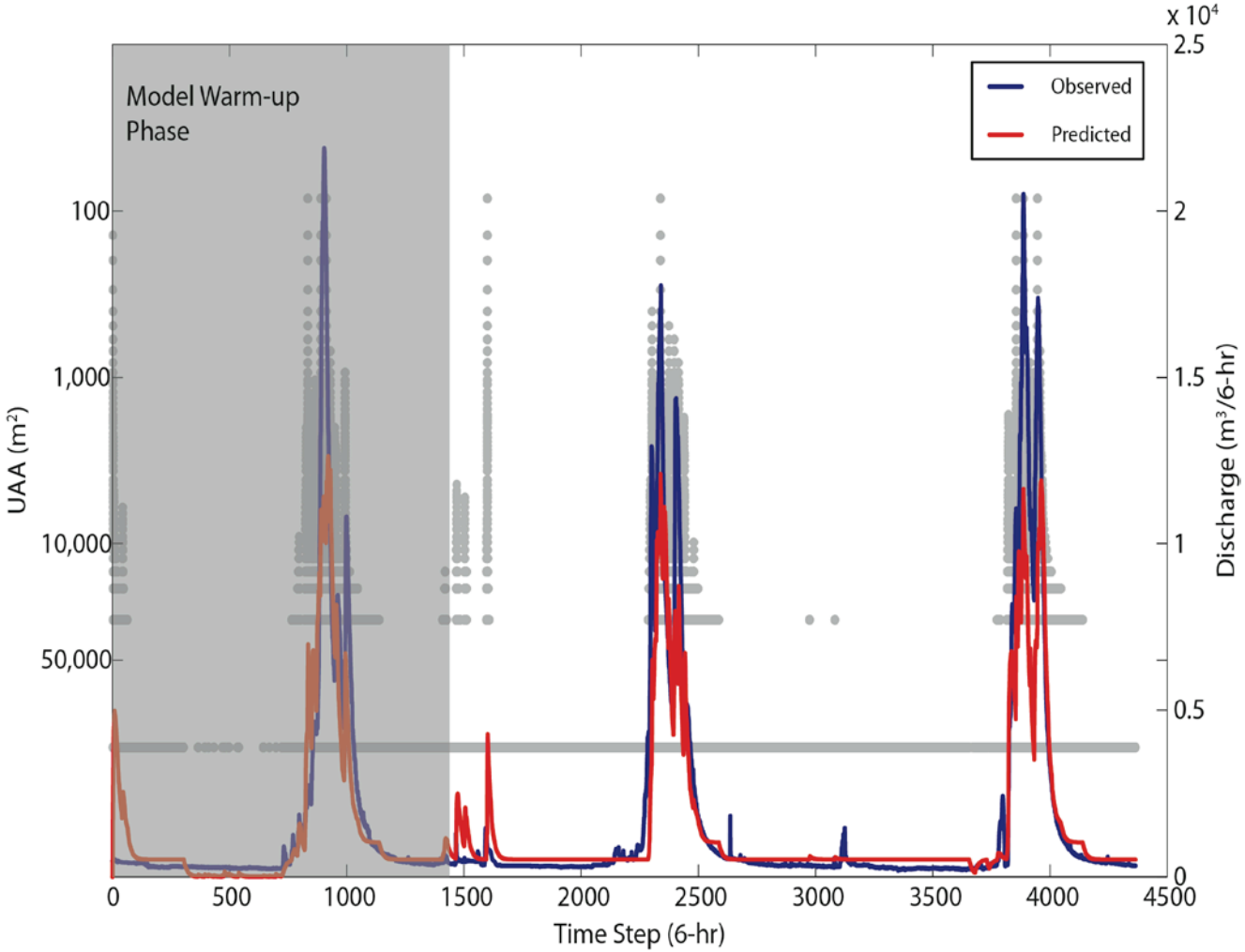


Implementation…

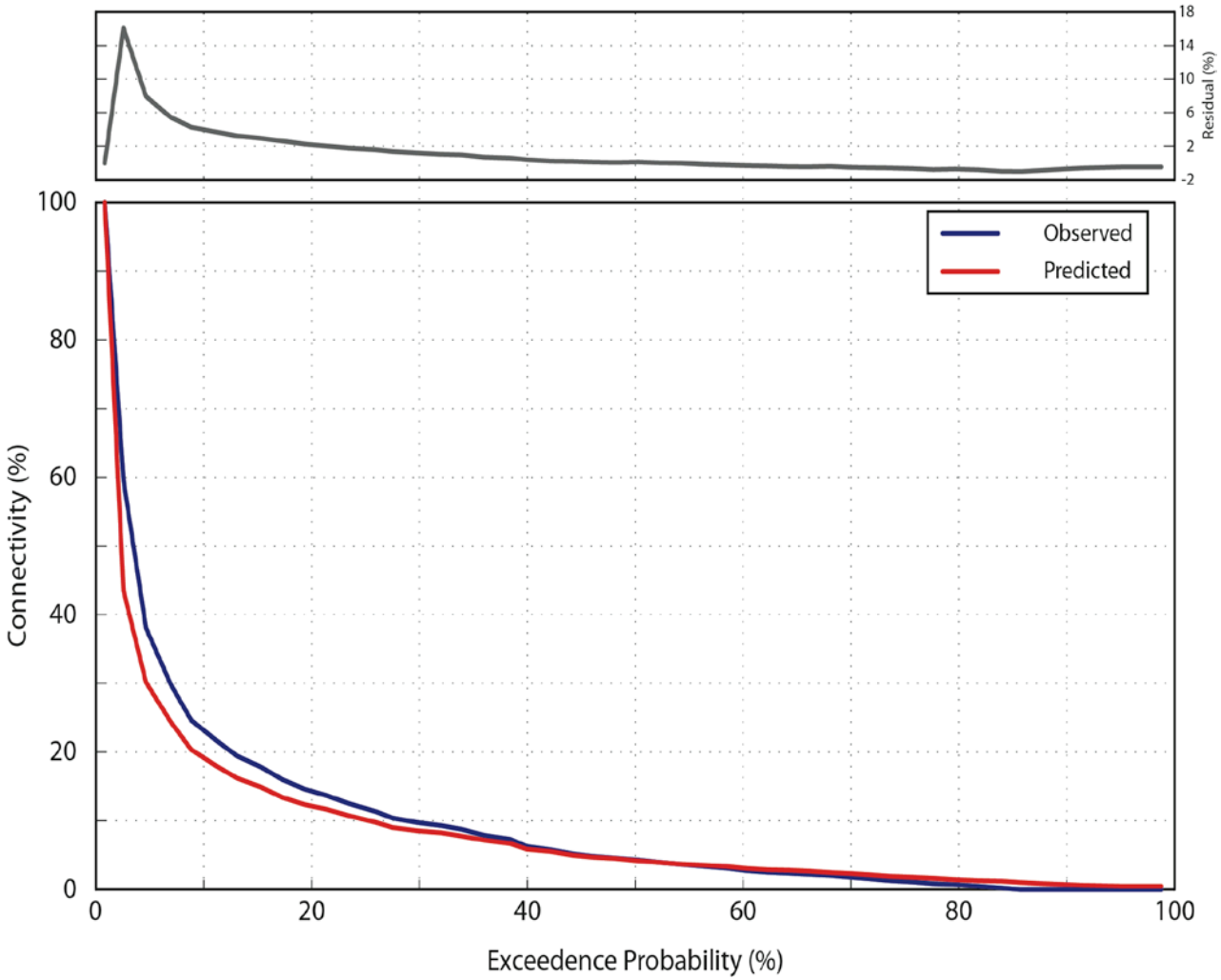
- Calibrate model parameters to observed streamflow via Bayesian statistical approach
- only six calibrated (model) parameters despite having 50 LU's

Parameter	Description
q^*	rate of discharge from each landscape unit
τ_r	residence time parameter (exponential filter)
δ	scaling parameter for watershed storage
κ	parameter describing the shape of the UAA-connectivity relationship
UAA_c	value of UAA above which continuous connectivity occurs
ET_x	evapotranspiration scaling factor
σ^2	the variance parameter of the likelihood function used in model calibration

Results…


Model Warm-up Phase
Observed
Predicted
UAA (m²)
100
1,000
10,000
50,000
x 10⁴
2.5
2
1.5
1
0.5
0
Discharge (m³/6-hr)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Time Step (6-hr)

Results…



- Strong predictive power
- Corroboration with internal observations
- "Stream-centric" perspective
- Limits in applicability?

Linking field observations, data management and models

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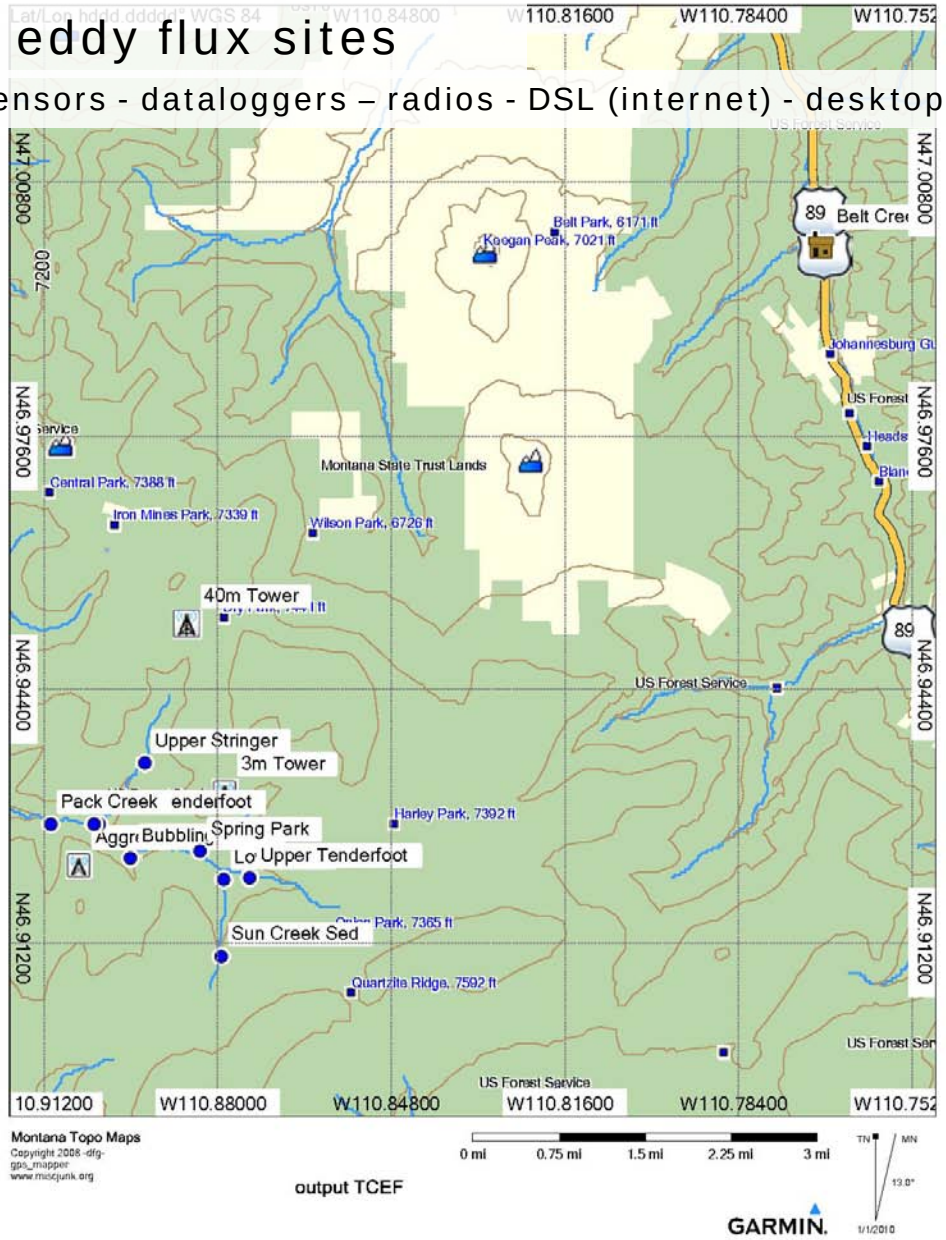
- The **CUAHSI Hydrologic Information System (CUAHSI-HIS)** provides web services, tools, standards and procedures that enhance access to more and better data for hydrologic analysis.

CUAHSI HIS
Sharing hydrologic data

- At MSU, we are harnessing the CUAHSI-HIS toolkit to help manage data from the field, to centralized data bases, (VOEIS) to hydrologic forecasts.

11 stream flow sites
2 eddy flux sites

Sensors - dataloggers – radios - DSL (internet) - desktop PC –VOEIS database



W110.89500
W110.88000
7600
40m Tower
US Forest Ser
Upper Stringer
N46.93500
Passionate Creek
6400
Pack Creek
Lower Tenderfoot
Spring Park
Aggregation
Bubbling Creek
Lower Upper Tenderfoot
7200
US Forest Service
Sun Creek Sed
Quartzite
W110.86500
0 mi
0.35 mi
0.7 mi
1.05 mi
1.4 mi
40m to Agg relay
GARMIN.

VOEIS

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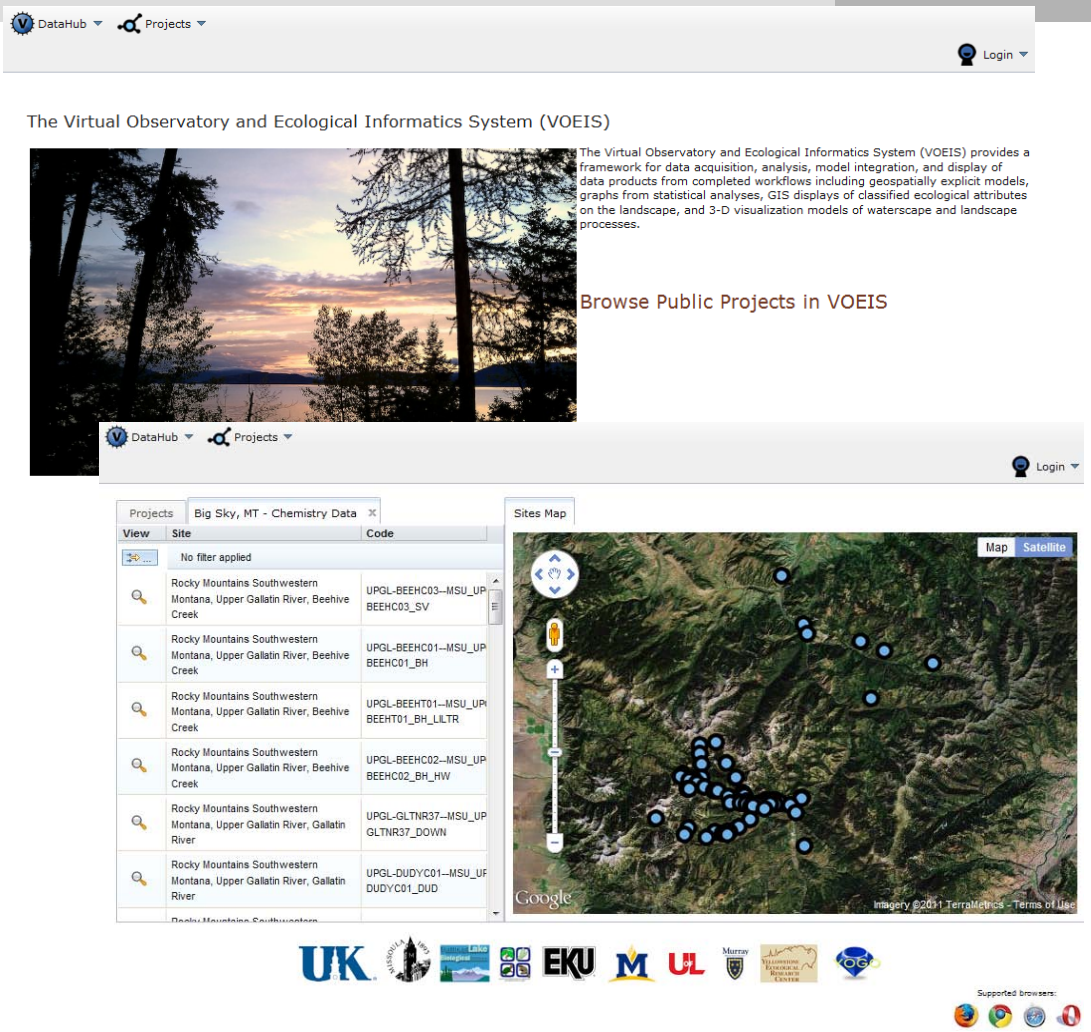
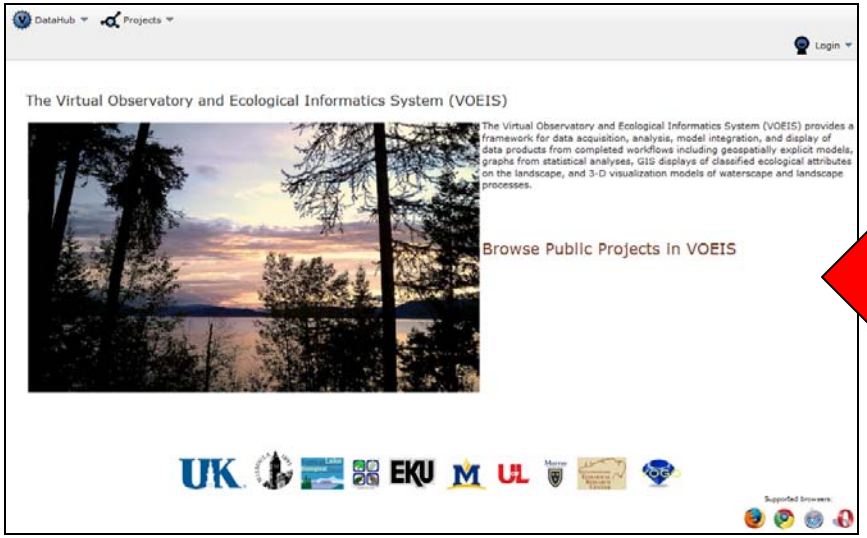
VOEIS: Virtual Observatory and Ecological Informatics System

- Integrated sensor and ecological informatics
- NSF EPSCOR Track 2*
- https://voeis.msu.montana.edu

*NSF Montana EPSCoR American Recovery and Reinvestment Act program with grant award M66012/66013



VOEIS-HIS gateway



CUAHSI HIS
Sharing hydrologic data

Conclusions and further work

Conclusions

- Synthesis of field observations show that topographically driven lateral redistribution of water drives transient upland-stream connectivity and runoff generation
- New modeling approaches based on these findings require little extra data, and are more consistent with field observations
- By linking field sensors, local databases, and hydrologic models (input and output) we may better manage and publish our hydrologic information ‘from the field to forecasts’
- *Current and Future Work*
  - The effect of vegetation and landscape topology on elements of the watershed water balance and runoff
  - The utility of hydrologic connectivity concepts across multiple watersheds and multiple years

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