PENNSTATE

1855

A collaborative approach to developing models for catchment-lake dynamics

Christopher Duffy, Penn State University
Gopal Bhatt, Penn State University
Lele Shu, Penn State University

National CZO Program

CSDMS
COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

CUAHSI HIS
Sharing hydrologic data

NSF

Workshop Outline

1. Overview of catchment modeling process

2. Accessing geospatial data from national data products

3. The model-data workflow

4. Research Opportunities in lake-catchment modeling

- Strategies for a fully coupled lake-catchment model
- Defining an experimental "Isoscape" for water and carbon
- The age of water and carbon in lake-catchment systems

6. Discussion

Essential Data
For Water Catchment Modeling

Consistent and accessible continental-scale geospatial data is a requirement for resolving the water cycle at scales relevant to national problems

Critical for detection and attribution of change for climate, landuse and ecosystem services for uncertainty assessment, decision making and policy

2,268 USGS
HUC 8
watersheds

The Catchment - River Basin

A Basis For Model-Data Collaboration

103,444 USGS
HUC 12
watersheds

ETV: Essential Terrestrial Variables

What they are and,
Why they are important?

Essential Terrestrial Variables: A Proposal

- Atmospheric Forcing (precipitation, snow cover, wind, relative humidity, temperature, net radiation, albedo, photosynthestic atmospheric radiation)
- Digital elevation models (30, 10, 3, 1m resolution)
- River/Stream discharge, stage, cross-section
- Soil (texture, C/N, organic, hydrologic & thermal properties)
- Groundwater (levels, extent, hydrogeologic properties, 3D Architecture)
- Land Cover (biomass/leaf area index, phenology,…….)
- Land Use (human infrastructure, demography, ecosystem disturbance, property & political boundaries)
- Environmental Tracers- stable isotopes
- Water Use and Water Transfers
- Lake/Reservoir/Diversion (levels, extent, discharge, operating rules)
- …to be cont'd……..??

Most data reside on federal and state servers ….many petabytes

An Initial ETV Data Bundle for CONUS

Category	Variables	Nat. Products	Reference	Size/Resolution
Atmospheric Forcing	precipitation, snow cover wind speed/direction relative humidity temperature atmospheric radiation albedo photosynthetic radiation	NLDAS II, NAAR	Bailey, 2004 NARR, 2011	8km, hourly, 5 TB per year
Digital Terrain	DEM, DTM, Lidar	NHD+	NHD, 2013	30m, 10TB
River/Stream	Discharge, stage	USGS Gauging	USGS, 2011	100 GB
Soil	class, hydrologic properties	SSURGO STATSGO	SSURGO, 2011 STATSGO, 2011	1 TB
Groundwater	Hydrogeological formations Hydrogeological properties Water Levels		NHD, 2011 ** USGS, 2013	
Surface Water Bodies	Lake/Reservoir Geometry Operating Rules Volume/Area/Level	USGS US COE US Bur Rec	USGS, 2013 NHD, 2013	
Land Cover	Leaf area index human infrastructure surface roughness	NLCD, MODIS	MODIS, 2011, NLDAS, 2011	30m, 5TB
Water Use	Wells diversions municipal supply storm flow/sewer networks irrigation drainage	USGS	USGS, 2013 NHD, 2013** ** ** ** **	
				Approximately 185 TB

HydroTerre: A Prototype for Data Access

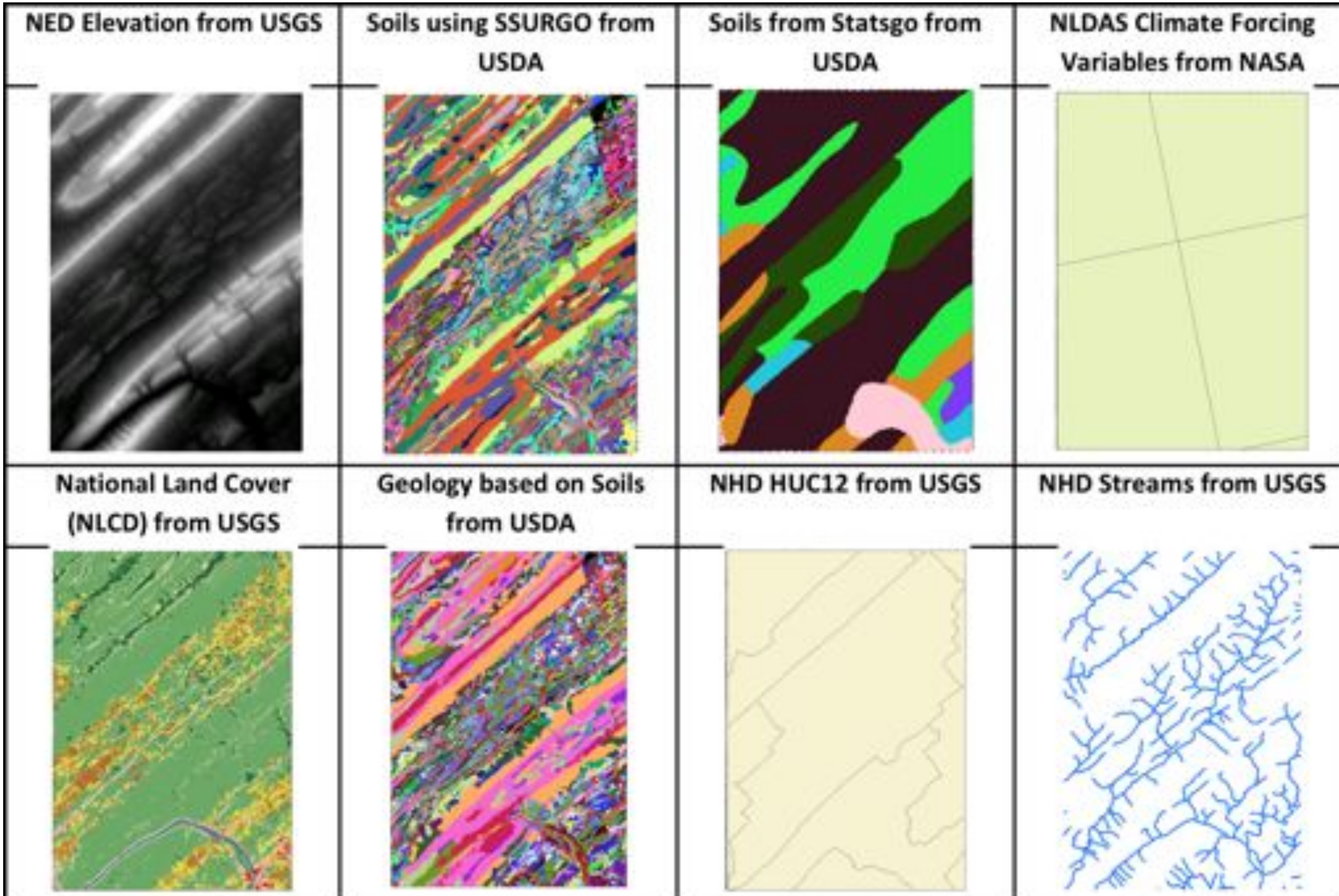


Figure 1: HydroTerre Essential Terrestrial Variables data and data sources

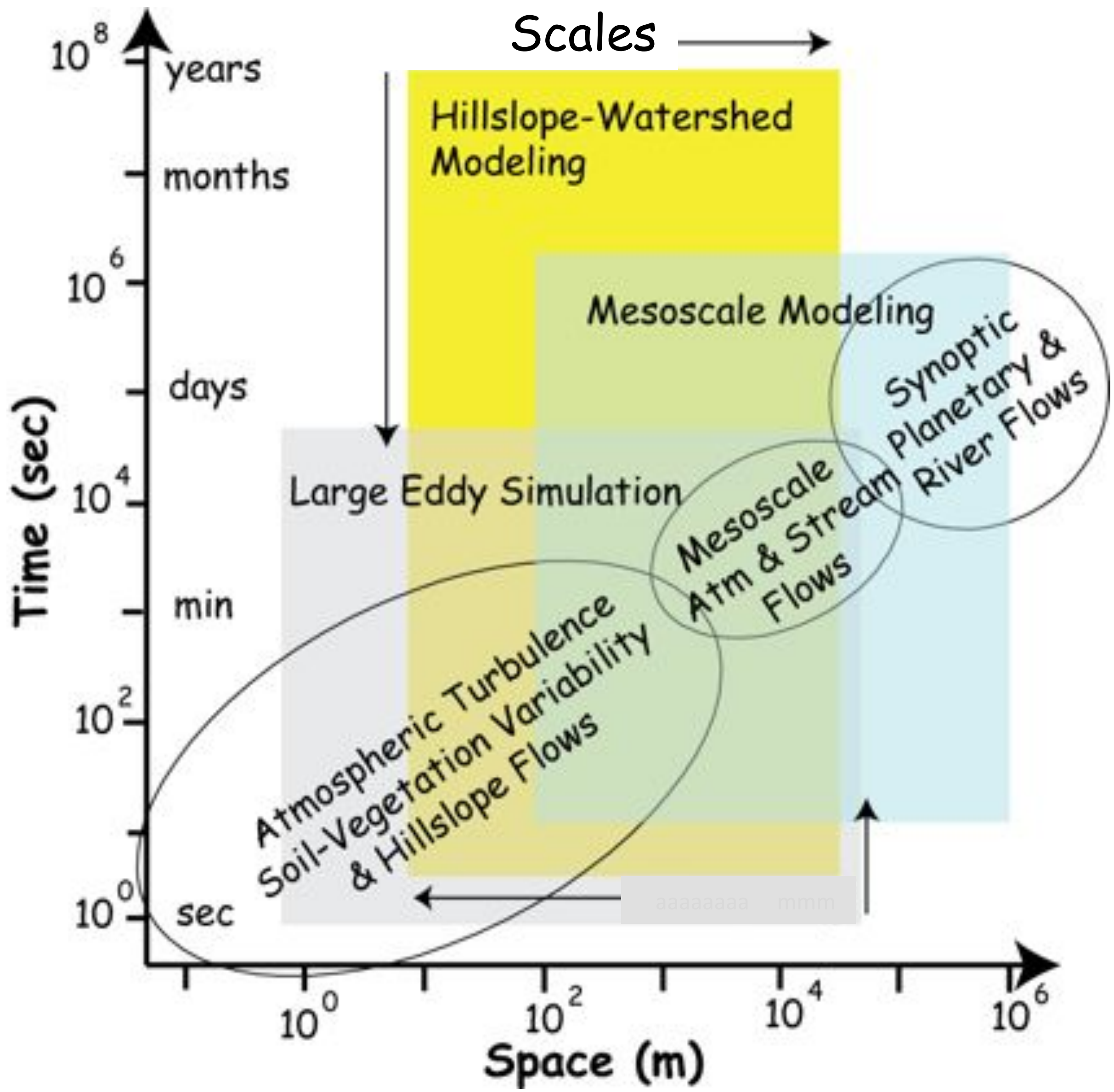
www.HydroTerre.psu.edu: Interface

HydroTerre: A Prototype for Model-Data Access

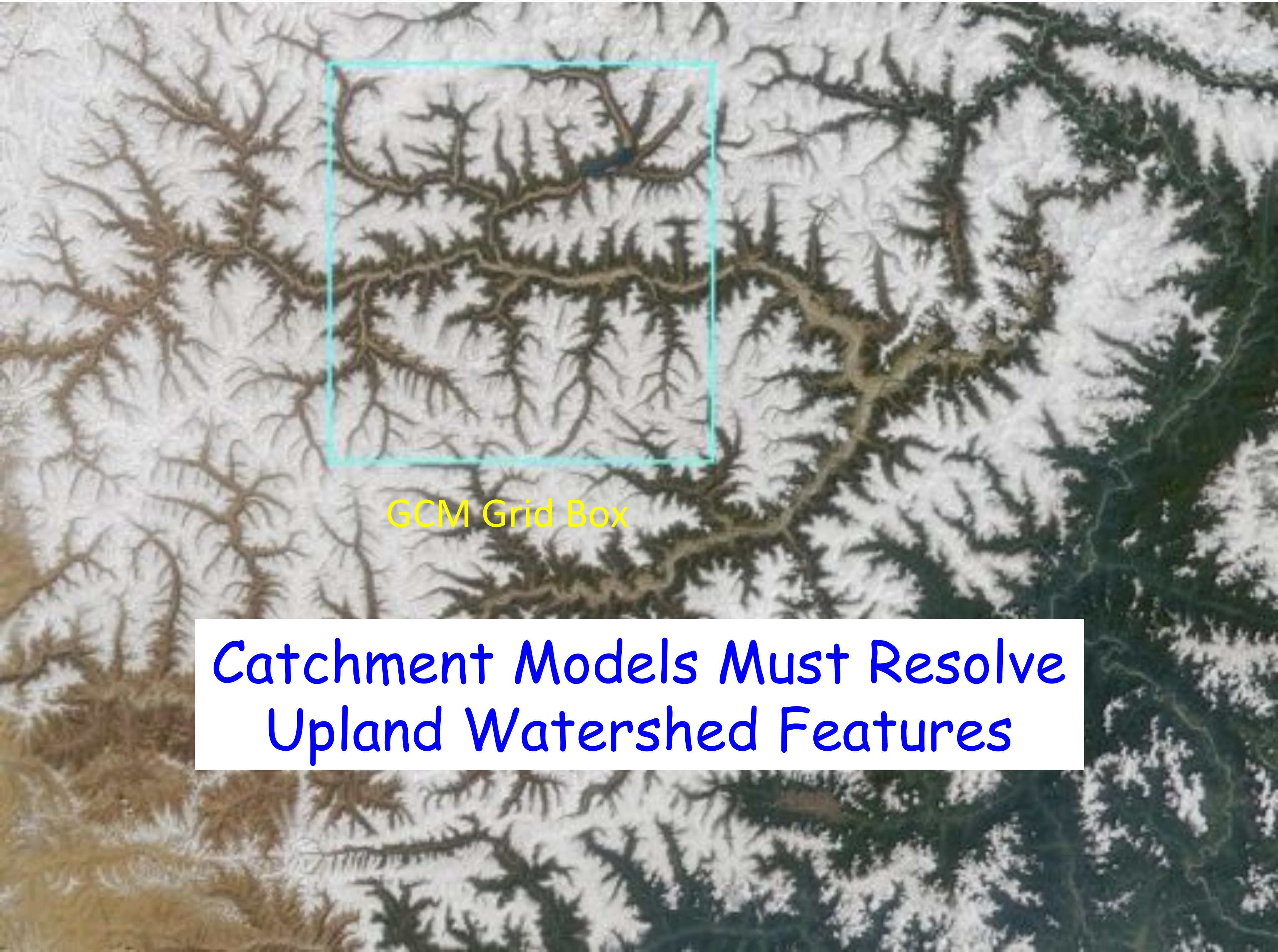
Land Parcel Data; NHD: Stream, Lake, HUC'; USDA: Soils/Crops; NLCD: LU_LC;

What scale/resolution of ETV's is important for Catchment research?

Multi-Scale Processes and Data Support



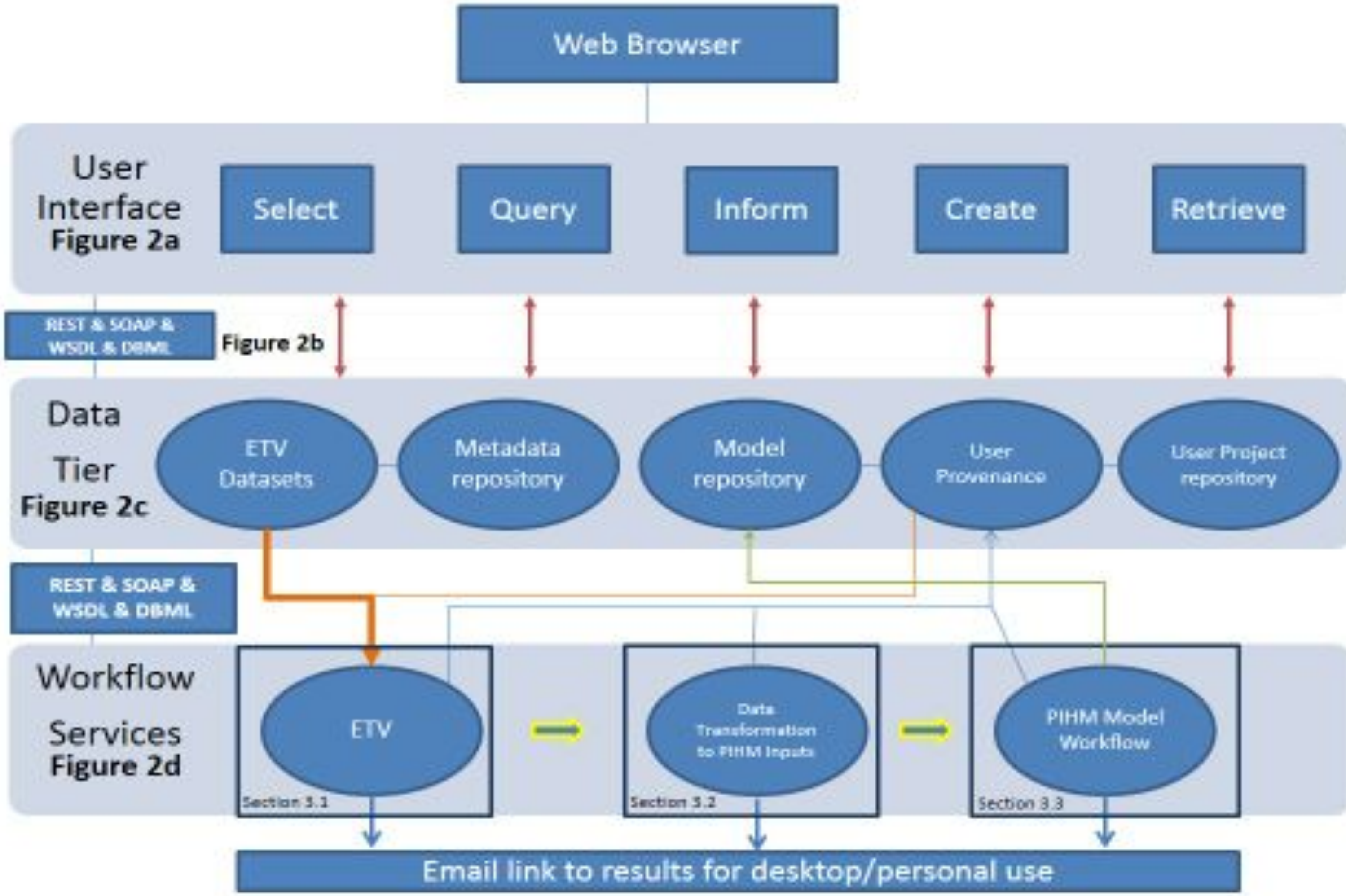
Catchment Models Must Resolve Upland Watershed Features



Automating the Catchment Model-Data Workflow

HydroTerre

Author Lorne Leonard



Service-oriented architecture for data-model workflows consists of three layers. The first layer is the web based user interface, supported by a data tier layer, and a workflow service layer. (under development)

HydroTerre: Extending the Prototype

Author Lorne Leonard

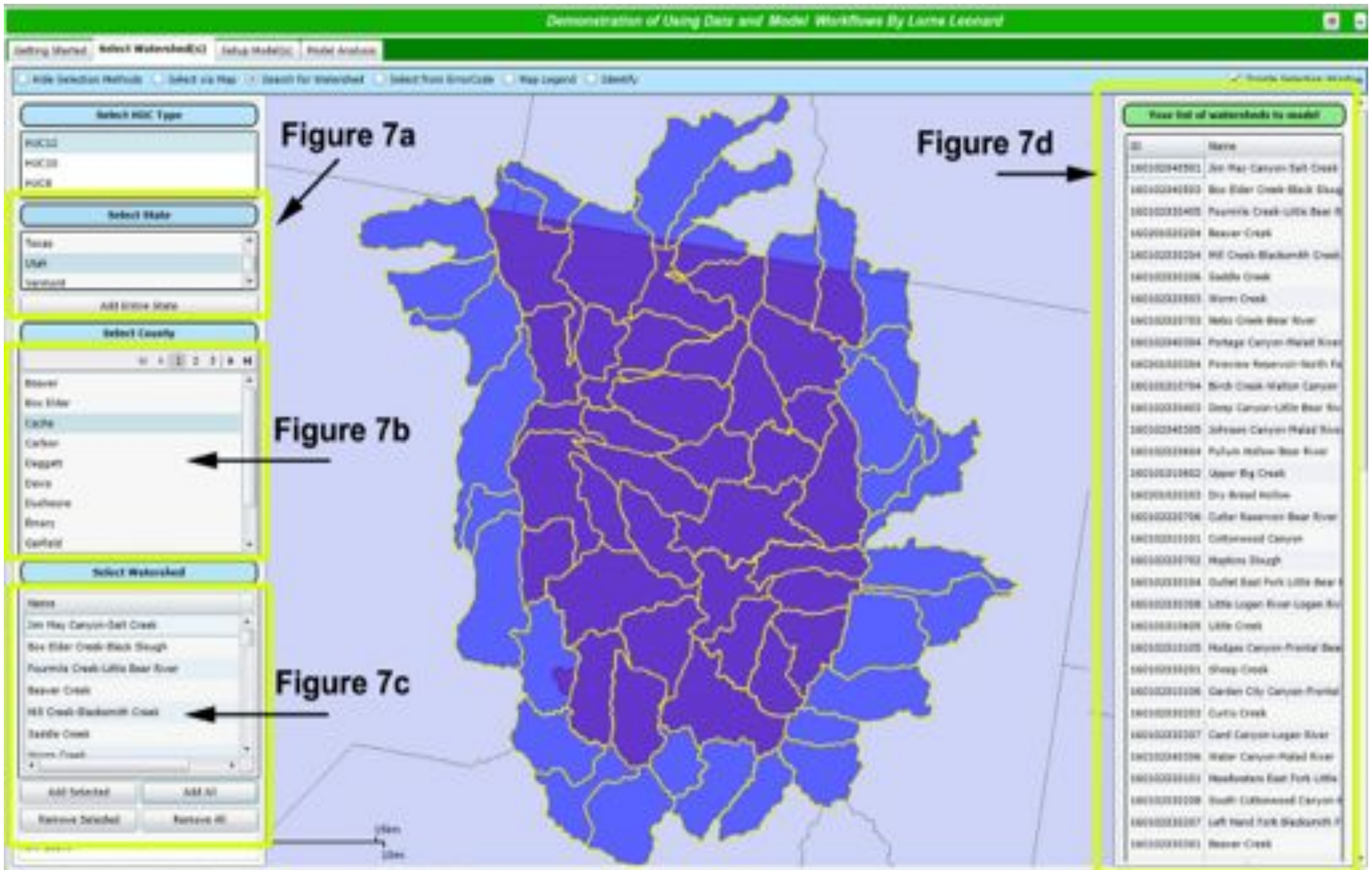
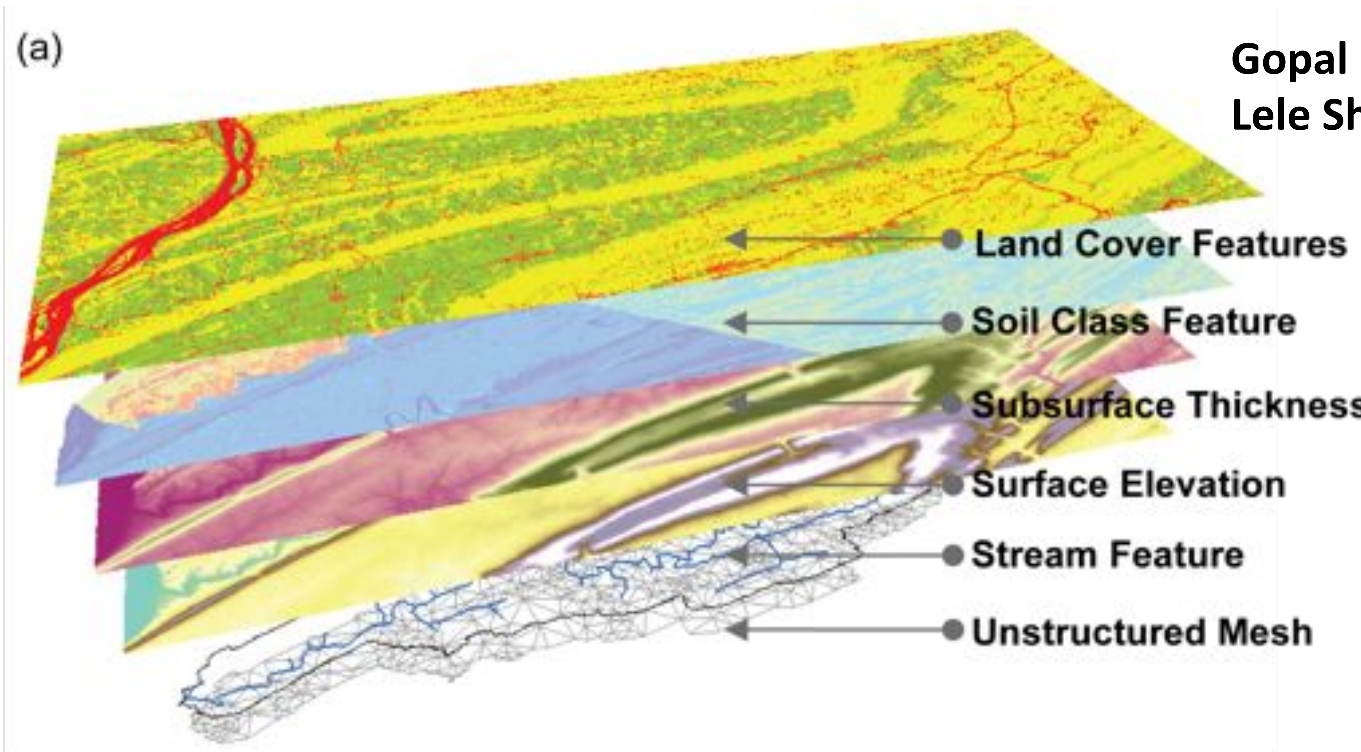


Figure 7: Web application interface to select HUC-12s within the CONUS. The user can select all HUC-12s within a US state (a) or county (b) or select individual HUC-12s (c) to construct a selection list (d). (under development)

Desktop Data-Model Workflow

Gopal Bhatt
Lele Shu

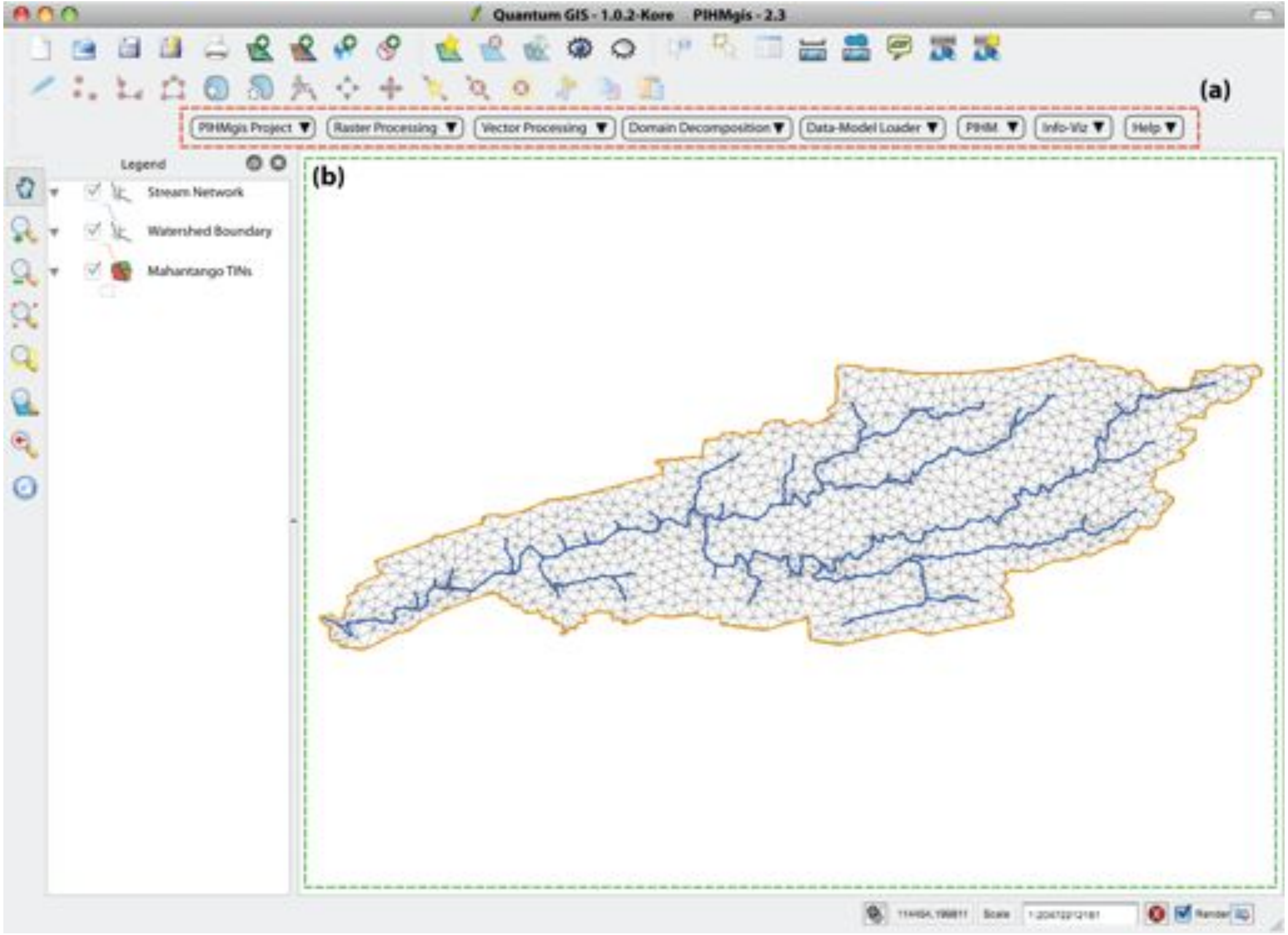


Data Parameterization: defined by representative parameter value of each data layer for each element

Topology for channel segments: defined by From Node, To Node, Upstream Segment, Downstream segment, Left TIN element, Right TIN element

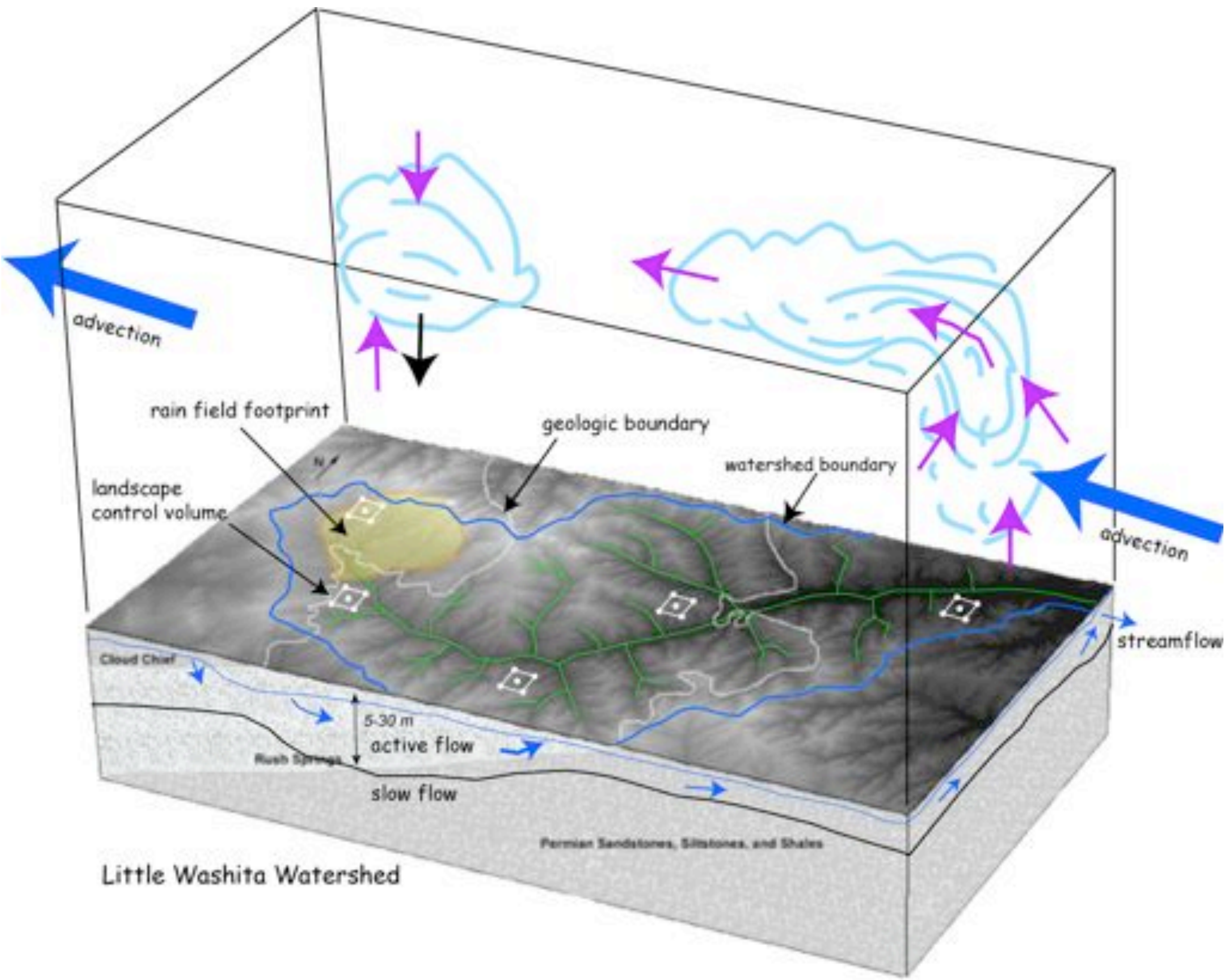
PIHM GIS: Desktop Tools for collaboration

Gopal Bhatt author

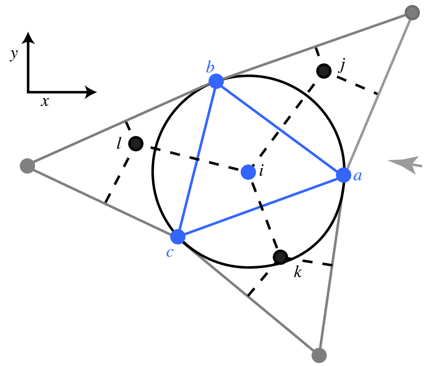


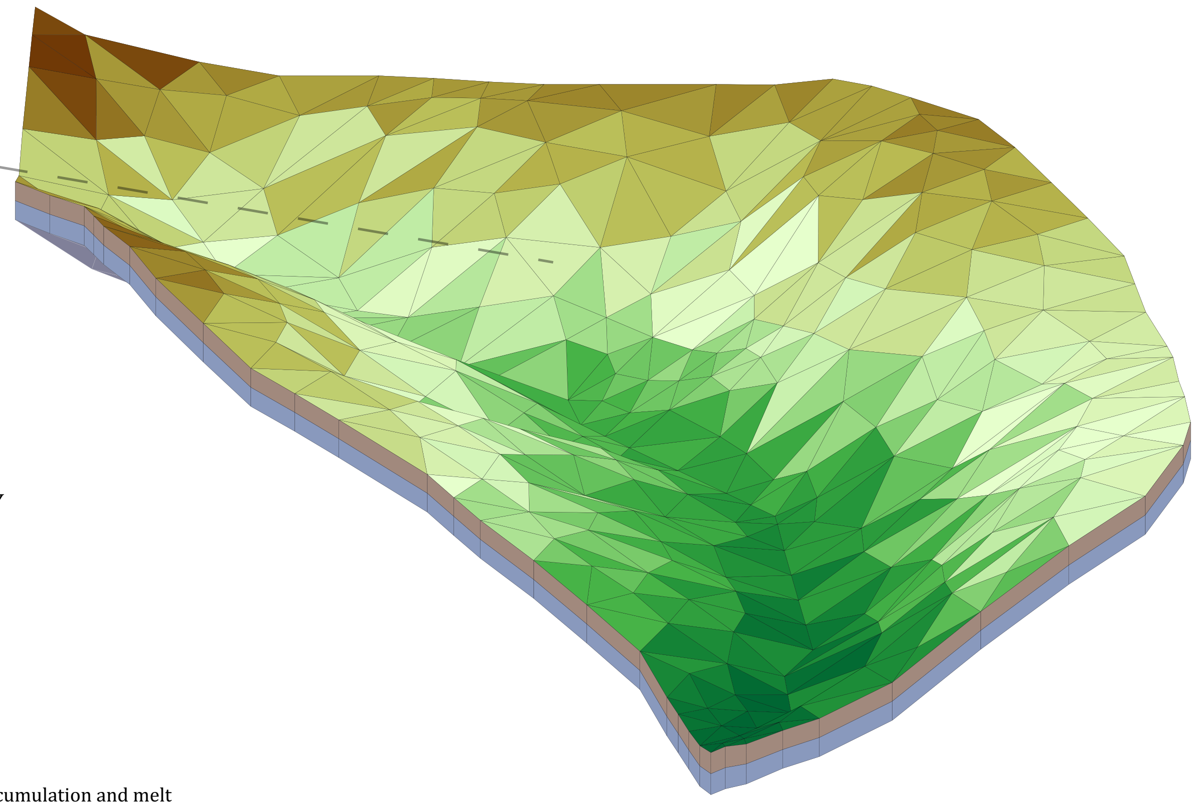
Role of the Conceptual Model

Defining the model purpose, scale, processes & data resources



PIHM

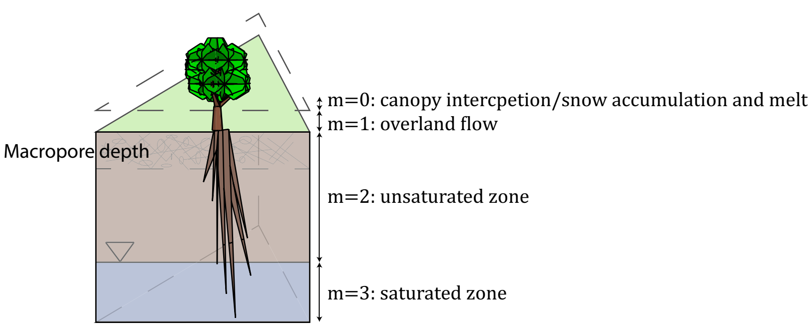


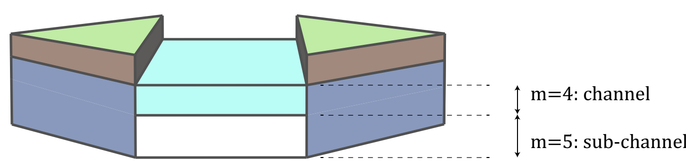


$$\frac{\partial\varphi}{\partial t} = \nabla\cdot(\varphi U) + \nabla\cdot(\Gamma\nabla\varphi) + Q_{ss}$$

$$\frac{\partial}{\partial t}\int_{V_i}\varphi\,dV = \int_{A_{ij}}\vec{n}\cdot(\varphi U)dA + \int_{A_{ij}}\vec{n}\cdot(\Gamma\nabla\varphi)dA + \int_{V_i}Q_{ss}\,dV$$

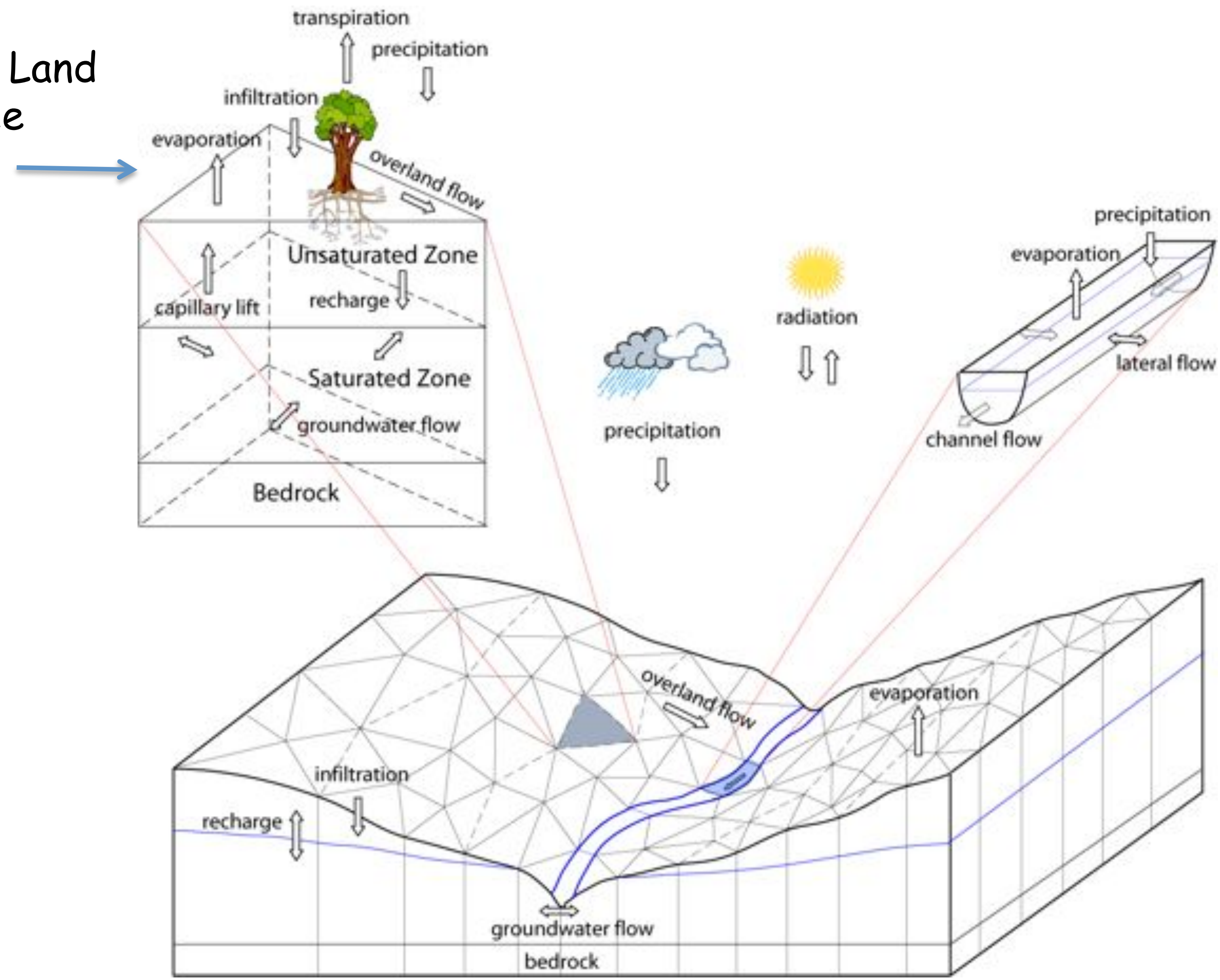
$$\left\{A_i\frac{d\bar{\phi}}{dt} = \sum_j \vec{n}\cdot\vec{C}A_{ij} + \sum_j \vec{n}\cdot\vec{D}A_{ij} + \bar{Q}_{ss}V_i\right\}\Bigg|_{m=0,1,\ldots,5}$$





Fully coupled processes but with reduced physics (ASAP)

NOAH Land Surface Model



Qu and Duffy 2007. Kumar, Bhatt, Duffy 2009

Semi-Discrete Finite Volume Formulation

Process	Governing equation/model	Original governing equations	Semi-discrete form
Channel Flow	St. Venant Equation	$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = q$	$\left(\frac{d\varsigma}{dt} = P_c - \sum Q_{gc} + \sum Q_{oc} + Q_{in} - Q_{out} - E_c \right)_i$ [1]
Overland Flow		$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = q$	$\left(\frac{\partial h}{\partial t} = P_o - I - E_o - Q_{oc} + \sum_{j=1}^{3} Q_s^{ij} \right)_i$ [1]
Unsaturated Flow	Richard Equation	$C(\psi) \frac{\partial \psi}{\partial t} = \nabla \cdot (K(\psi) \nabla (\psi + Z))$	$\left(\frac{d\xi}{dt} = I - q^0 - ET_s \right)_i$ [2]
Groundwater Flow		$C(\psi) \frac{\partial \psi}{\partial t} = \nabla \cdot (K(\psi) \nabla (\psi + Z))$	$\left(\frac{d\zeta}{dt} = q^0 + \sum_{j=1}^{3} Q_g^{ij} - Q_l + Q_{gc} \right)_i$ [3]
Interception	Bucket Model	$\frac{dS_I}{dt} = P - E_I - P_o$	$\left(\frac{dS_I}{dt} = P - E_I - P_o \right)_i$
Snowmelt	Temperature Index Model	$\frac{dS_{snow}}{dt} = P - E_{snow} - \Delta w$	$\left(\frac{dS_{snow}}{dt} = P - E_{snow} - \Delta w \right)_i$
Evapotranspiration	Pennman-Monteith Method	$ET_0 = \frac{\Delta (R_n - G) + \rho_a C_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma (1 + \frac{r_s}{r_a})}$	$\left(ET_0 = \frac{\Delta (R_n - G) + \rho_a C_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma (1 + \frac{r_s}{r_a})} \right)_i$

National CZO Program

Example 1: The Susquehanna/Shale Hills Critical Zone Observatory

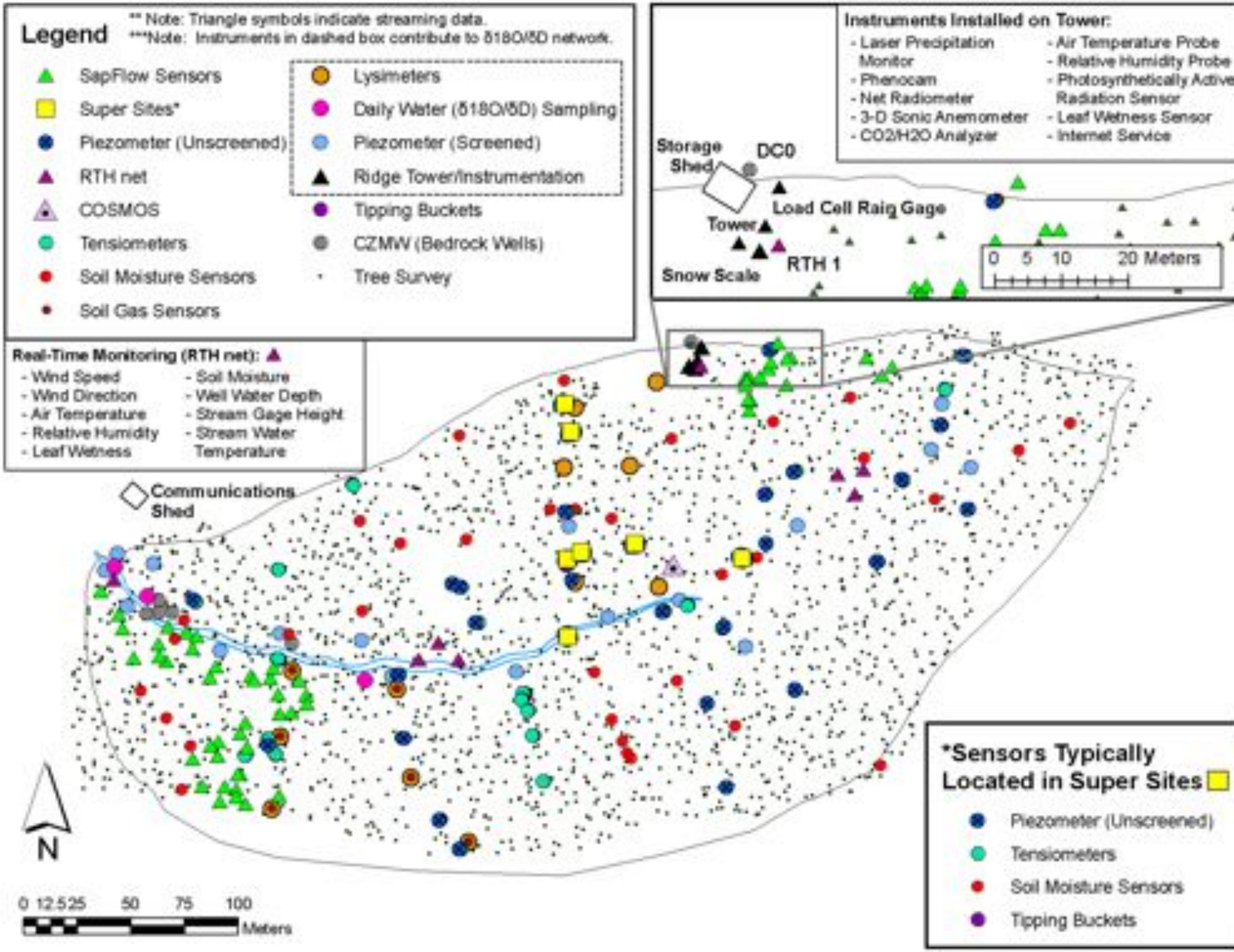
Advancing interdisciplinary studies of earth surface processes

Chris Duffy, PI 07-13
Sue Brantley
Rudy Slingerland
David Eissenstat
Henry Lin
Ken Davis
Kamini Singha
Laura Toran
Pat Reed
Karen Salvage
Eric Kirby
Tim White
Kevin Dressler
Doug Miller
Brian Bills
Beth Boyer
Colin Duffy
Ray Fletcher
Michelle Tuttle
Paul Bierman
Peter Lichtner
Carl Steefel
Rich April
Ryan Mather
David Harbor
Larry McKay
Teferi Tsegaye
HernanSantos
Evan Thomas
Xuan Yu
Yu Zhang
Ryan Jones
Beth Boyer

PENNSTATE 1855

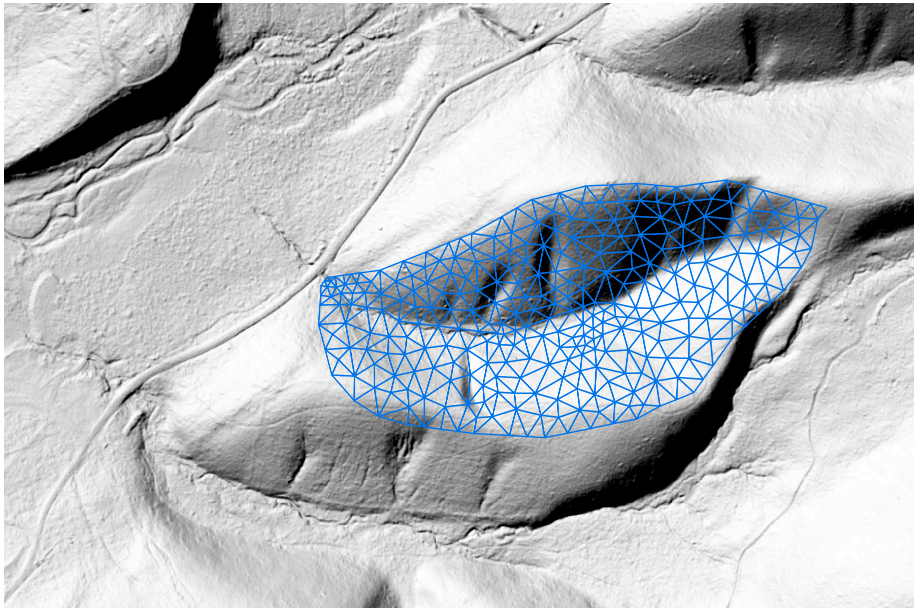
The Shale Hills Critical Zone Observatory

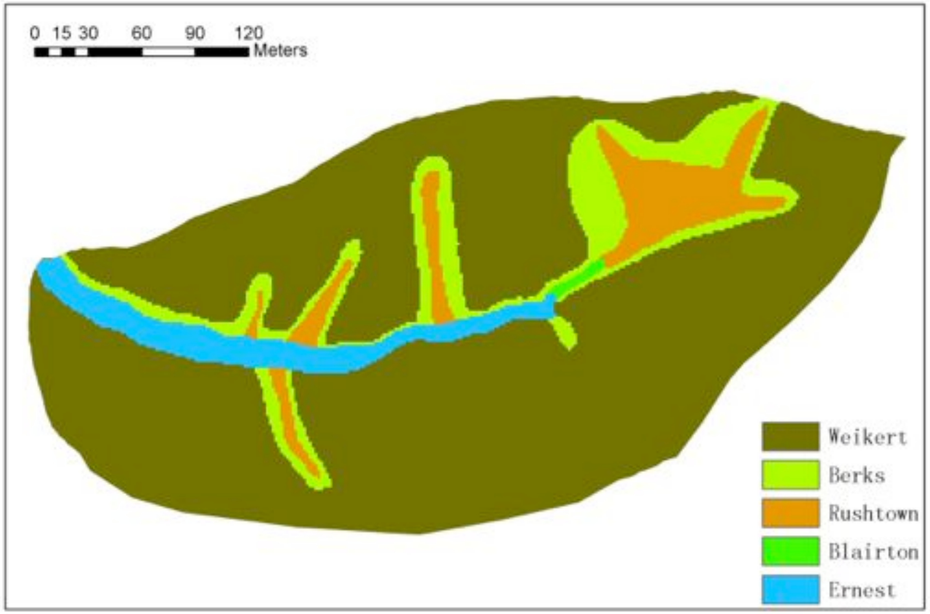
Bedrock: Rose Hill Shale ($K \sim 10^{-15}$ cm/s)
Soil: ($K \sim 10^{-6}$ cm/s)
~400x300m

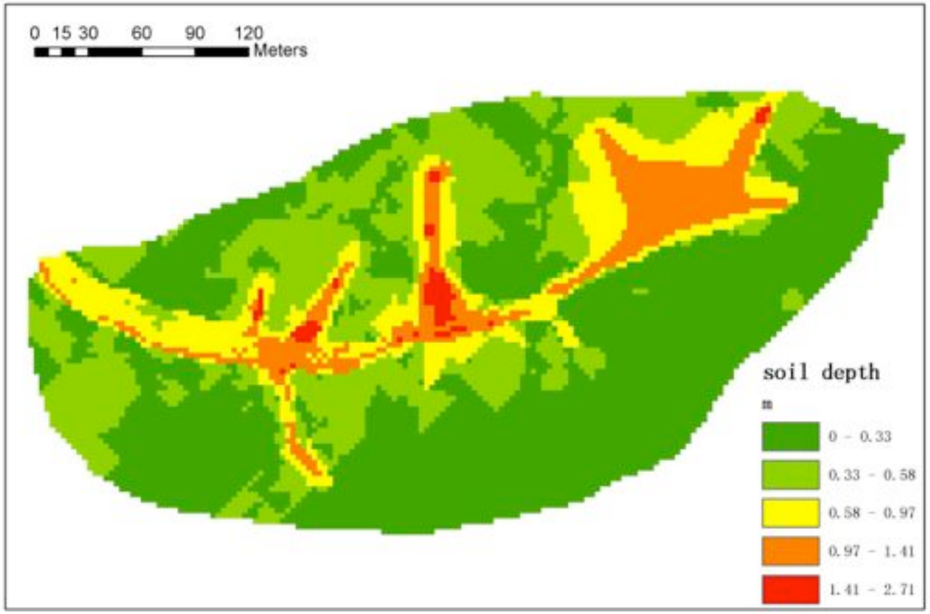


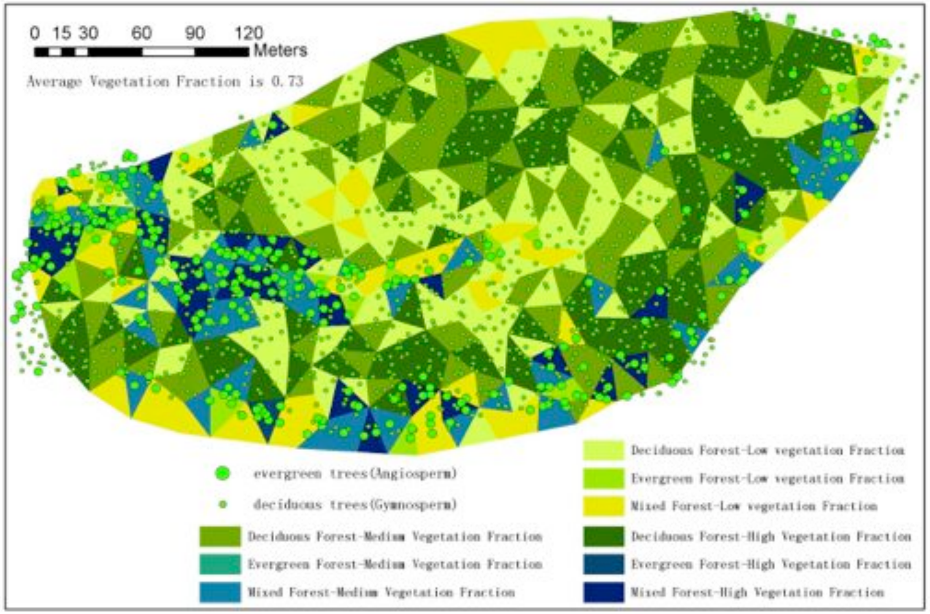
Legend
** Note: Triangle symbols indicate streaming data.
***Note: Instruments in dashed box contribute to δ18O/δD network.
SapFlow Sensors
Super Sites*
Piezometer (Unscreened)
RTH net
COSMOS
Tensiometers
Soil Moisture Sensors
Soil Gas Sensors
Lysimeters
Daily Water (δ18O/δD) Sampling
Piezometer (Screened)
Ridge Tower/Instrumentation
Tipping Buckets
CZMW (Bedrock Wells)
Tree Survey
Real-Time Monitoring (RTH net):
- Wind Speed
- Wind Direction
- Air Temperature
- Relative Humidity
- Leaf Wetness
- Soil Moisture
- Well Water Depth
- Stream Gage Height
- Stream Water Temperature
Instruments Installed on Tower:
- Laser Precipitation Monitor
- Phenocam
- Net Radiometer
- 3-D Sonic Anemometer
- CO2/H2O Analyzer
- Air Temperature Probe
- Relative Humidity Probe
- Photosynthetically Active Radiation Sensor
- Leaf Wetness Sensor
- Internet Service
Storage Shed
DC0
Load Cell Rain Gage
Tower
RTH 1
Snow Scale
0 5 10 20 Meters
Communications Shed
N
0 12.5 25 50 75 100
Meters
*Sensors Typically Located in Super Sites
Piezometer (Unscreened)
Tensiometers
Soil Moisture Sensors
Tipping Buckets

CZO Data ->lidar, Soil, Regolith,Veg

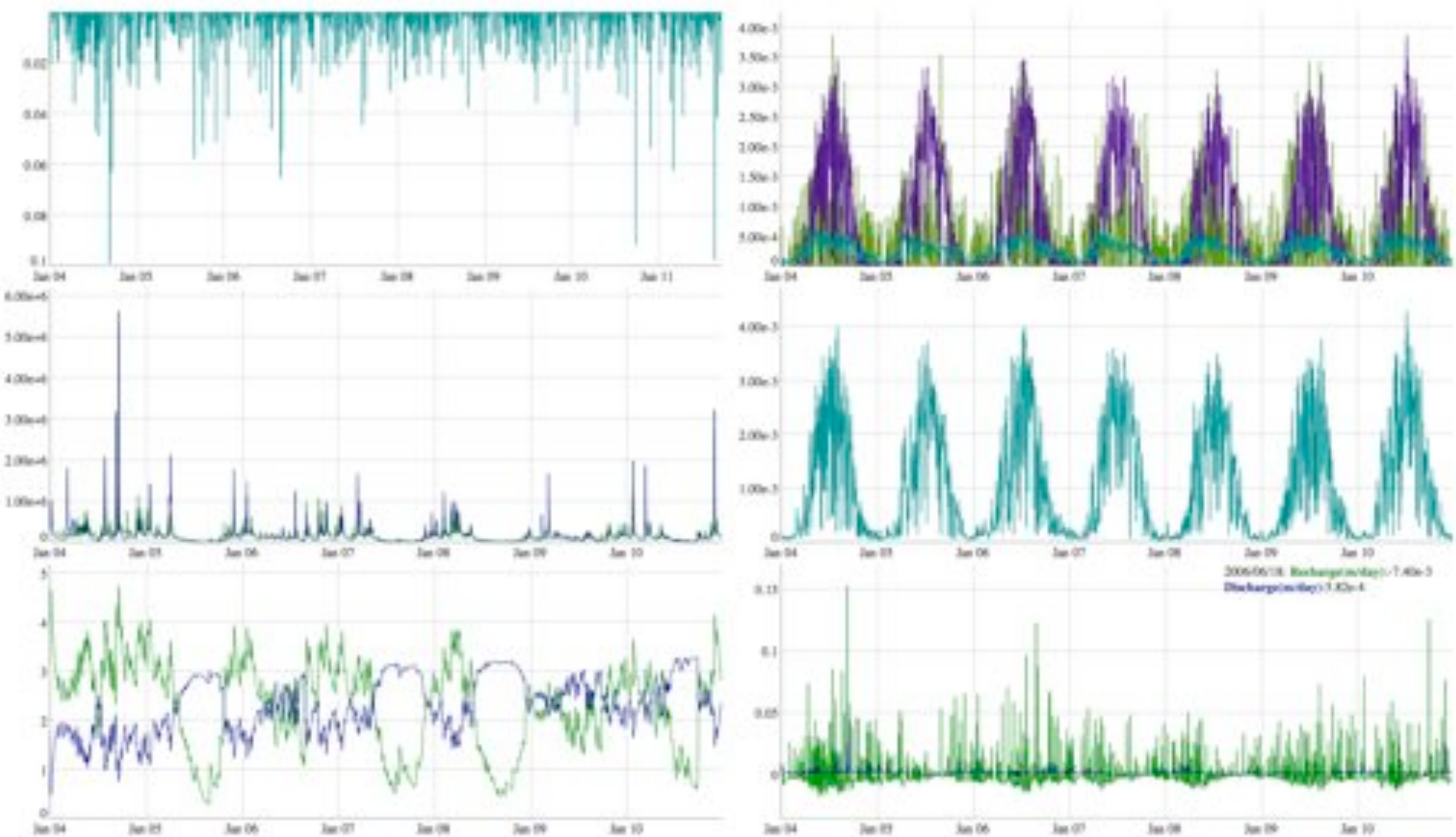






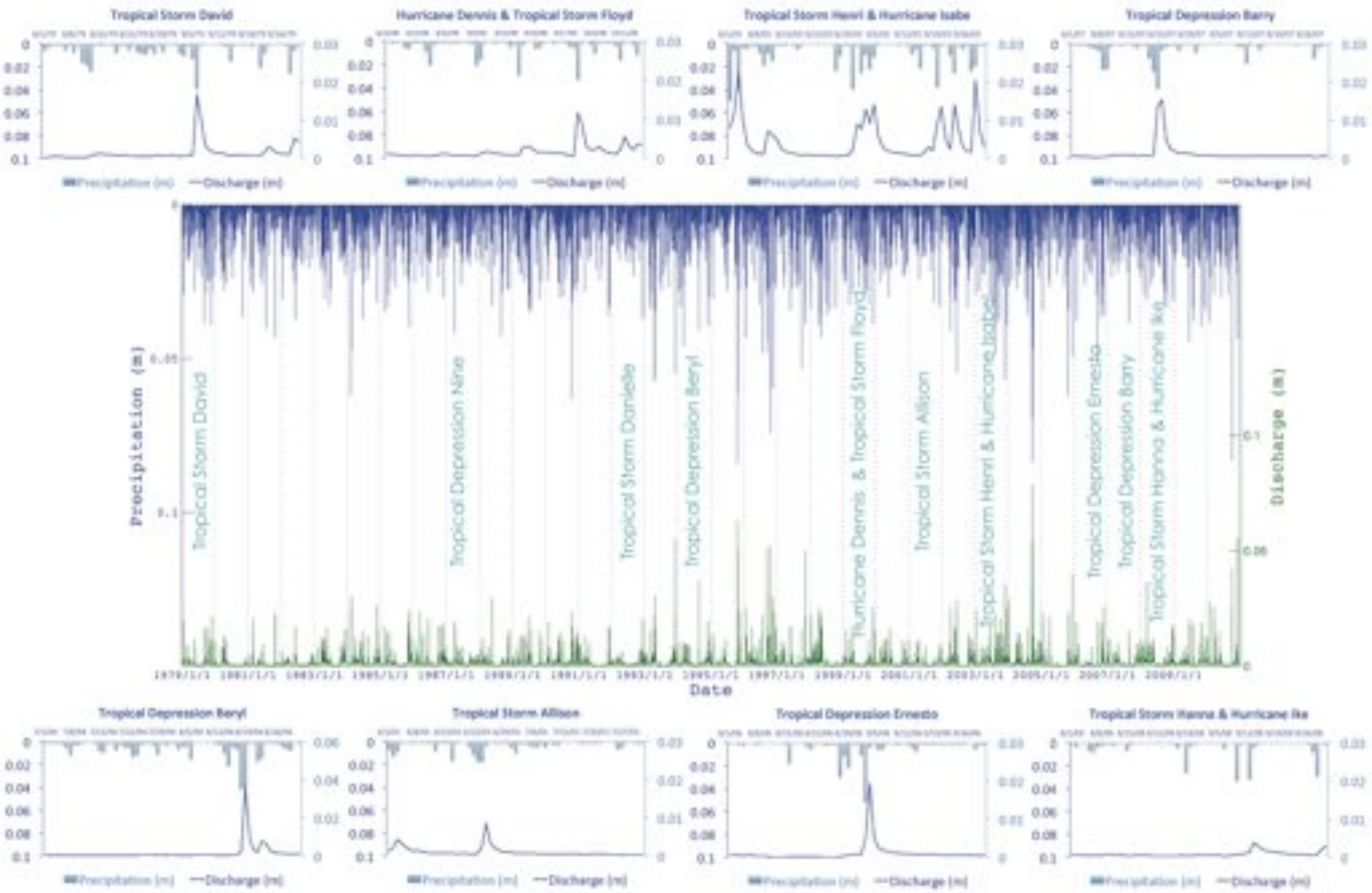


Reconstructing the Hydrologic Site History: 1979-Present from Reanalysis



http://www.pihm.psu.edu/applications.html

Reconstructing the CZO Storm Library: 1979-2010



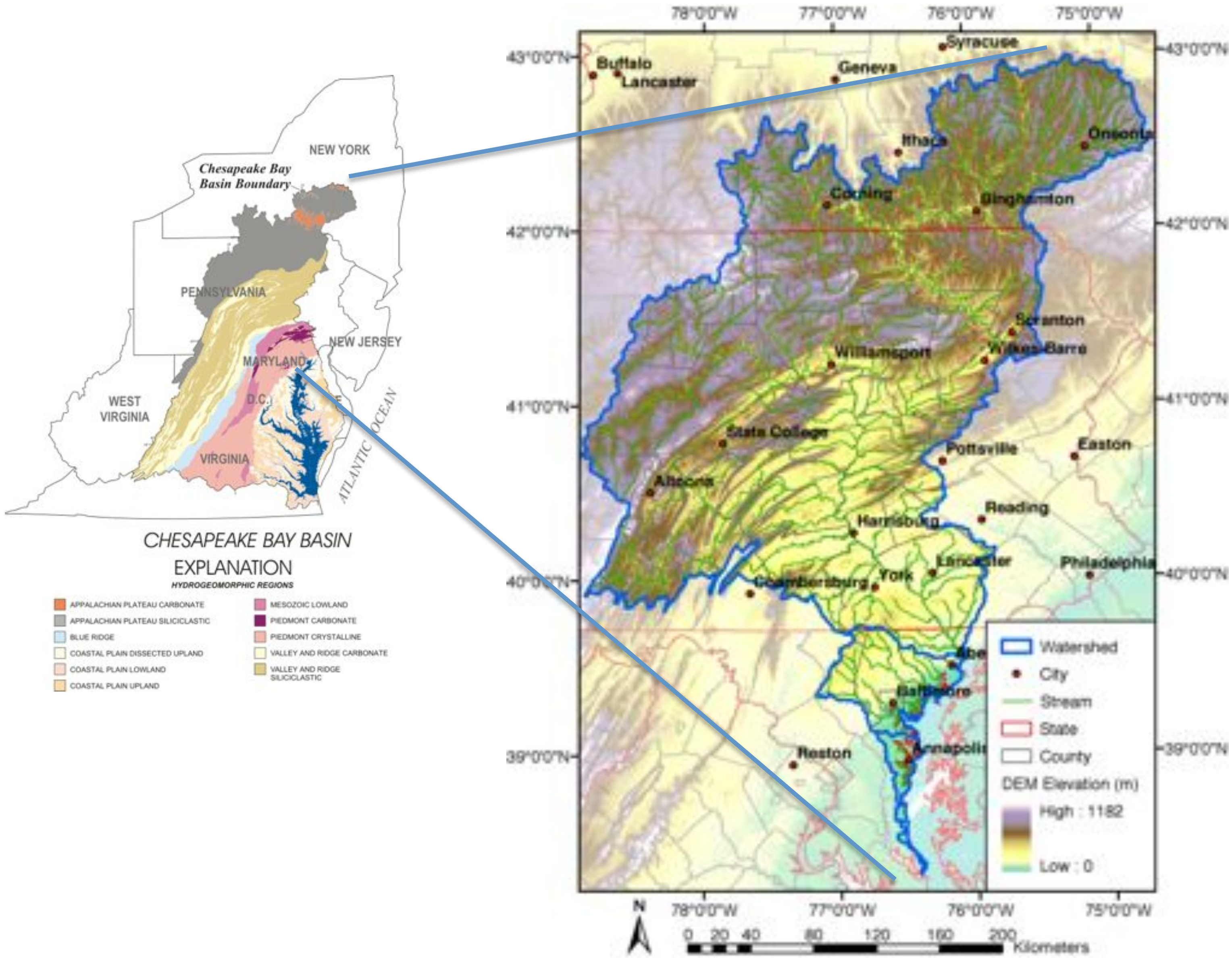
Example 2
Wetland Vulnerability to Climate Change

Team
Chris Duffy
Xuan Yu
Gopal Bhatt
Ray Najaar
Michael Nassry
Denice Wardrop

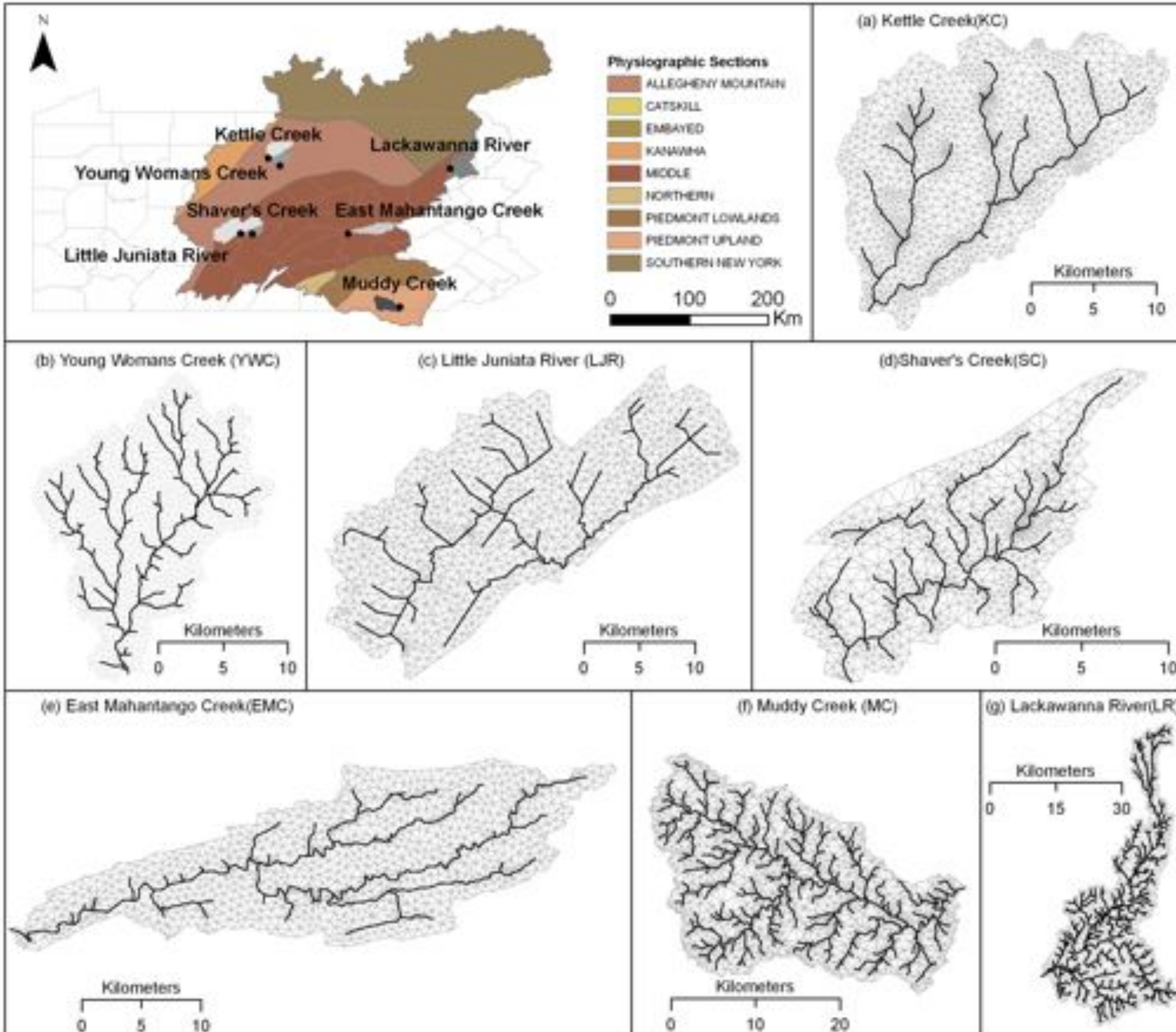
Ecoregions (4)
Ridge and Valley
Piedmont
Unglaciated Plateau
Glaciated Plateau

Watersheds (7)
Muddy Creek
Kettle Creek
Shaver's Creek
Young Womans Creek
East Mahantango Creek
Little Juniata River
Lackawanna River

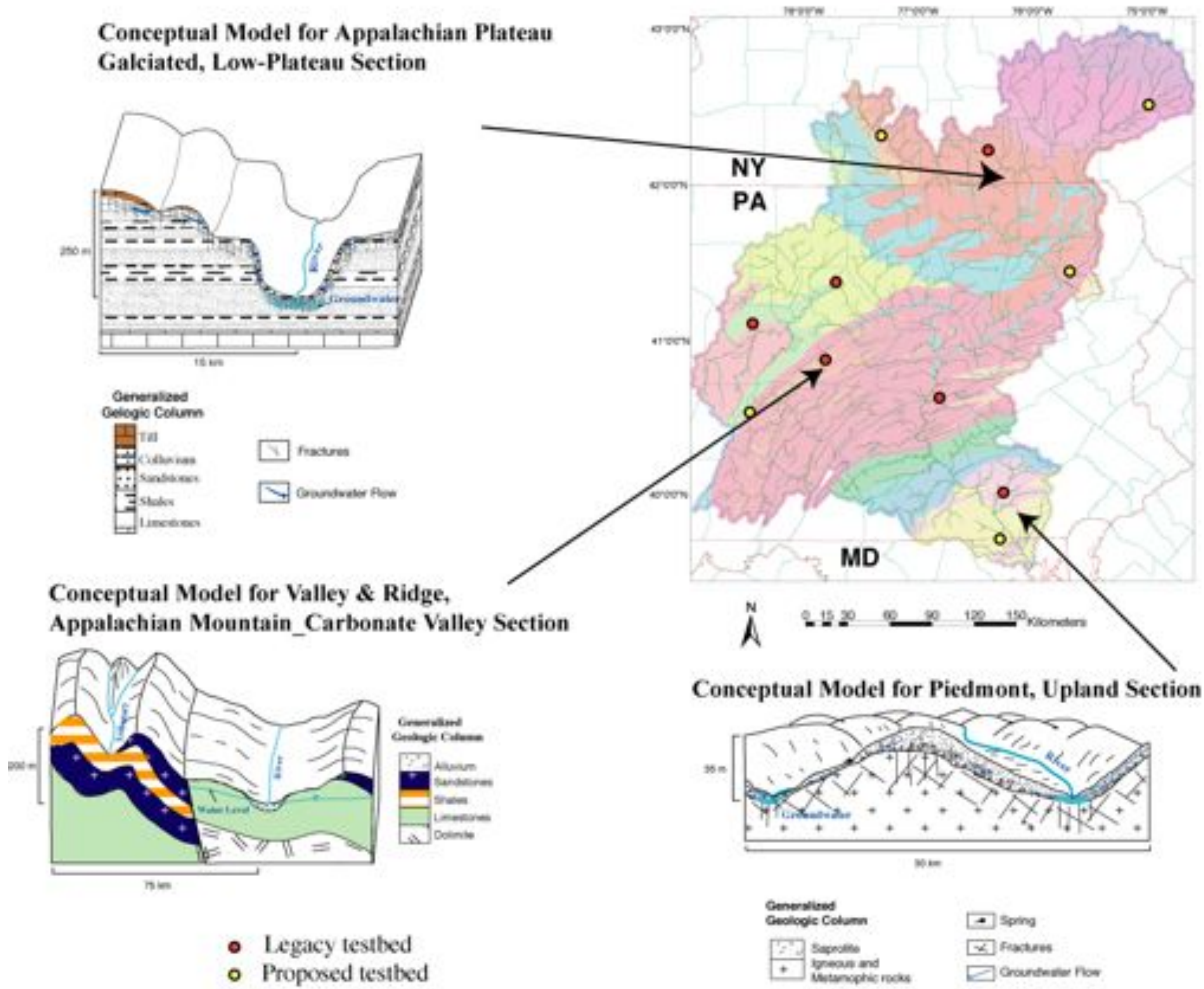
20-Year Climate Scenarios (2)
Historical: 1979 - 1998
Future: 2046 - 2065



NEW YORK
Chesapeake Bay Basin Boundary
PENNSYLVANIA
NEW JERSEY
MARYLAND
D.C.
WEST VIRGINIA
VIRGINIA
ATLANTIC OCEAN
CHESAPEAKE BAY BASIN
EXPLANATION
HYDROGEOMORPHIC REGIONS
APPALACHIAN PLATEAU CARBONATE
APPALACHIAN PLATEAU SILICICLASTIC
BLUE RIDGE
COASTAL PLAIN DISSECTED UPLAND
COASTAL PLAIN LOWLAND
COASTAL PLAIN UPLAND
MESOZOIC LOWLAND
PIEDMONT CARBONATE
PIEDMONT CRYSTALLINE
VALLEY AND RIDGE CARBONATE
VALLEY AND RIDGE SILICICLASTIC
78°0'0"W
77°0'0"W
76°0'0"W
75°0'0"W
43°0'0"N
42°0'0"N
41°0'0"N
40°0'0"N
39°0'0"N
Syracuse
Buffalo
Lancaster
Geneva
Ithaca
Oneonta
Corning
Binghamton
Scranton
Wilkes-Barre
Williamsport
State College
Pottsville
Easton
Altoona
Reading
Harrisburg
Lancaster
Philadelphia
Chambersburg
York
Baltimore
Annapolis
Reston
Watershed
City
Stream
State
County
DEM Elevation (m)
High : 1182
Low : 0
N
0 20 40 80 120 160 200
Kilometers



N
Physiographic Sections
ALLEGHENY MOUNTAIN
CATSKILL
EMBAYED
KANAWHA
MIDDLE
NORTHERN
PIEDMONT LOWLANDS
PIEDMONT UPLAND
SOUTHERN NEW YORK
Kettle Creek
Lackawanna River
Young Womans Creek
Shaver's Creek
East Mahantango Creek
Little Juniata River
Muddy Creek
0 100 200 Km
(a) Kettle Creek(KC)
(b) Young Womans Creek (YWC)
(c) Little Juniata River (LJR)
(d)Shaver's Creek(SC)
(e) East Mahantango Creek(EMC)
(f) Muddy Creek (MC)
(g) Lackawanna River(LR)
Kilometers


Conceptual Model for Appalachian Plateau
Galciated, Low-Plateau Section
250 m
River
Groundwater
15 km
Generalized
Gelogic Column
Till
Colluvium
Sandstones
Shales
Limestones
Fractures
Groundwater Flow
NY
PA
MD
N
0 15 30 60 90 120 150 Kilometers
Conceptual Model for Valley & Ridge,
Appalachian Mountain_Carbonate Valley Section
200 m
Water Level
75 km
Generalized
Geologic Column
Alluvium
Sandstones
Shales
Limestones
Dolomite
Conceptual Model for Piedmont, Upland Section
55 m
River
Groundwater
90 km
Generalized
Geologic Column
Saprolite
Igneous and
Metamophic rocks
Spring
Fractures
Groundwater Flow
Legacy testbed
Proposed testbed

Workflow

Set up models using HydroTerre data

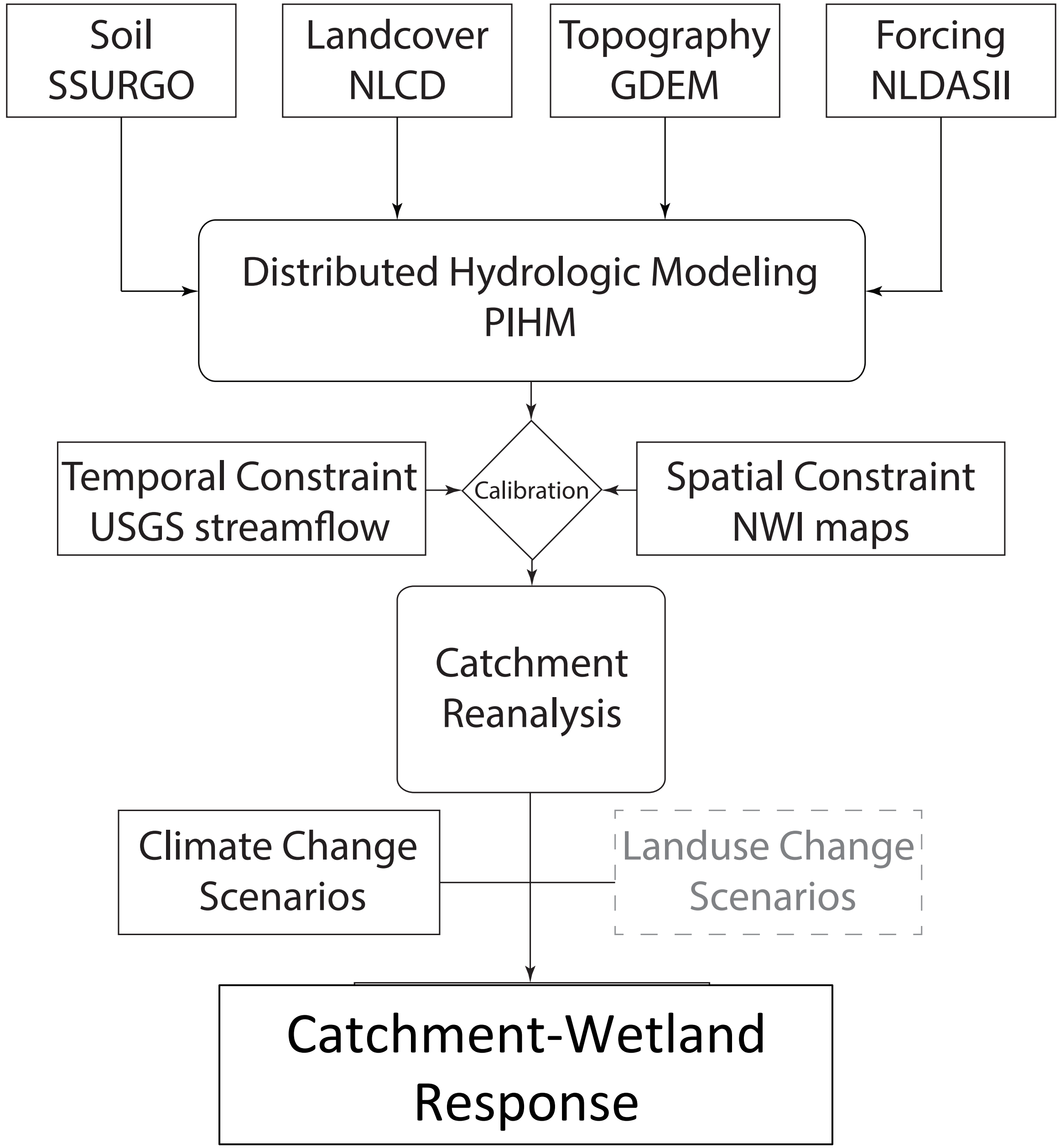
Calibrate catchments on historic data (1979-1998)

HydroGeoMorphic (HGM) classification of wetlands

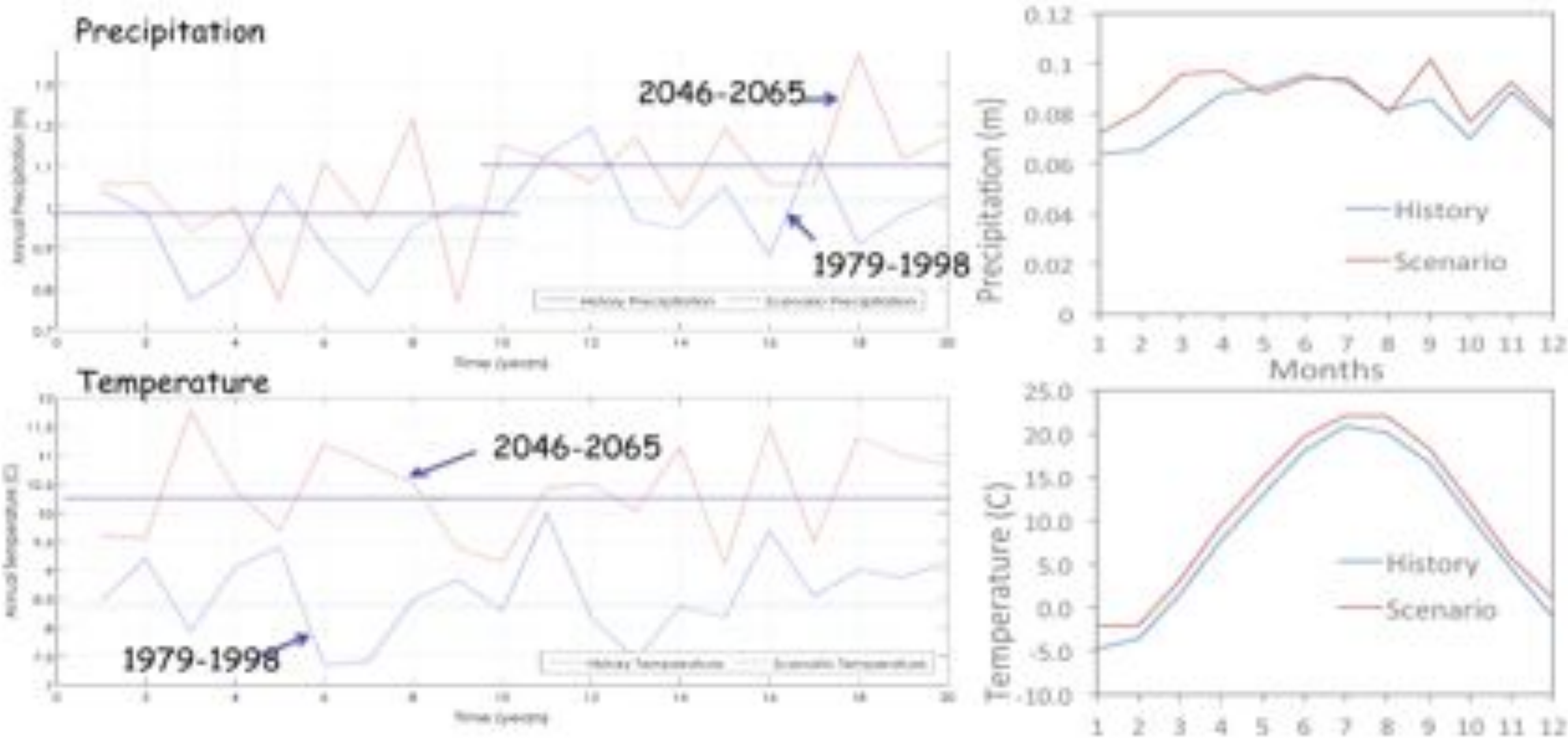
- Riverine
- Slope
- Depression

Run IPCC future climate scenario (2046-2065)

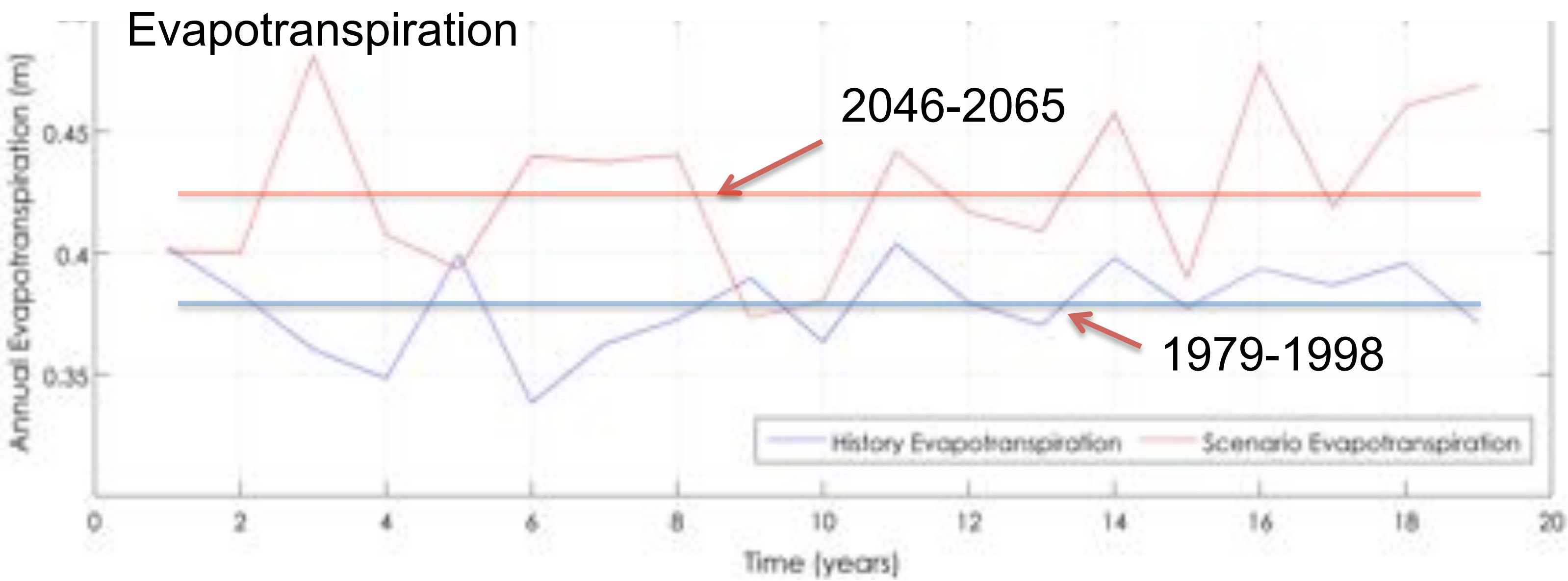
Use relative *gwl* change to measure wetland vulnerability

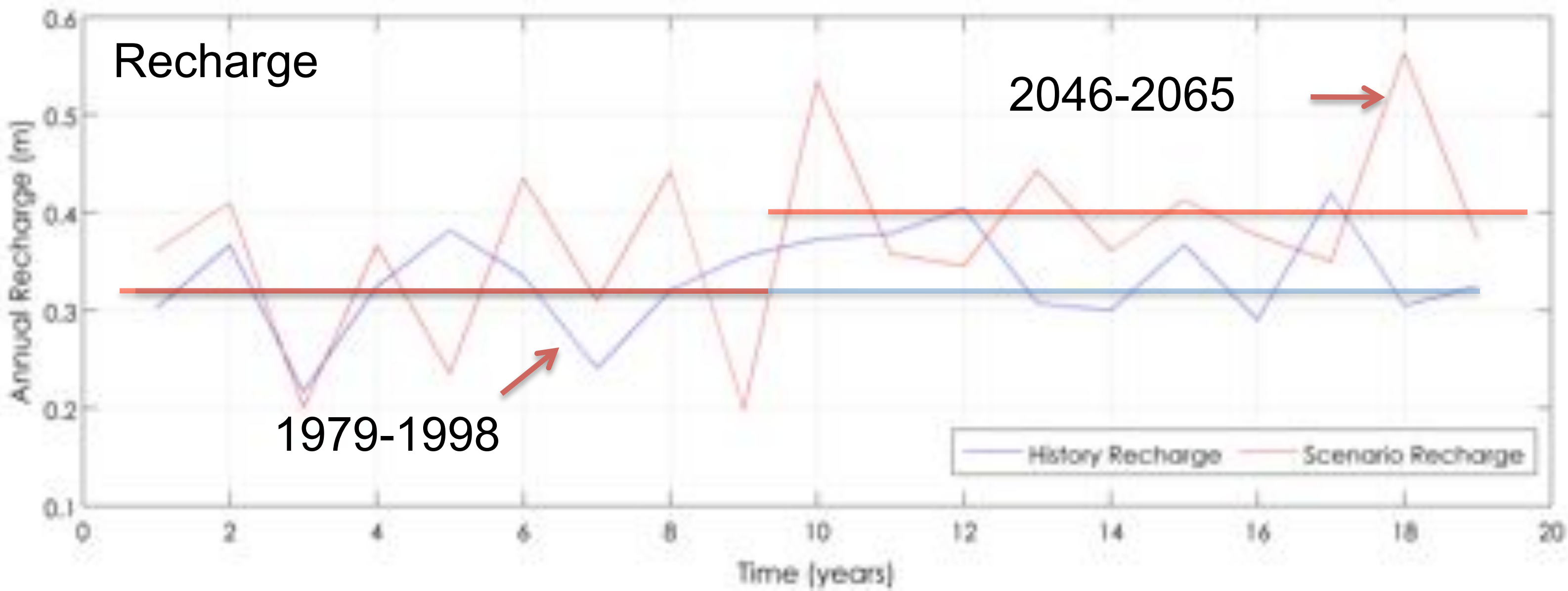

Soil
SSURGO
Landcover
NLCD
Topography
GDEM
Forcing
NLDASII
Distributed Hydrologic Modeling
PIHM
Temporal Constraint
USGS streamflow
Calibration
Spatial Constraint
NWI maps
Catchment
Reanalysis
Climate Change
Scenarios
Landuse Change
Scenarios
Catchment-Wetland
Response

Historical - IPCC Precip-Temp

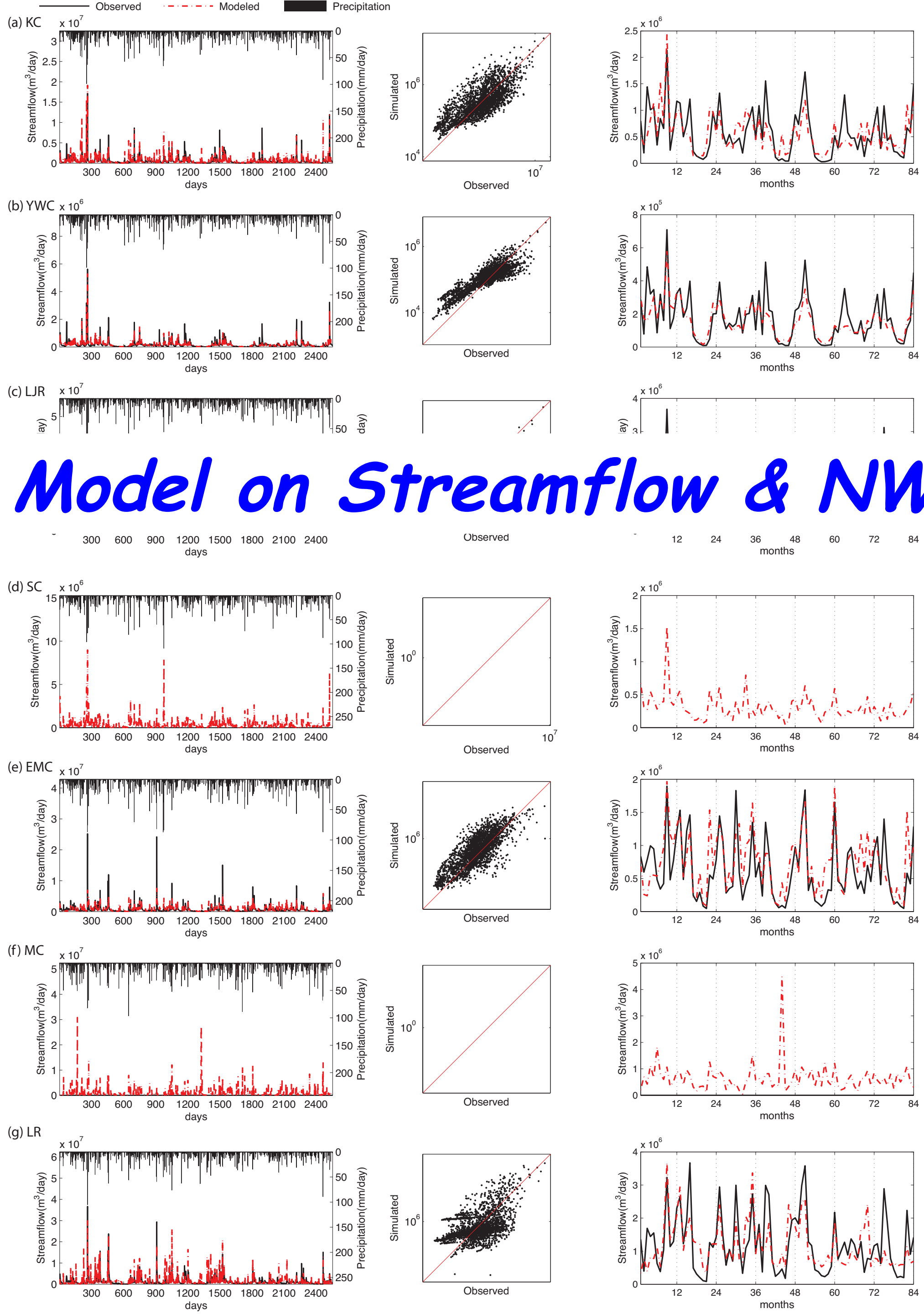


Historical vs IPCC Simulations

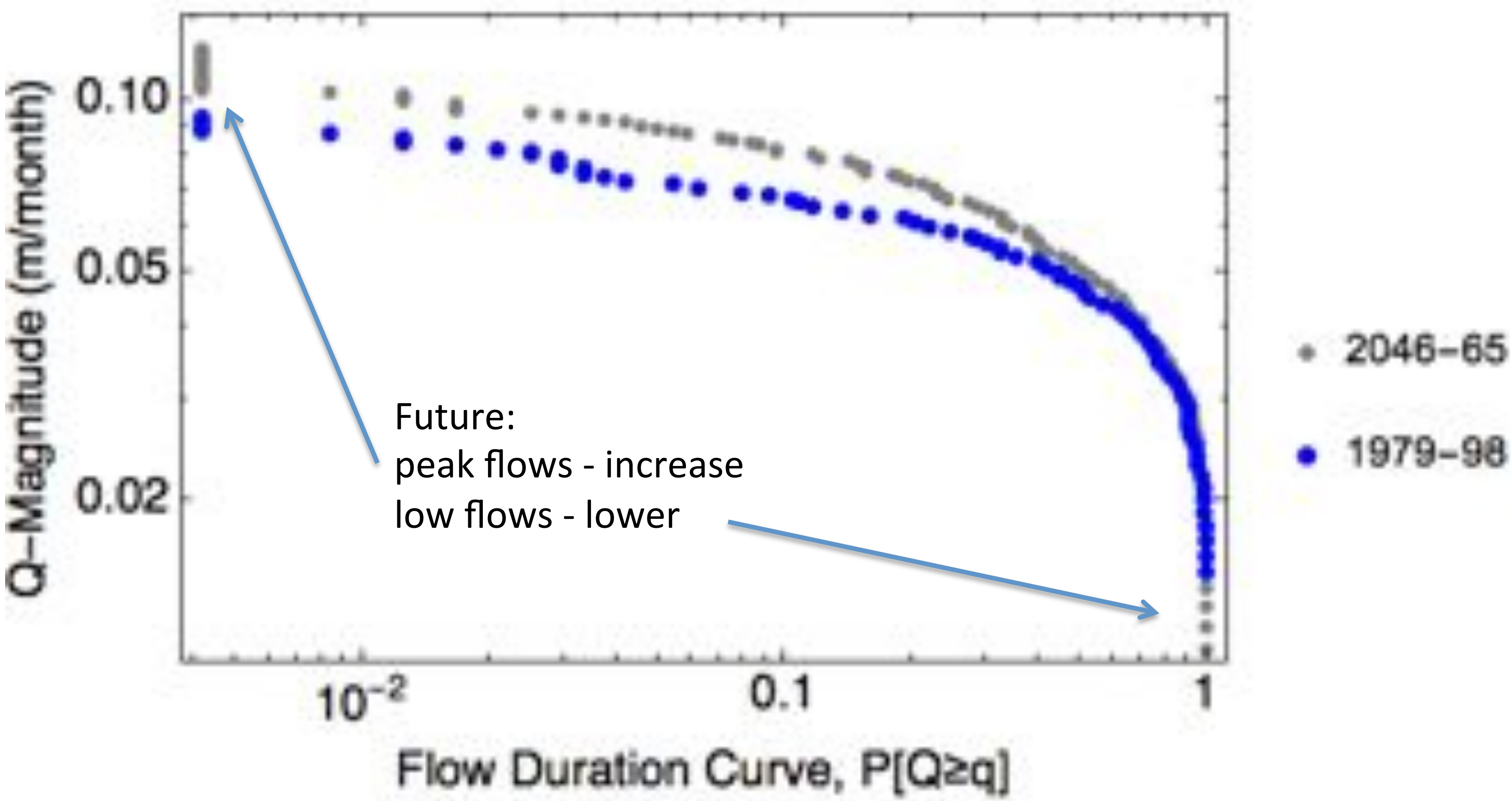




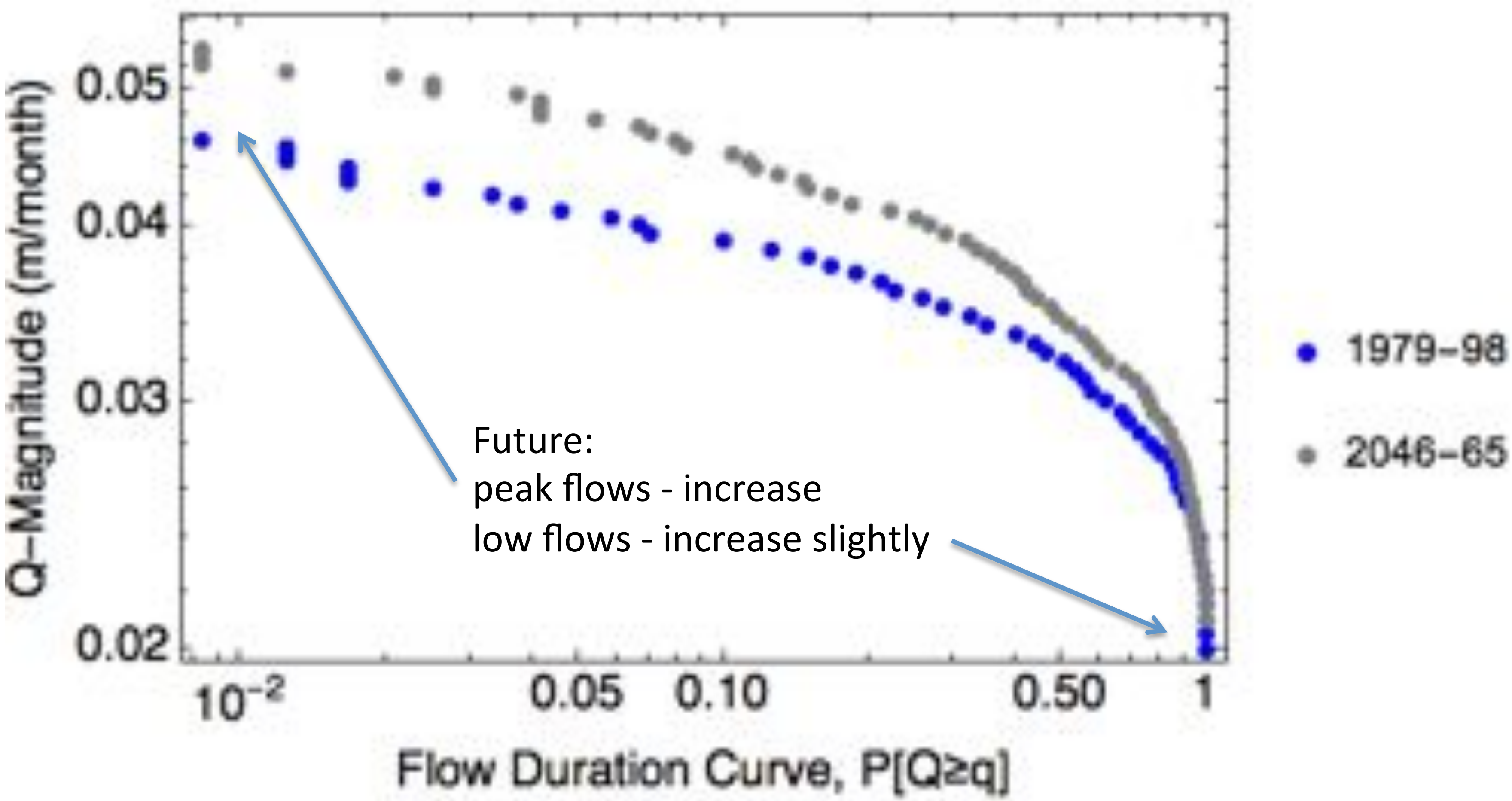
“Constrain” Model on Streamflow & NWI Wetlands



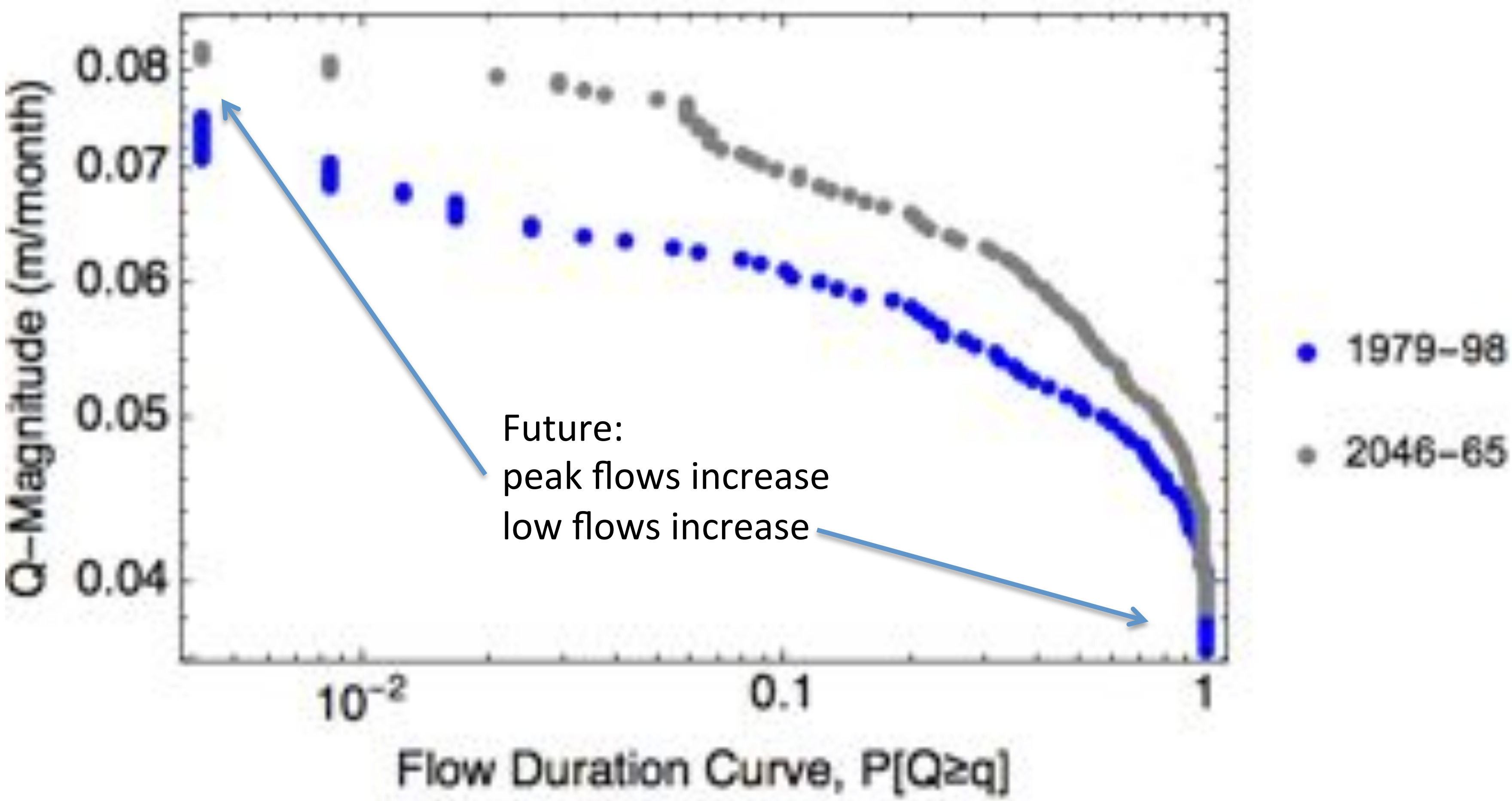
FDC Young Woman's Creek



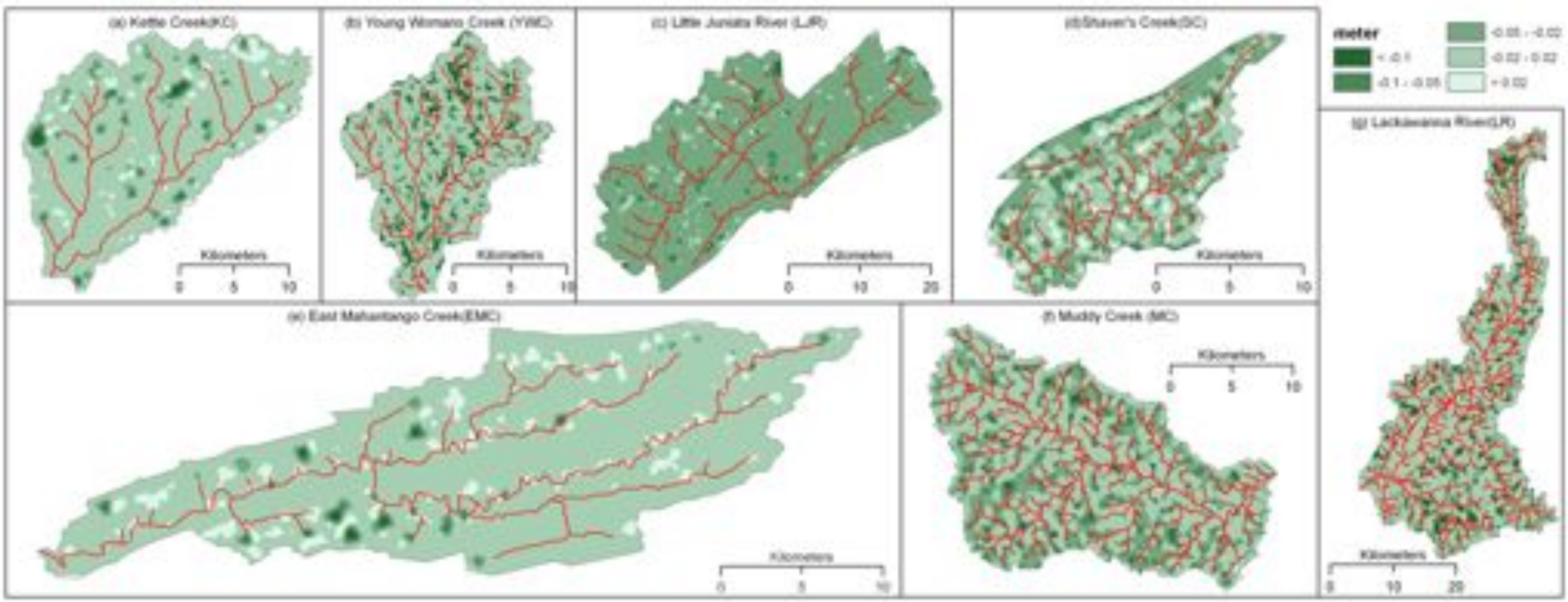
FDC Shaver Creek



FDC Lackawanna

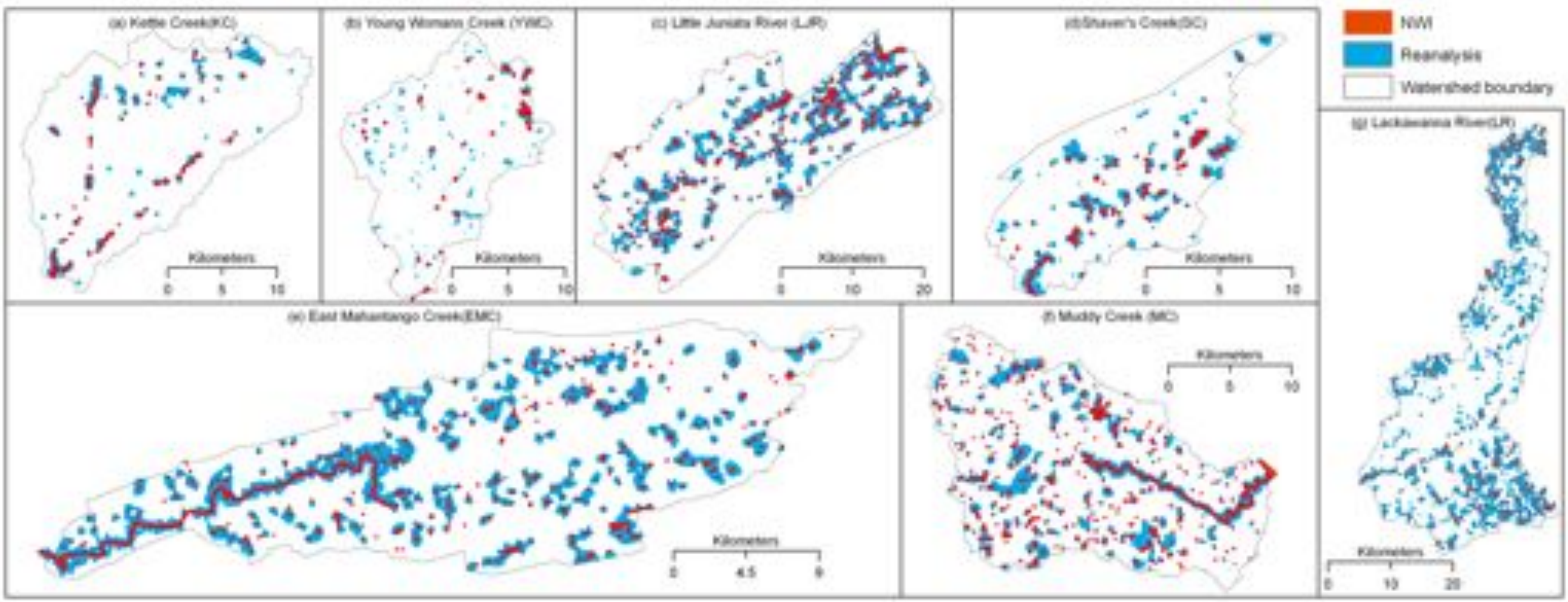


2046-2065 Scenario for Depth to Water Table

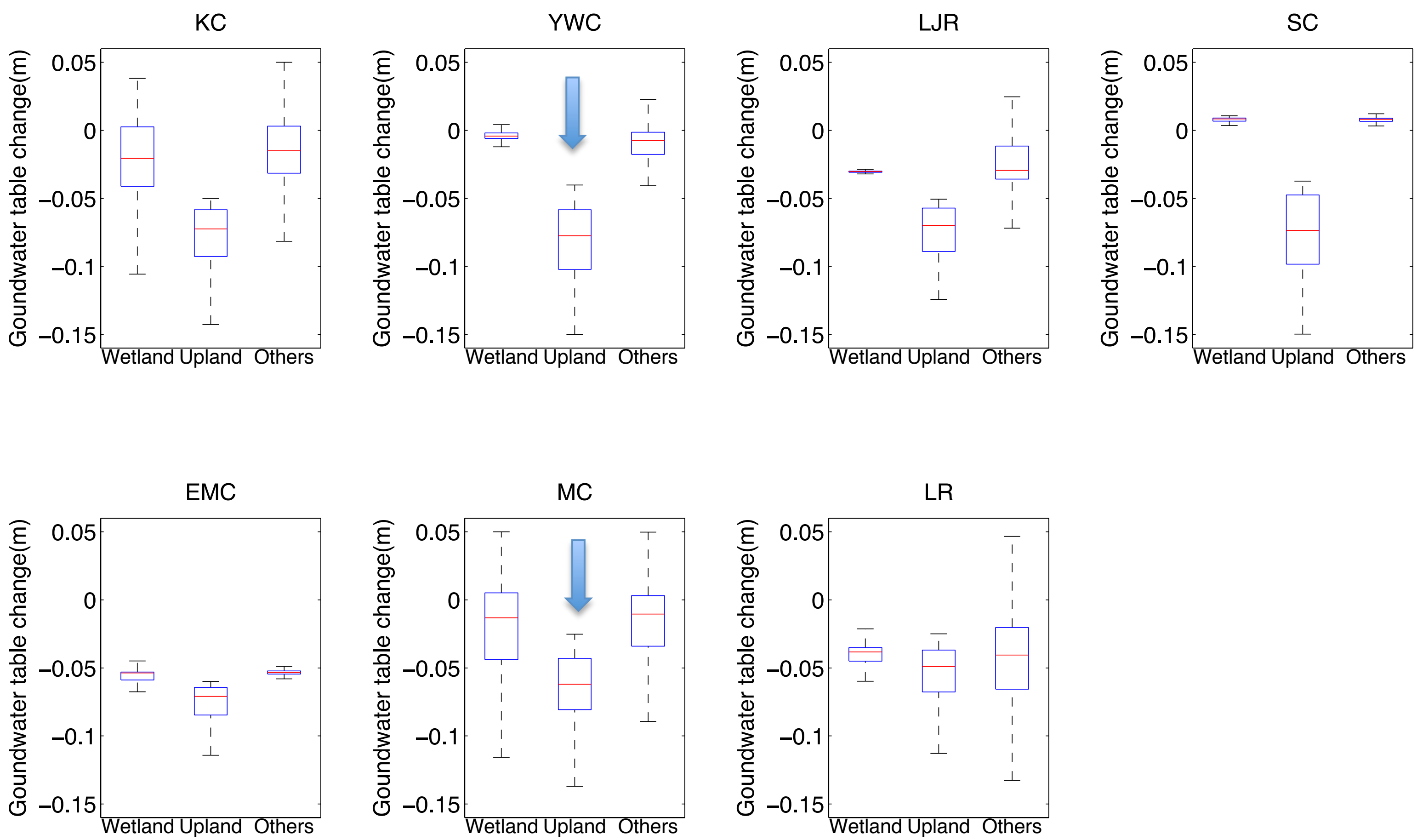


Simulated-Observed Wetlands

Working definition: wetland is defined as having a water table within 30 cm of the surface



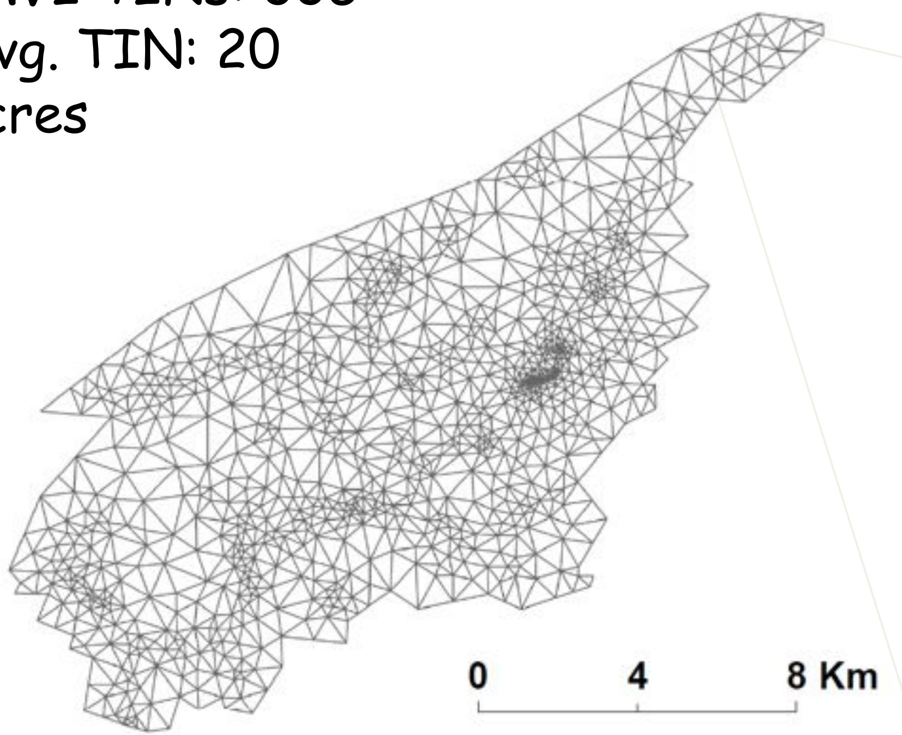
Upland catchments are the most impacted landscape Based on depth to groundwater

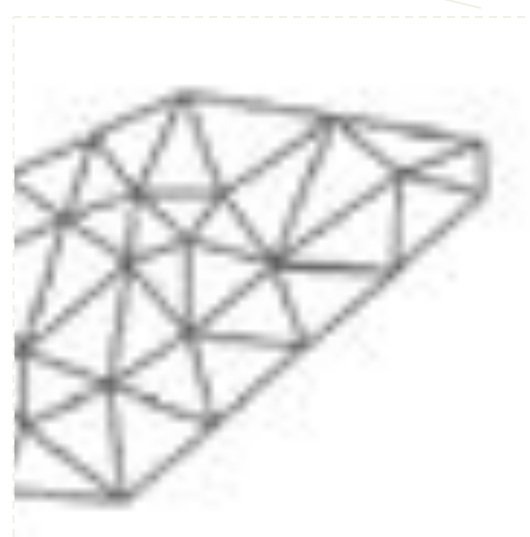


Detailed View of Shaver Creek Catchment

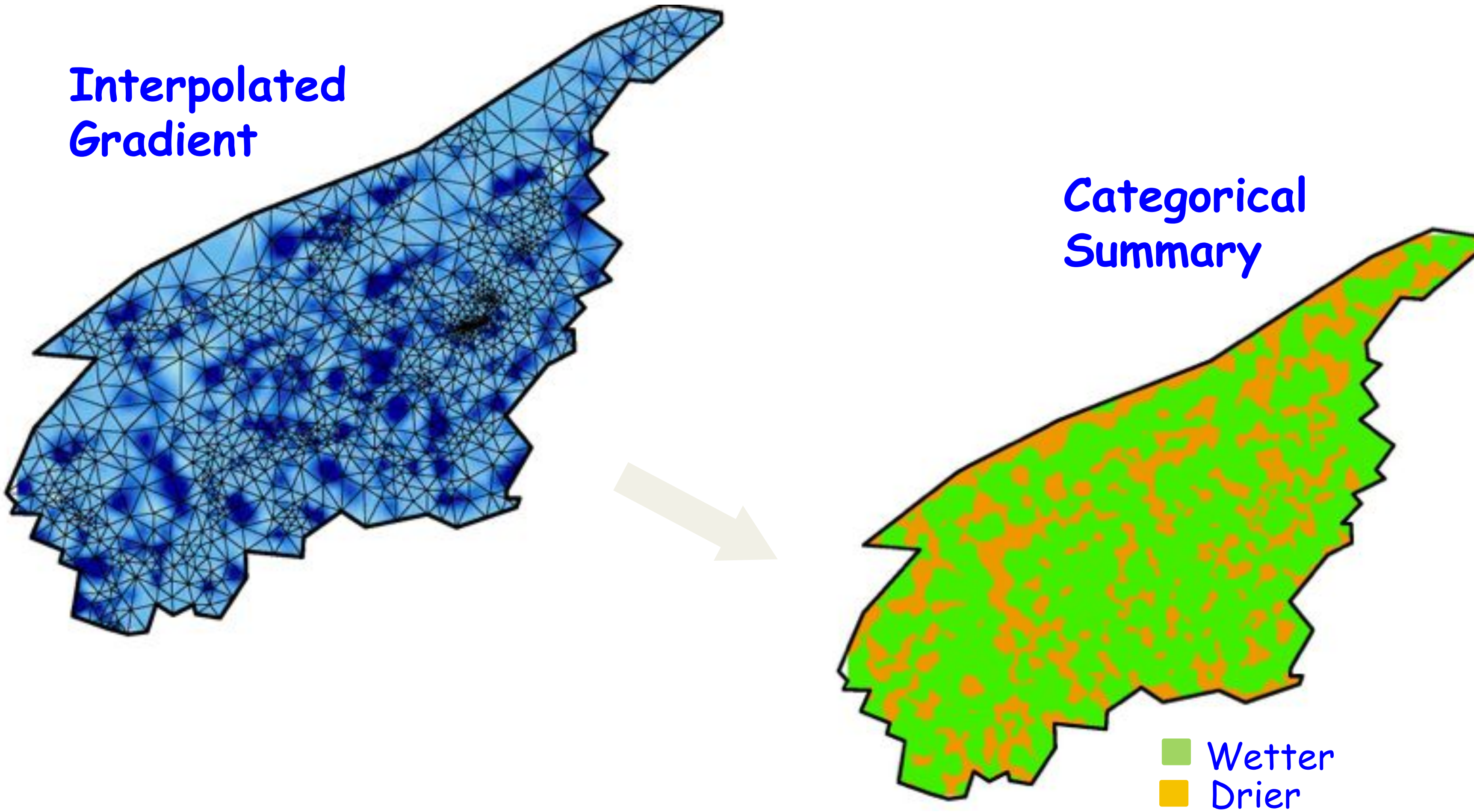
Shaver's Creek
163 km^2
Total TINs: 1986
NWI TINs: 335
Avg. TIN: 20 acres

TINs
Triangular **I**rregular **N**etwork



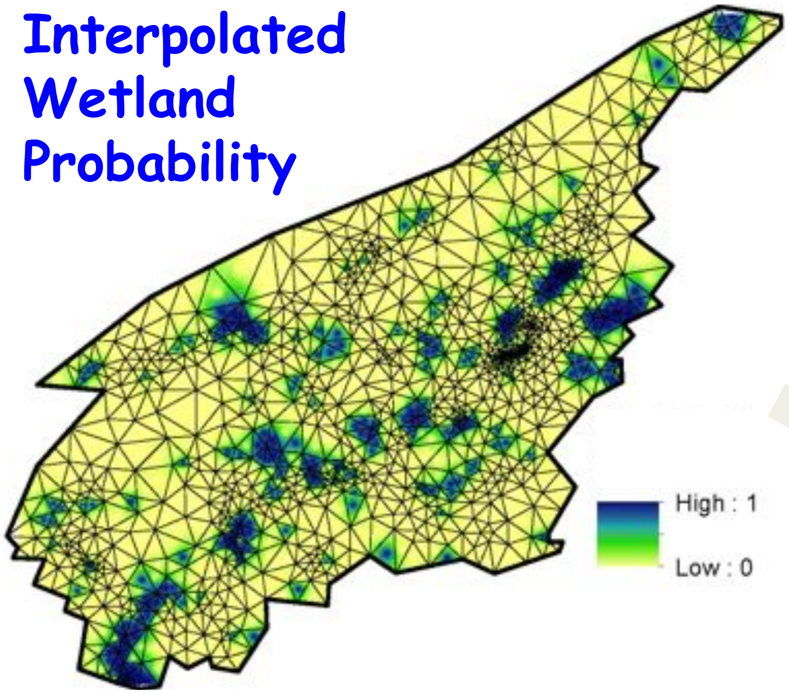


Groundwater Change

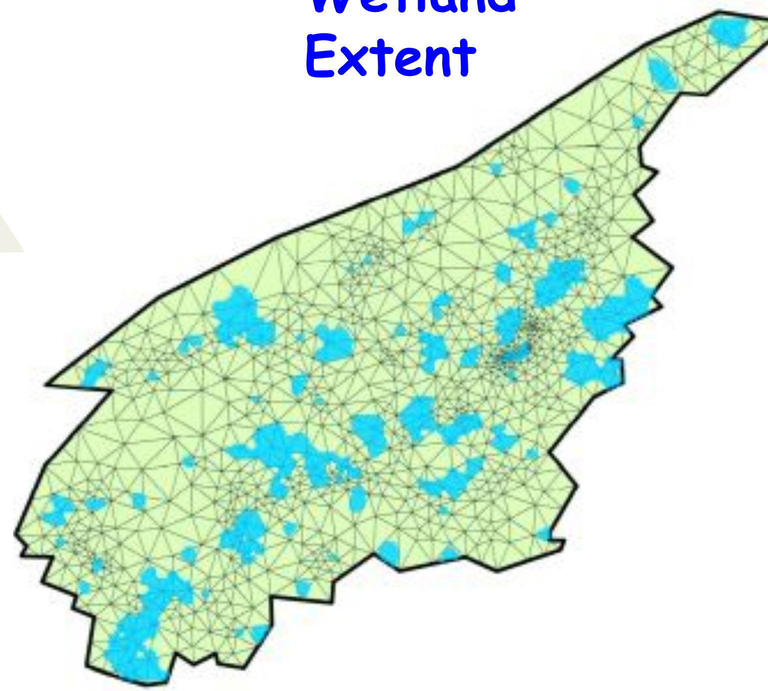


Modeling Wetland Extent

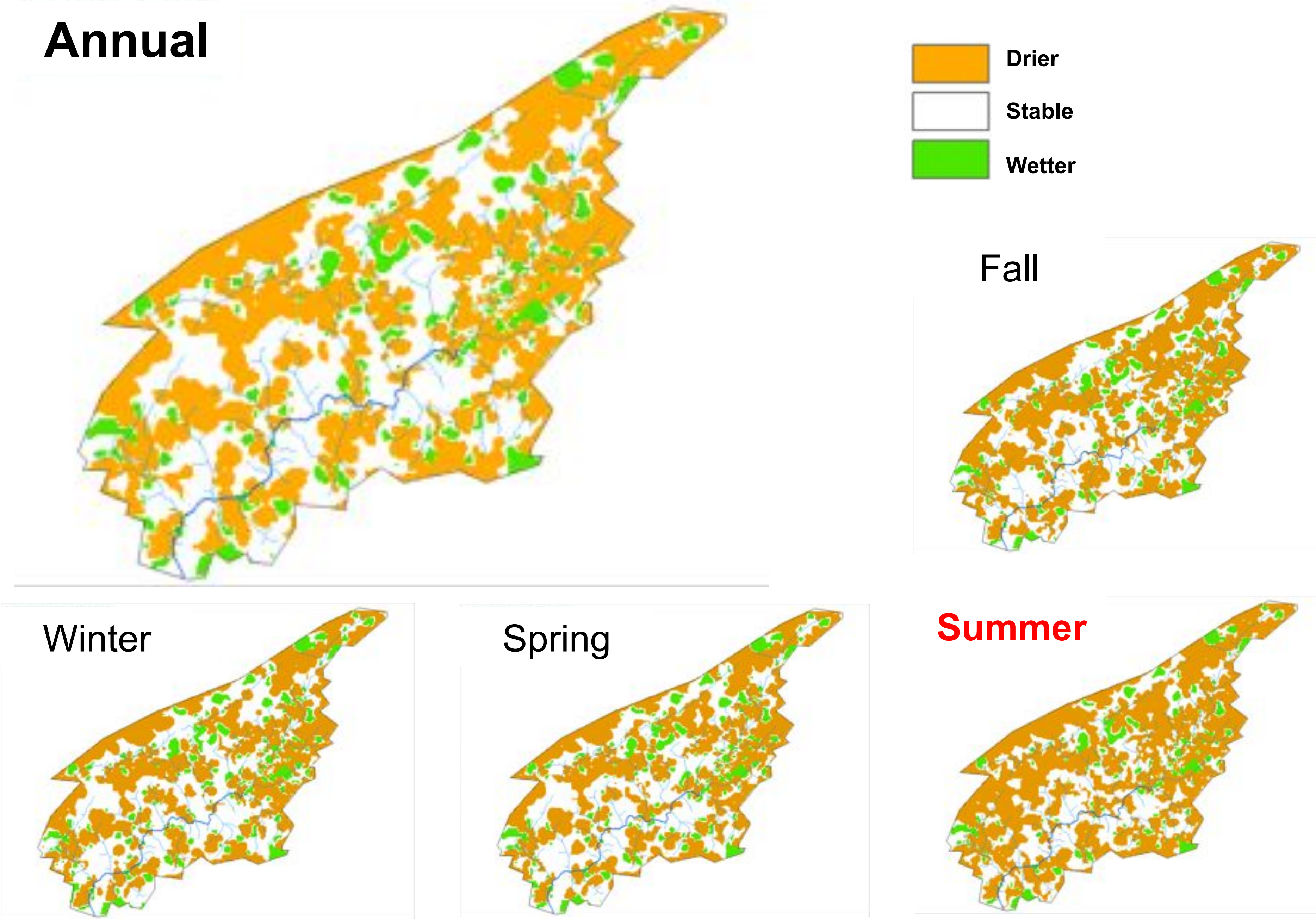
Interpolated
Wetland
Probability



Modeled
Wetland
Extent



Seasonal GW Change Scenario Shavers Creek



Shaver's Creek Wetland Results

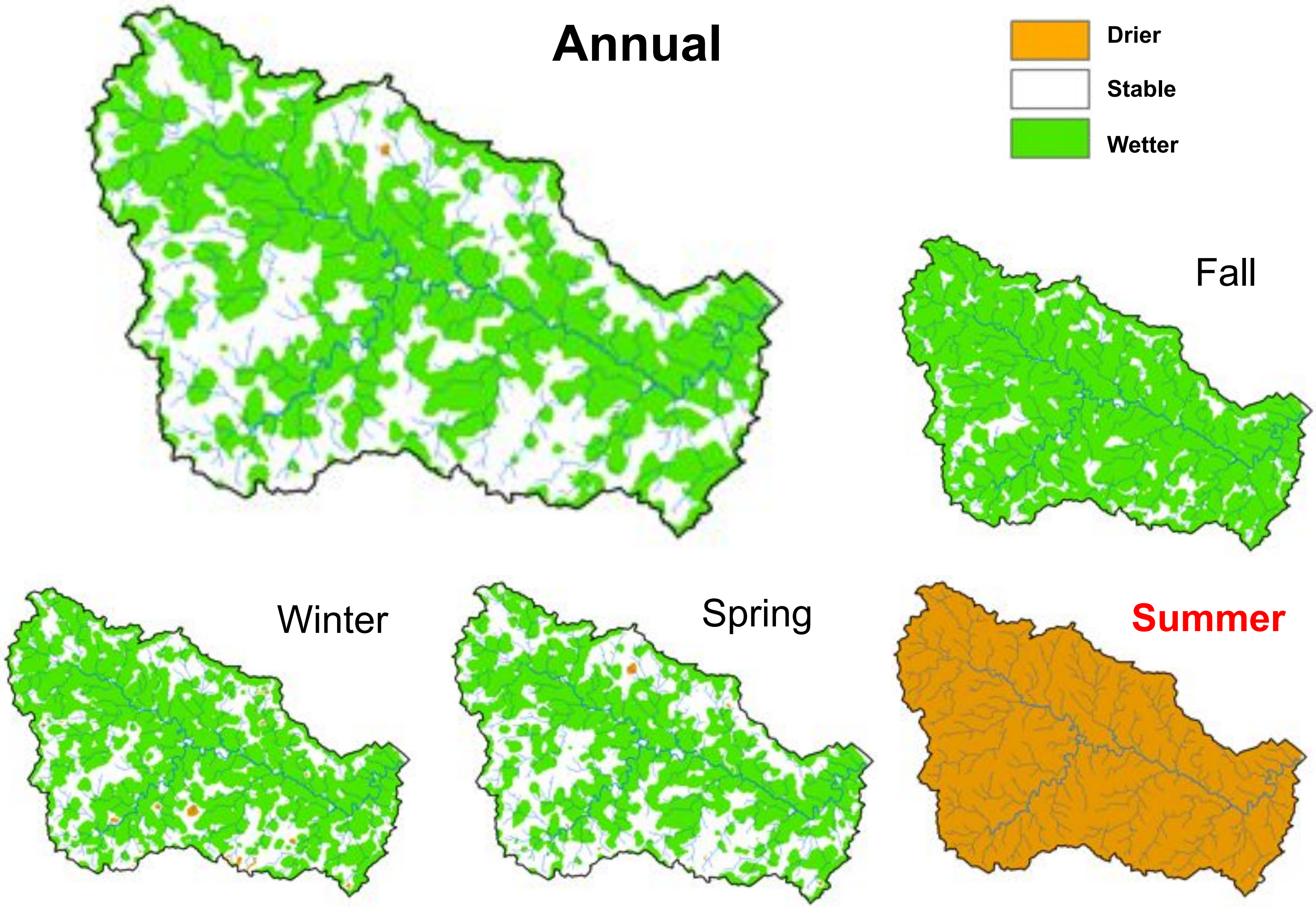
Largest Losses:
Isolated Depressions

Largest Gains:
Riverine Floodplains

Watershed Overview	Drier	Wetter
Entire Watershed	33%	67%
NWI Wetlands	20%	80%
PIHM Wetlands	25%	75%

PIHM Wetlands (HGM)	Drier	Wetter
PIHM-Depression	27%	73%
PIHM-Slope	25%	75%
PIHM-Riverine	19%	81%

Seasonal GW Change Scenario: Muddy Creek



7 Catchment Results

	NWI Wetlands		PIHM Depression		
	Drier	**Wetter**	**Drier**	**Wetter**	**Ecoregion**
Lackawanna River	**74%**	**26%**	**71%**	**29%**	**Glaciated Plateau**
Young Womans Creek	62%	38%	63%	37%	Unglaciated Plateau
Kettle Creek	47%	53%	62%	38%	Unglaciated Plateau
East Mahantango Creek	40%	60%	50%	50%	Ridge and Valley
Shaver's Creek	**20%**	**80%**	**27%**	**73%**	**Ridge and Valley**
Little Juniata River	71%	29%	64%	36%	Ridge and Valley
Muddy Creek	35%	65%	35%	65%	Piedmont

Workshop Outline

1. Overview of catchment modeling process

2. Accessing geospatial data from national data products

3. The model-data workflow

4. Research Opportunities in lake-catchment modeling

- Strategies for a fully coupled lake-catchment model
- Defining an experimental "Isoscape" for water and carbon
- The age of water and carbon in lake-catchment systems

6. Discussion