Short Rotation Woody Biomass Sustainability

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Feedstocks Platform Review

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Goal Statement

Overall Project Goal:

Use watershed-scale experiments along with a distributed catchment modeling approach to evaluate the environmental sustainability (water quality and quantity) of intensive short-rotation pine practices for bioenergy in the Southeastern U.S.

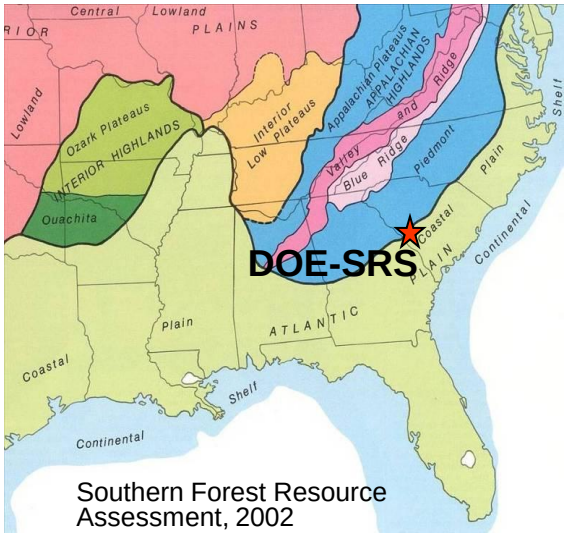
DOE OBP Feedstock Strategic Goal:

Develop sustainable technologies to provide a secure, reliable, and affordable biomass feedstock supply for the U.S. bioenergy industry in partnership with USDA and other key stakeholders (DOE OBP MYPP Nov 2010)

Project Overview

History: Initiated in 2009 at Savannah River Site (SRS). Watersheds (600 hectares of old-field forest) set aside by SRS for environmental R&D of intensive biomass to support regional sustainable feedstock supplies (e.g., SRS wood-based power plants consume ~250,000 tons/year)

Context: The Southeastern U.S. will be a dominant feedstock source for bioenergy. High-yield targets have been demonstrated experimentally (incl. SRS). Stream and groundwater quality impacts of these practices (annual weed control & fertilization) coupled with advanced genetics have not been adequately validated <u>in combination at the catchment scale.</u> Current forestry BMPs in the S.E. have not been tested on silviculture of this intensity



Southern Forest Resource Assessment, 2002

Objectives: Directly assess the effects of intensive silviculture practices on watershed hydrology and water quality relative to contaminant standards, integrate hydrologic processes across scales, and apply distributed modeling to generalize and interpret results and suggest mitigation strategies

Overall Technical Approach

The experiment uses a before-after control-intervention (BACI) design involving the study of three adjacent watersheds at SRS

- Intensive silviculture practices are "state of the art" for woody crops and include soil ripping, multiple herbicide applications, annual fertilization, and advanced genetic material
- Monitoring of hydrology, and stream and groundwater quality allows for a direct assessment of environmental effects at an operational scale
- Distributed modeling allows integration of water flowpaths and mass balances across all time scales at the plot, hillslope, and watershed spatial scales to generalize results to the Coastal Plains area of the Southeastern U.S., an area projected to be a dominant contributor to woody biomass feedstocks for bioenergy production
- Process-level field observations on water isotopes, subsurface flow, and N-cycling, coupled with precision spatial data will enhance interpretation of model results

Overall Management Approach

Division of tasks: water quality (ORNL), hydrology (UGA), hydrologic modeling (OSU), operational forestry practices (SRS-USFS), and forest nutrition (SRS-USFS)

Project management:

- Monthly conference calls to discuss progress
- Bi-annual project meetings (Dec 2010 at UGA, July 2011 at OSU)
- On-site field technician (UGA) collects samples and maintains equipment

2010/2011 Milestones divided by tasks to monitor progress:

Milestone	Due Date	Group(s) Responsible	Status
Begin water quality sampling	2/1/2010	ORNL/UGA	Completed
Collect water samples during storms	5/30/2010	ORNL/UGA	Completed
Watershed characterization and install monitoring equipment	9/30/2010	UGA	Completed
Model hillslope-scale hydrology	9/30/2010	OSU	Completed
Analysis of water quality samples collected in FY10	12/31/2010	ORNL	Completed
Initial parameterization of distributed watershed model	3/31/2011	OSU	75% complete
Develop plan for silviculture treatments	6/30/2011	USFS	75% complete
Analysis of water quality of undisturbed southern pine watersheds prior to establishing treatments for bioenergy feedstock production	9/30/2011	ORNL	25% complete

Process Overview/Timeline

FY10

FY11

progress to date

- Site selection and determination of experimental treatments, including development of silviculture plan
- Initiate watershed characterization: install hydrology and water quality monitoring equipment
- Determine baseline hydrology and water quality conditions in all 3 watersheds

FY12

FY13

- Implement short-rotation pine treatments in 2 watersheds (conversion of ~40% of extant forest to short-rotation pine)
- Continue monitoring in all 3 watersheds to assess impacts of forest conversion on hydrology and water quality, and compare impacts to both baseline values and the reference watershed

FY14

FY15

- Continue monitoring hydrology and water quality to assess longer-term effects of conversion and management of short-rotation pine
- Compare and evaluate effects of short-rotation pine on hydrology and water quality to existing BMPs and regulatory standards

Data collected from watershed characterization and hydrologic measurements will be used to develop and inform hillslope- and watershed-scale hydrologic models.

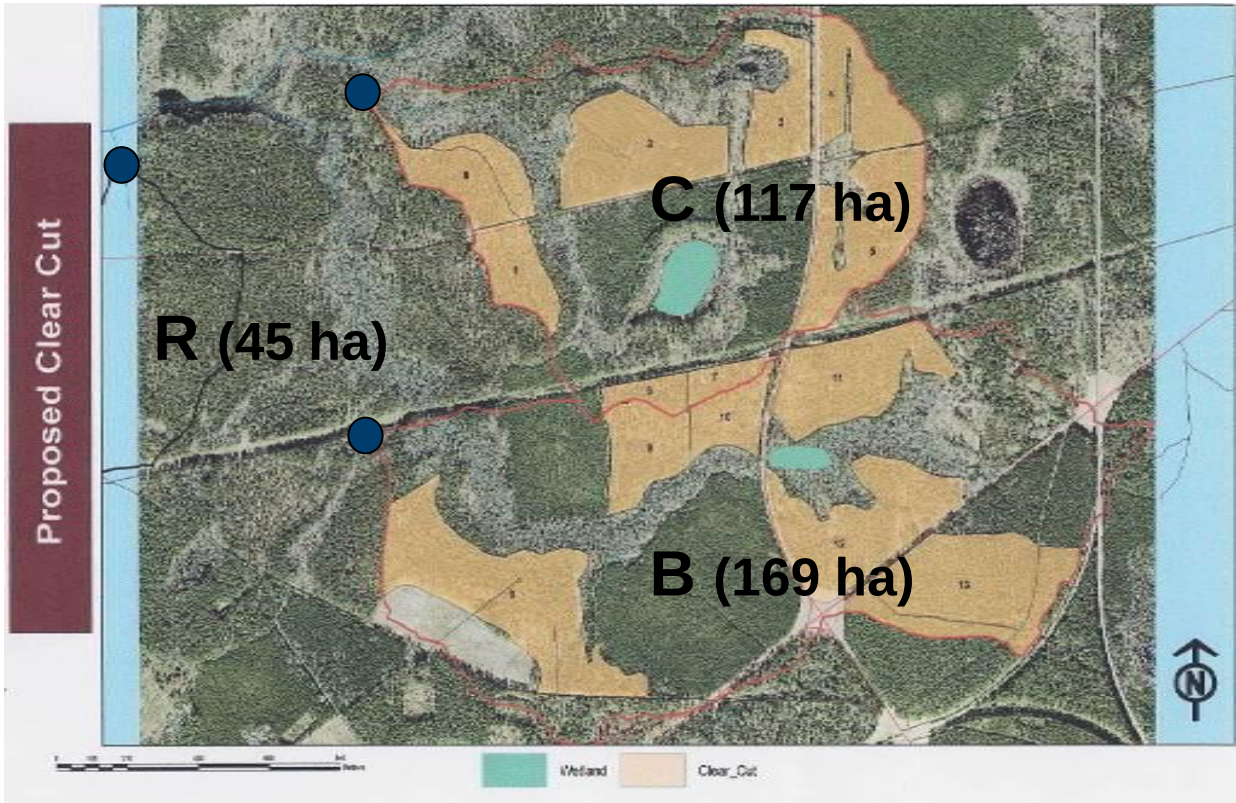
Model development and application to bioenergy feedstock sustainability in the Southeastern U.S. will occur in parallel throughout entire study.

Progress on Site Selection & Experimental Treatments

- Three large old-field forested watersheds with intermittent stream and ephemeral channels mapped.
- One reference (R-45 ha) and two treatment (B-169 ha, C-117 ha) watersheds. Intensive practices planned on 40+% (130 ha) involving site preparation, planting advanced genetic loblolly pine, repeated herbicide application, and annual N fertilization.

- Acquired and integrated Savannah River Site detailed soils, vegetation, topography, groundwater, streams, and meteorological databases from SRNL and USFS.

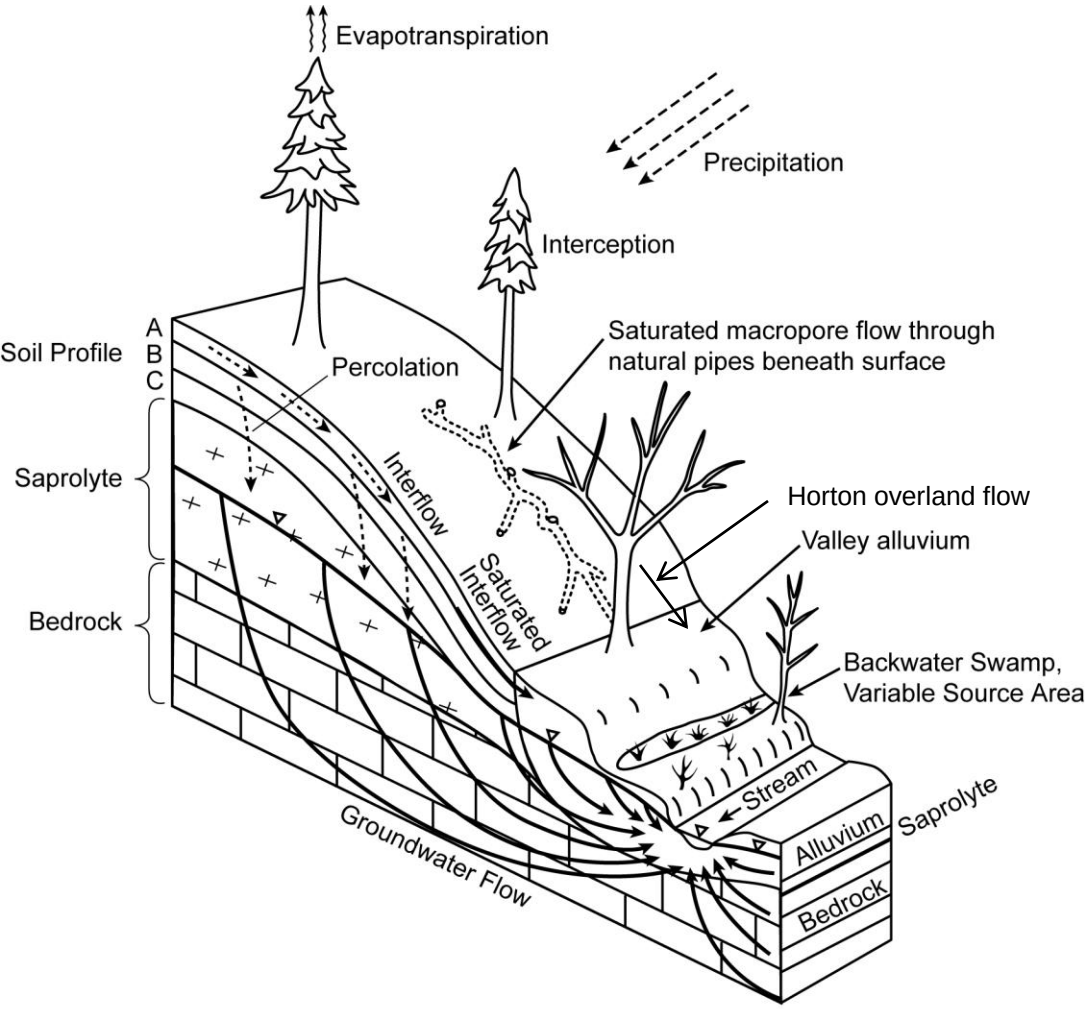
Planned harvest units in tan color.

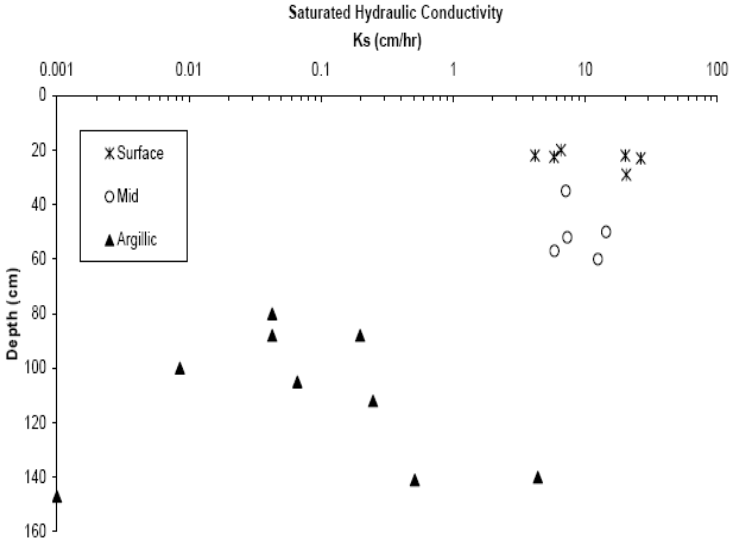


Progress on Intensive Silviculture Treatment Plan

- Schedule for harvesting and implementation of intensive silviculture:
  - Precision LiDAR flown to map topography and vegetation biomass 2009-10
  - Harvest of extant forest in Dec 2011-Mar 2012
  - Award seedling contract in Oct 2011; site preparation contracts in Mar 2012; and planting contract in September 2012
  - Broadcast application of herbicide (imazapyr-glyphosate) in summer 2012
  - Mechanical site preparation -ripping of planting rows in Oct 2012
  - Plant advanced genetic material of loblolly pine in Dec 2012-Feb 2013
  - Award herbicide and fertilization contracts in Dec 2012
  - Banded application of herbicide Feb/Mar 2013 for herbaceous control
  - Fertilization of planting rows with NP in May-June 2013
  - Banded application of herbicide Feb/Mar 2014 for herbaceous control
  - Fertilization of planting rows with N in May-June 2014
  - Fertilization of planting rows with N in May-June 2015

Progress on Watershed Characterization: Instrumentation





Progress on Watershed Characterization: Instrumentation

- We have instrumented hillslopes and streams in three watersheds
- We are collecting data to characterize flow behavior and parameterize the distributed model. Installations include:
  - 3 flumes (intermittent sites) and 3 control stations (ephemeral sites) on 3 streams
  - 6 ISCO automated stream samplers
  - 3 interflow interception trenches for a total of 200 m, subdivided into 22 separately monitored sections
  - 104 maximum rise piezometers on 3 hillslopes
  - 9 nests (topsoil, clay, below clay) of recording piezometers on hillslopes
  - 9 lysimeter nests
  - 20 soil moisture nests

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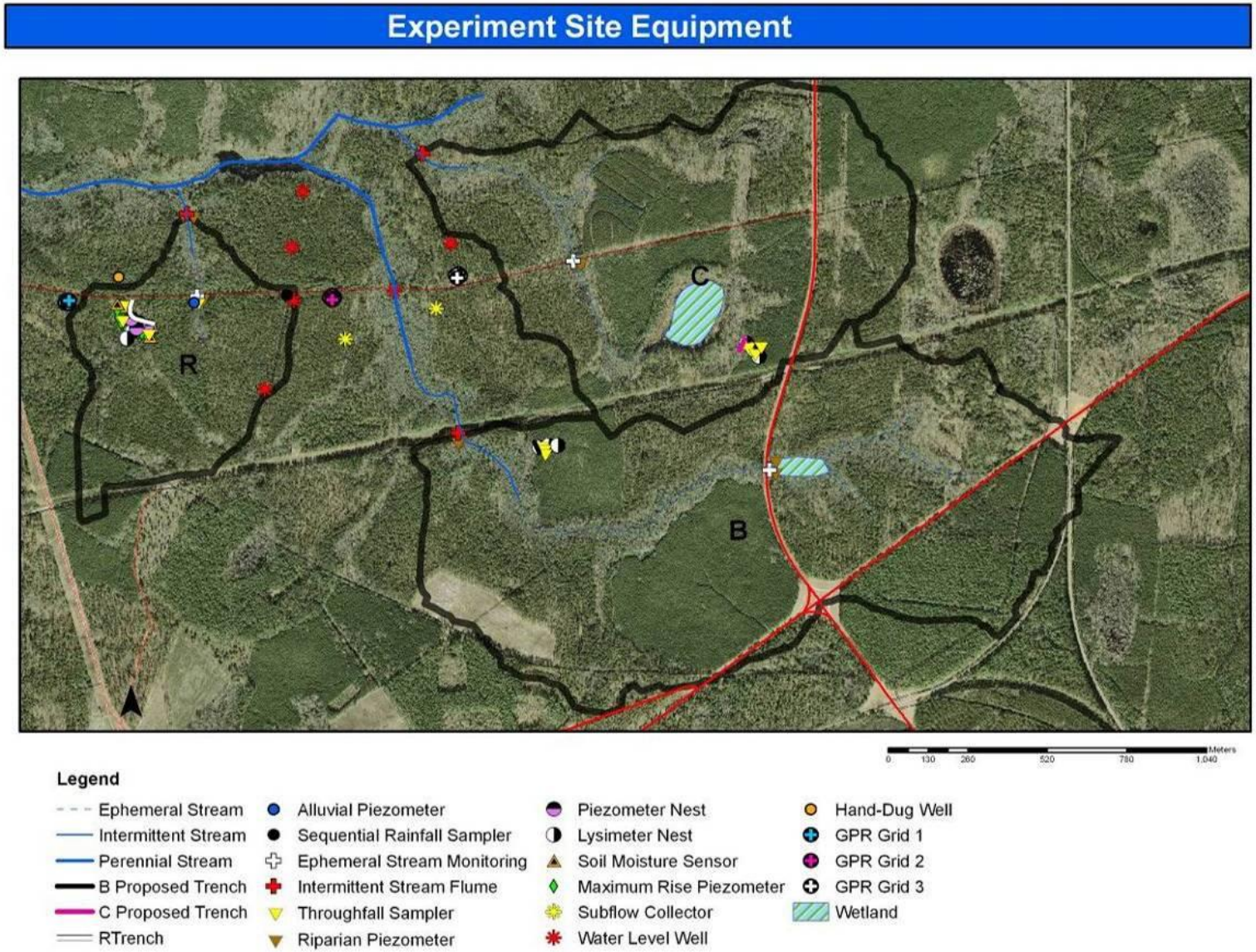
Progress on Watershed Characterization: Instrumentation



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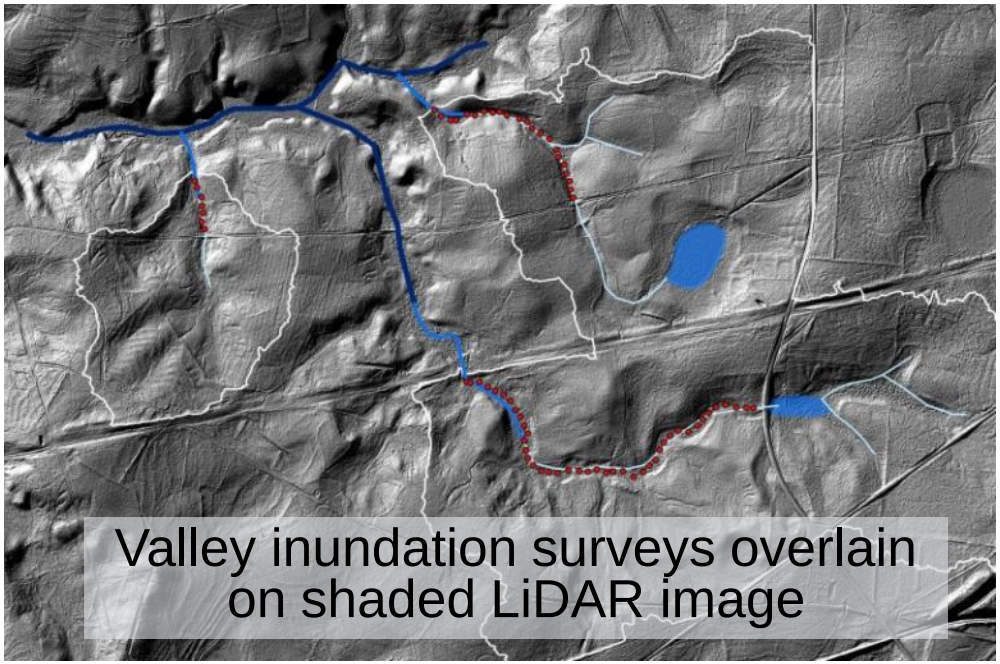
Progress on Watershed Characterization: Measurements

- Water isotope sampling intervals:
  - Weekly grab stream sampling
  - Ephemeral stream storm sampling
  - Monthly well sampling
  - Storm sampling of piezometers
  - Storm sampling of trench flows
  - Monthly sampling of lysimeters adjacent to streams
- Miscellaneous tasks:
  - Monthly valley inundation surveys
  - In-situ measurements of clay conductivity
  - GPR survey of clay anomalies at three locations
  - LiDAR-derived topographic wetness indices (see additional slide)



Valley inundation surveys overlain on shaded LiDAR image

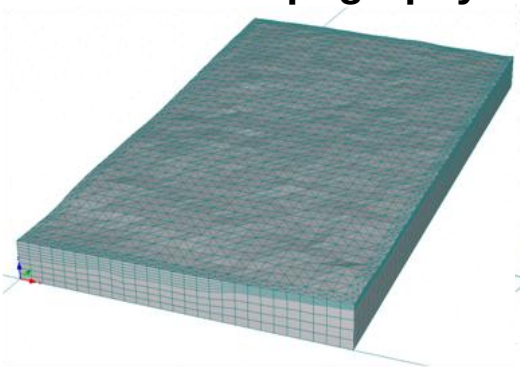
Results to date from Watershed Characterization

- Perching on clay horizon is common based on maximum rise piezometer data, but interflow only occurs with large storms on wet soils
- Lateral macropore flow has not been observed and in-situ saturated hydraulic conductivities of clays are highly variable (from 0.001 cm/hr to 5 cm/hr, 4 orders of magnitude)
- There is significant variability between trench segments with some segments flowing when others do not
- Peak stream flows and flow durations differ between the three watersheds
- Stream flows and valley saturation surveys indicate strong seasonality of intermittent stream flows
- Data from SRS background wells and project wells indicates that the groundwater fluctuates up to 5 m with seasonal and annual rainfall
- No signs of overland flow under forest

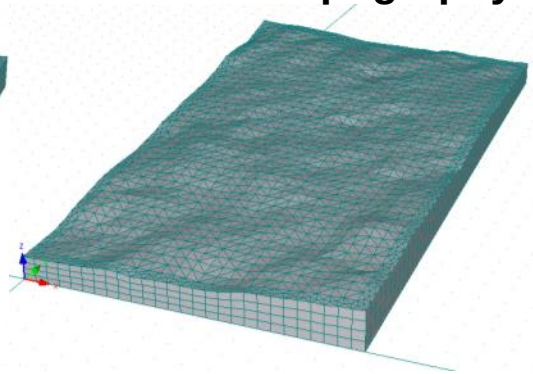
Results to date from Small-scale Hillslope Modeling

Objective: To better understand the contribution of interflow for stream flow generation in low-relief landscapes

surface topography



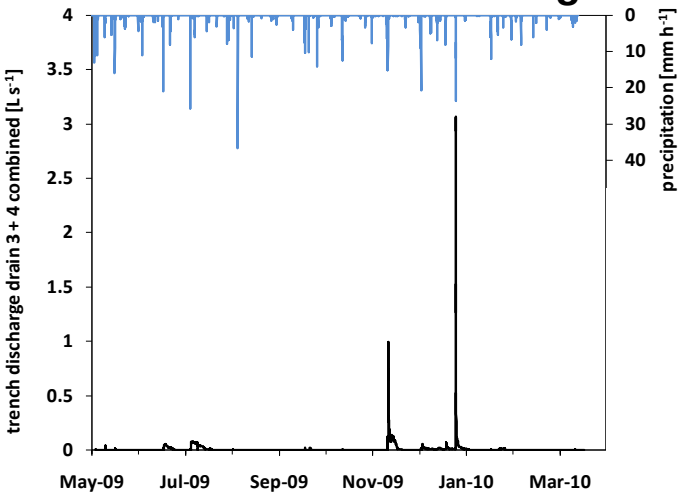
subsurface topography



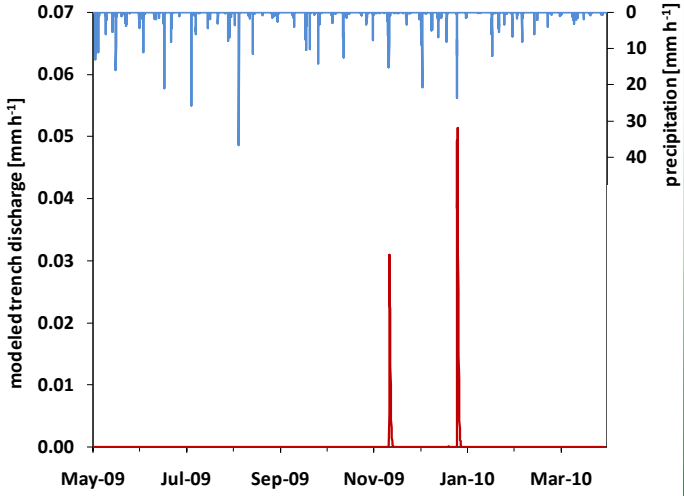
- HYDRUS-3D: based on measured surface and subsurface topography, saturated hydraulic conductivities, and moisture release curves at Watershed R
- Initial simulated flow modeled on hourly climate records in 2009 (rain, evapotranspiration)

- Rainfall for 2009 partitioned between leakage through clay layer, ET loss, and interflow

measured trench discharge



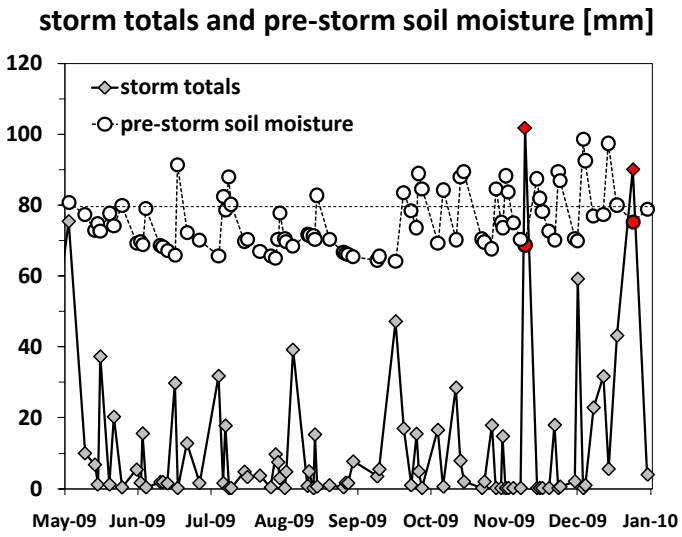
simulated interflow

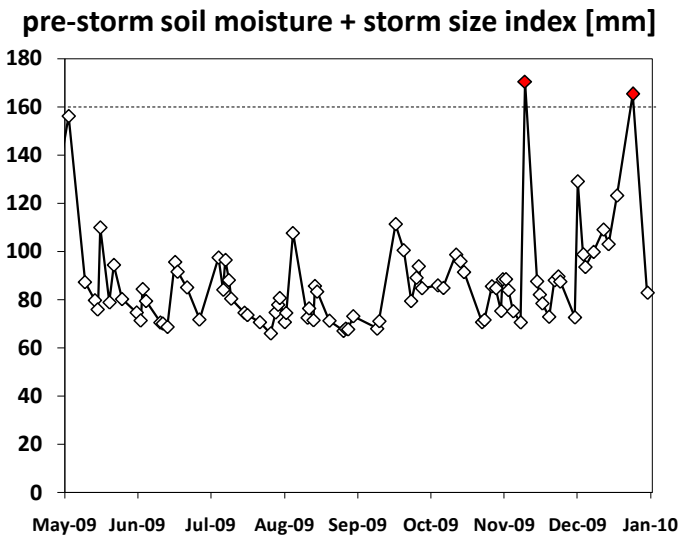


Results to date from Small-scale Hillslope Modeling

Objective: Threshold analysis of rainfall is needed to induce interflow?

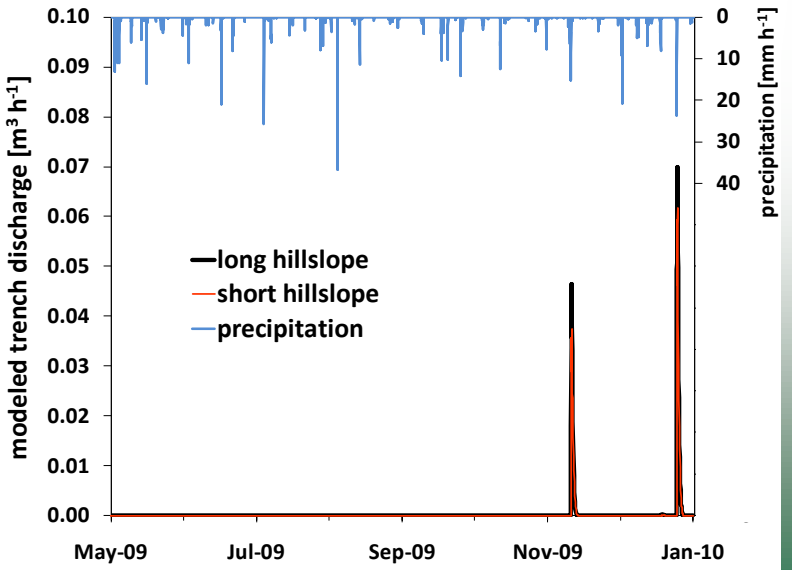
- Storm size (>80 mm) as well as a combined index of storm size and pre-storm soil moisture (>160mm) are markedly higher for the two interflow-generating events (shown in red dots) for the 2009 period





Objective: Role of slope length for generating interflow

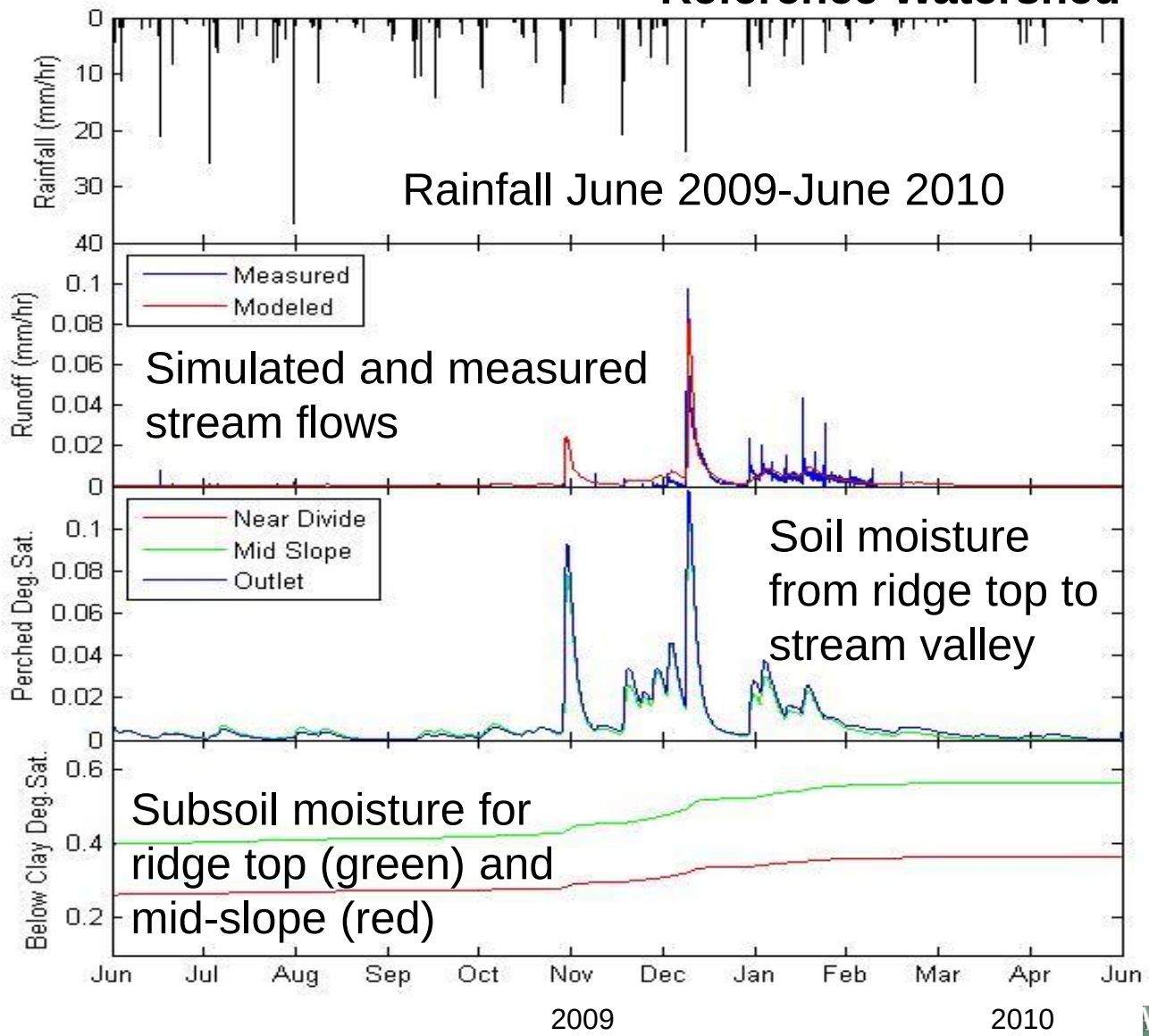
- Simulations with a hillslope with doubled slope length (90 m) suggest that the interflow-generating distance is about ~40-50 m, which can be interpreted as the typical travel distance of interflow in a low-relief landscape



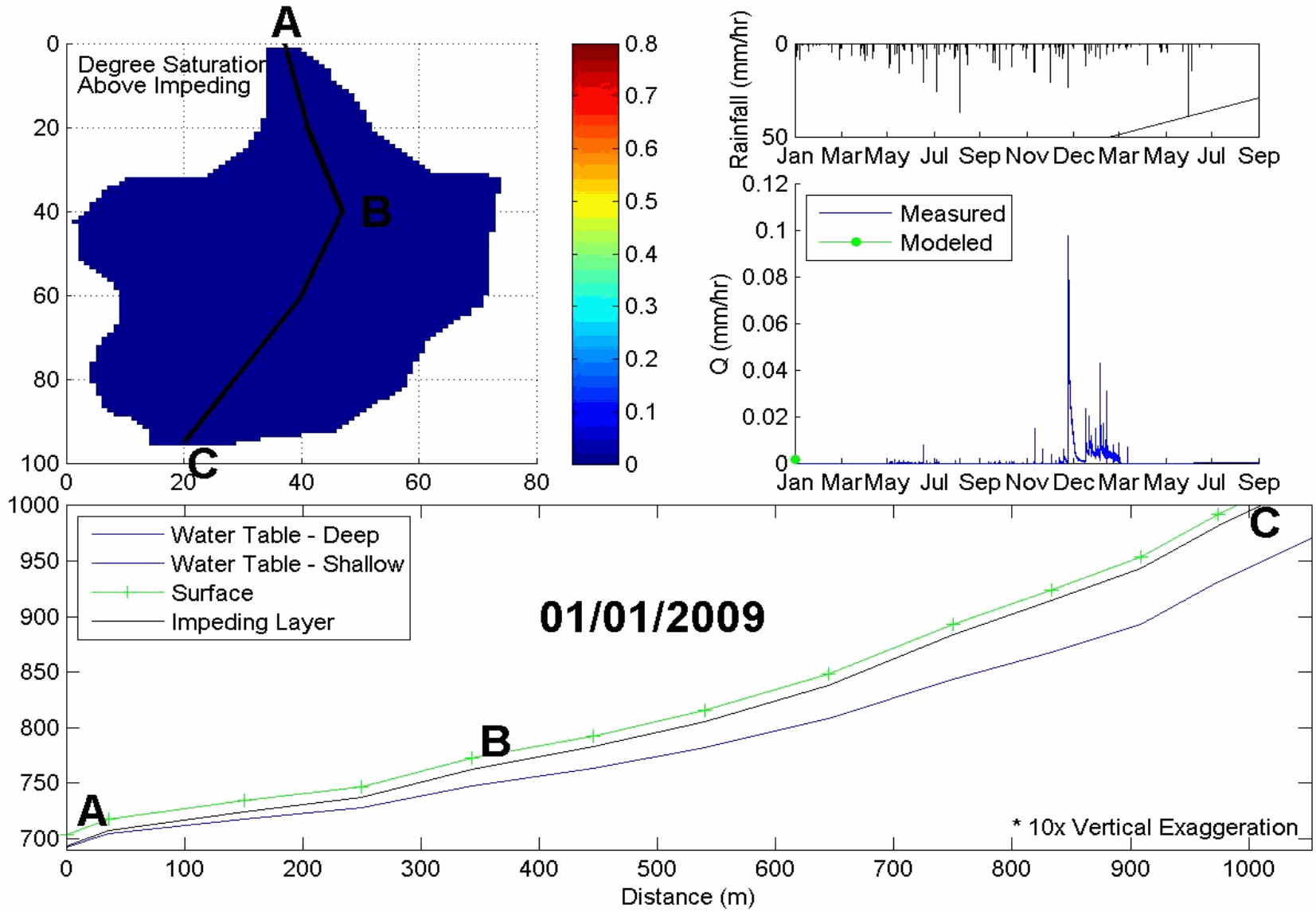
Results to date from Watershed Modeling

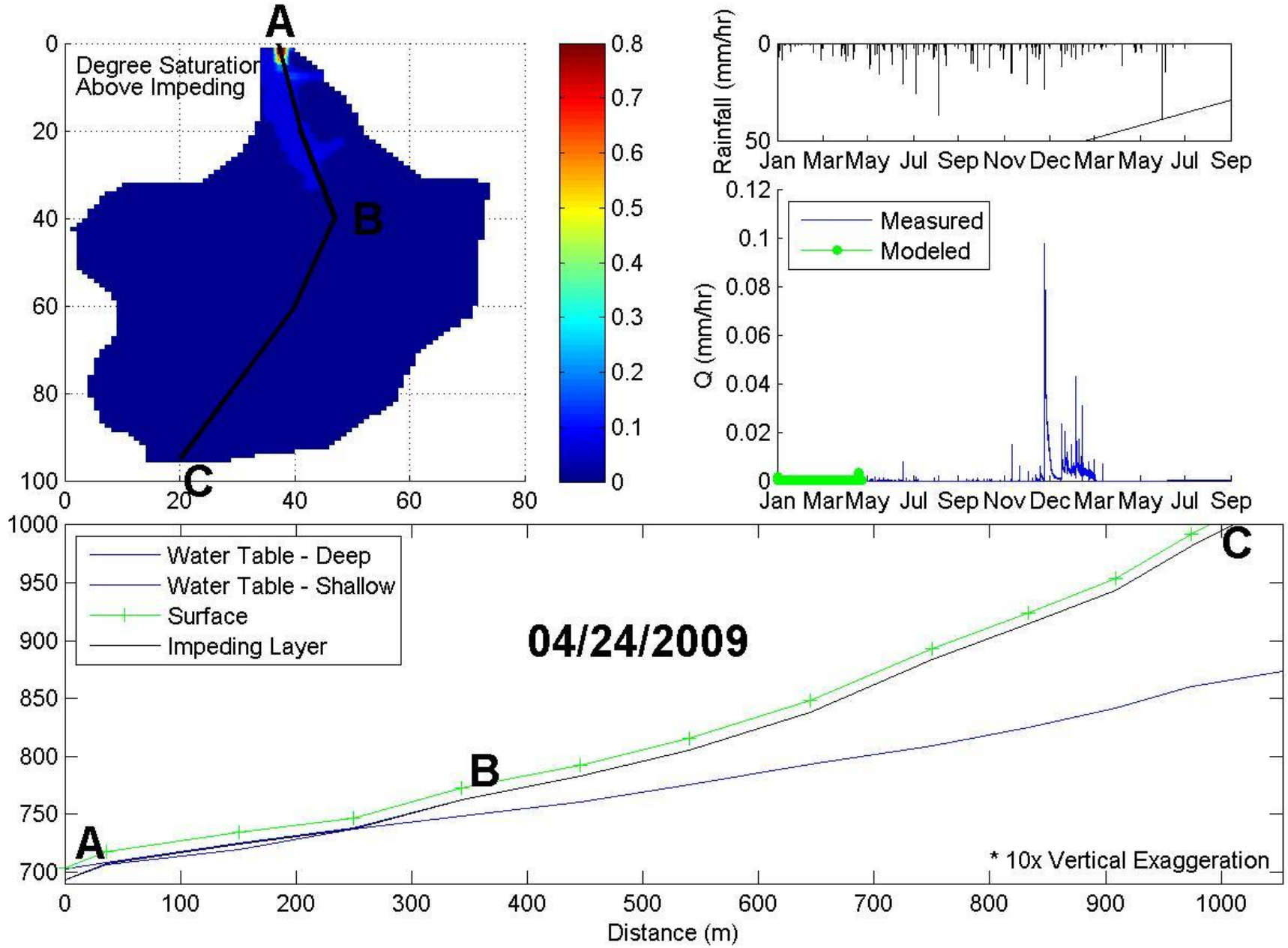
- Pre-treatment simulations are completed, and will be updated as additional data are collected
- Simulated and observed stream flows for 2009-2010 calibration period show good agreement

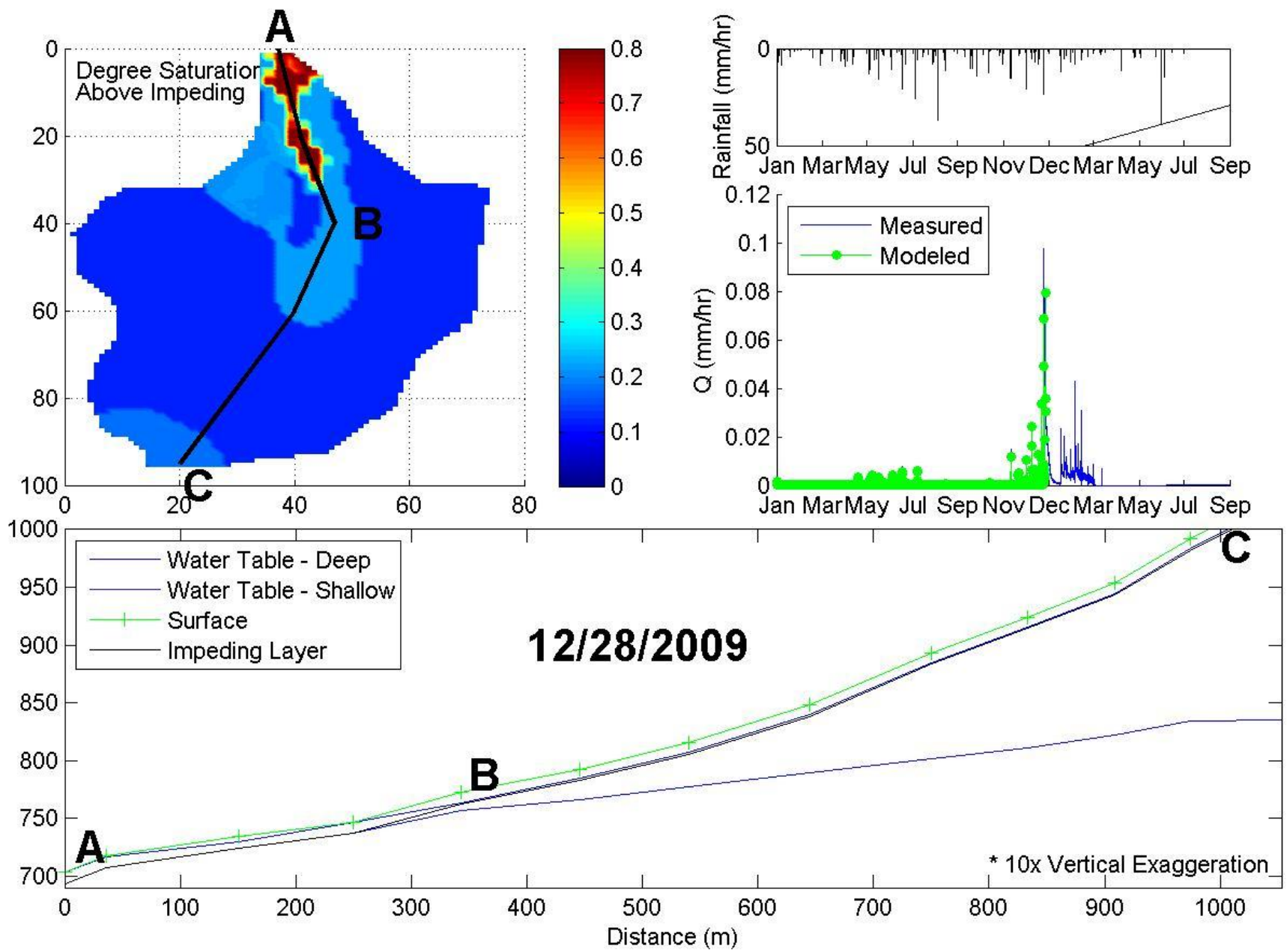
Reference Watershed



Results to date from Watershed Modeling




Degree Saturation
Above Impeding
A
B
C
Rainfall (mm/hr)
Jan Mar May Jul Sep Nov Dec Mar May Jul Sep
Measured
Modeled
Q (mm/hr)
Water Table - Deep
Water Table - Shallow
Surface
Impeding Layer
04/24/2009
* 10x Vertical Exaggeration
Distance (m)


Degree Saturation
Above Impeding
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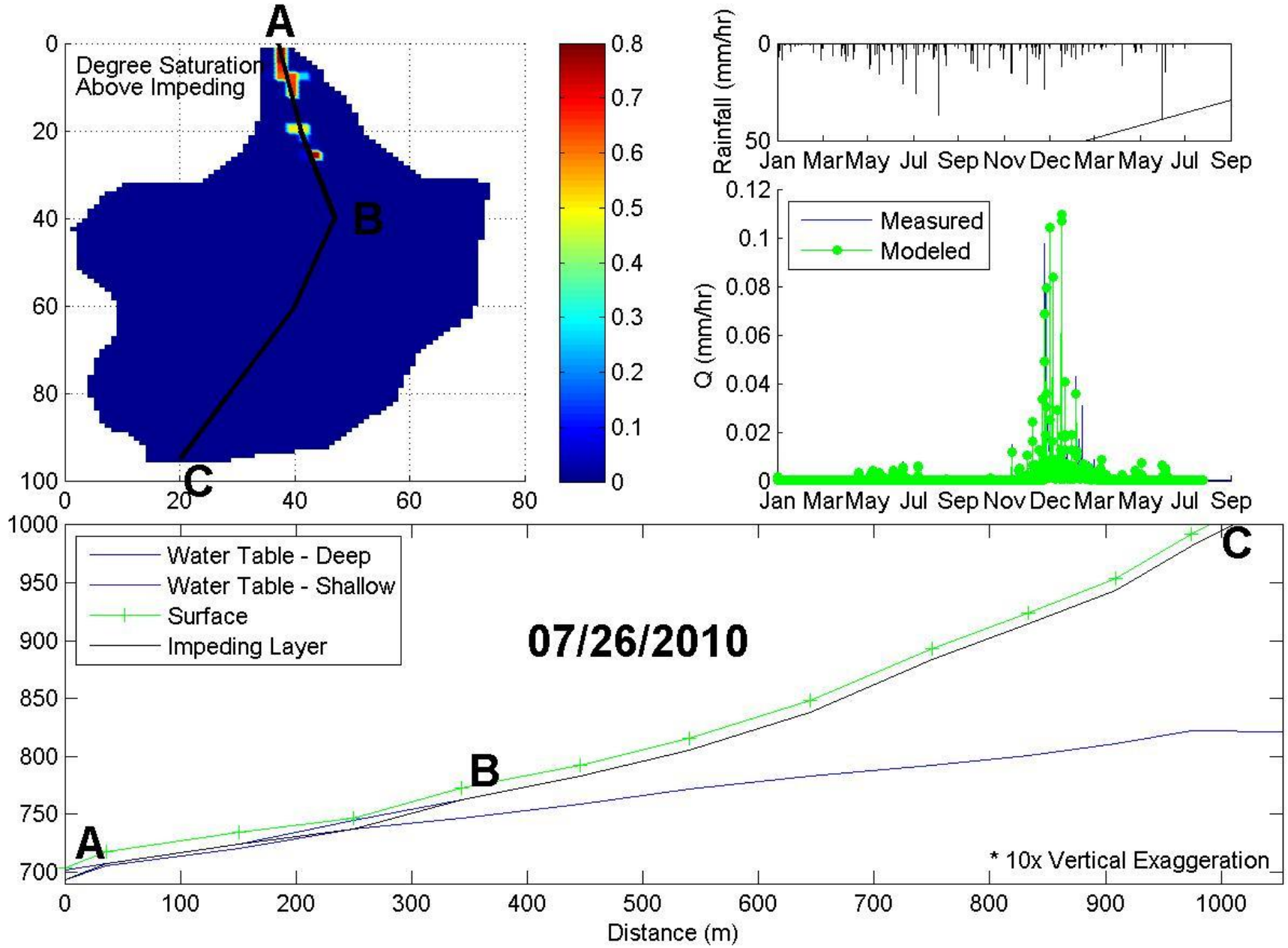
Rainfall (mm/hr)
Jan Mar May Jul Sep Nov Dec Mar May Jul Sep
Measured
Modeled
Q (mm/hr)
Water Table - Deep
Water Table - Shallow
Surface
Impeding Layer
12/28/2009
* 10x Vertical Exaggeration
Distance (m)


Degree Saturation
Above Impeding
A
B
C
Rainfall (mm/hr)
Jan Mar May Jul Sep Nov Dec Mar May Jul Sep
Measured
Modeled
Q (mm/hr)
Water Table - Deep
Water Table - Shallow
Surface
Impeding Layer
07/26/2010
* 10x Vertical Exaggeration
Distance (m)

Results to date from Watershed Modeling

- Streamflow in intermittent streams occurs only during the wet season (winter/spring)
- Runoff ratios during the simulation period are very low (0.0054 from 5/5/2009 to 1/1/2010, based on 908 mm of precipitation and 4.95 mm of discharge) and streamflow occurs only after the regional water table rises
- Seasonal groundwater dynamics control when streamflow begins and ends
- Simulations require the inclusion of groundwater dynamics to effectively capture streamflow
- Longer discharge records at four locations, groundwater levels, and soil moisture are being used to evaluate and improve model results

Progress on Water Quality: Sampling Design

Rationale: We are utilizing high-frequency sampling of environmentally-relevant water quality parameters in order to accurately quantify how short-rotation pine may affect concentrations and fluxes in managed watersheds

- Establishment of sampling location and frequency:
  - Ephemeral and intermittent stream sites
    - Weekly
    - During storms
  - Precipitation collectors
    - Weekly
  - Riparian groundwater wells
    - Monthly
    - During storms
  - Tension lysimeters (soil water)
    - Monthly
  - Interflow interception trenches (shallow groundwater flow)
    - During storms
- Selection of key water quality measurements:
  - Nutrients (nitrogen, phosphorus)
  - Dissolved organic carbon
  - Suspended sediments
  - Specific conductivity
  - Herbicides (imazapyr, sulfometuron methyl, glyphosate)
  - Isotopic tracers in nitrate (^{15}N, ^{18}O) as an indicator of nitrogen cycling processes and potentially evidence of fertilizer loss

YSI datasonde in B stream

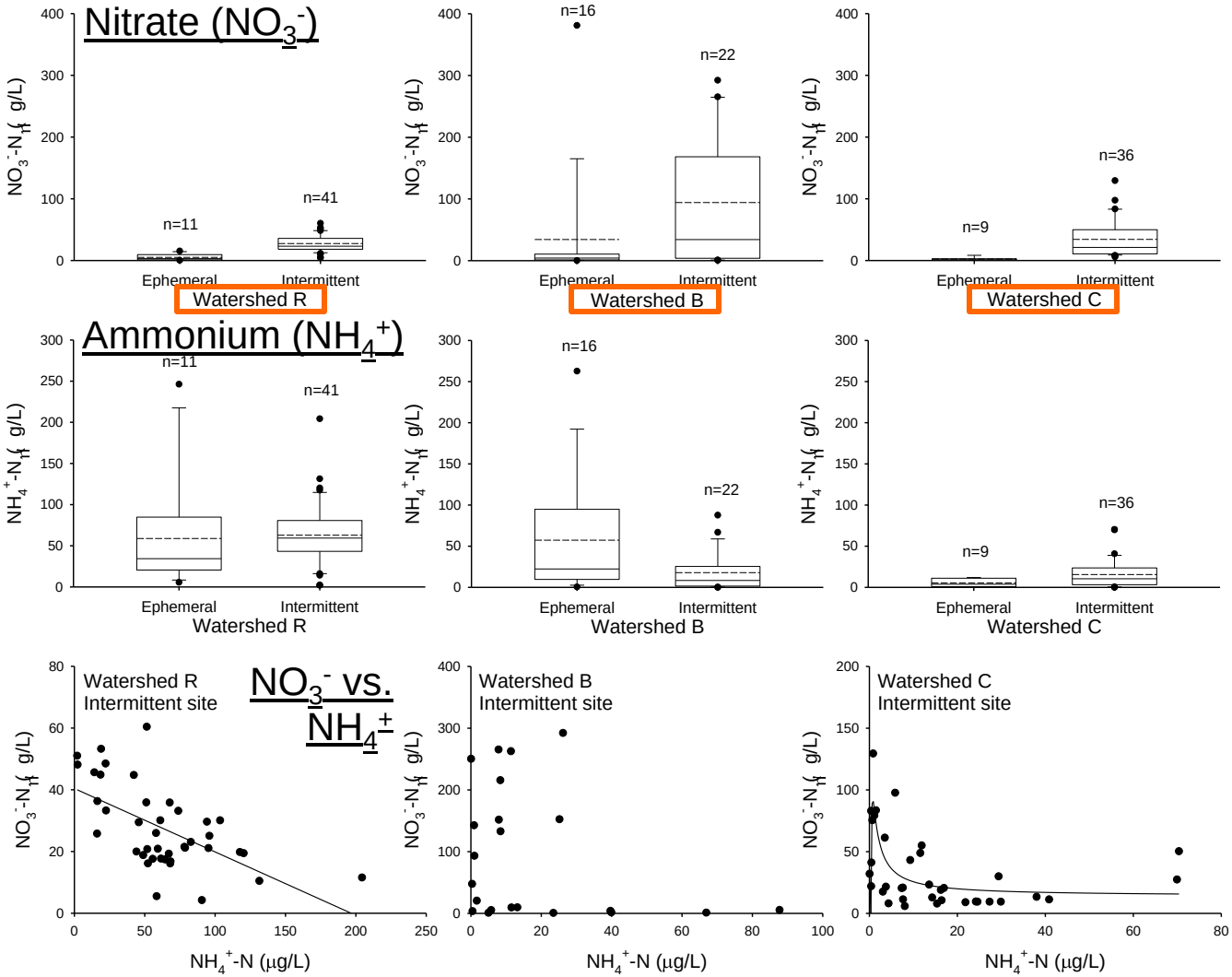
Results to date on Water Quality: Nitrogen

Quantifying 'baseline' nutrient concentrations in the 3 watersheds is important in order to determine any effects that short-rotation pine management may have on water quality

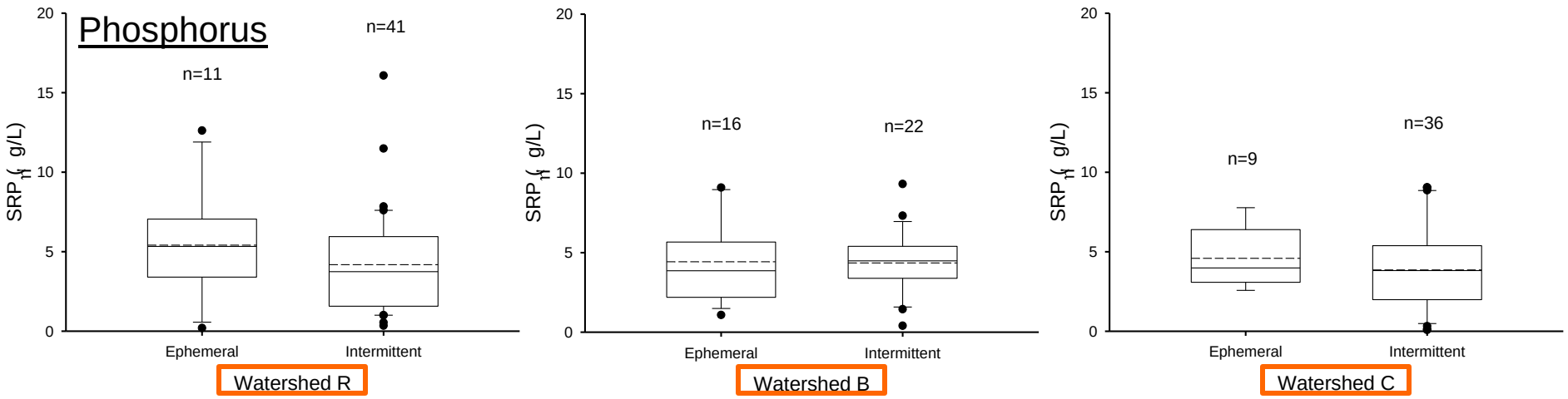
Post-treatment measurements will show whether stream water nutrient concentrations increase with short-rotation pine management (via fertilizer applications)

Results:

- Pre-treatment ('baseline') concentrations of nitrate (NO_3^-) and ammonium (NH_4^+) vary by watershed
- Inverse relationship between NO_3^- and NH_4^+ in 2 of 3 watersheds suggests importance of temporally-variable anaerobic processes



Results to date on Water Quality: Phosphorus



- Pre-treatment ('baseline') concentrations of soluble reactive phosphorus (SRP) are similar among watersheds

Relevance

- Environmental sustainability of intensive bioenergy feedstock systems is an important goal and objective of the Biomass Program's MYPP. Protection of domestic water sources is critical in the Southeastern U.S.
- This project will directly assess the environmental sustainability (water quantity and quality) resulting from emerging high-yield woody crops technology using a watershed-scale experiment
- This project will expand and generalize results through the application of a distributed hydrologic model and will interpret combined effects of this technology (high-yield woody crops) in terms of hydrologic processes across scales
- This project will evaluate whether current forestry BMPs are adequate to protect hydrology and water quality when applying this technology for bioenergy feedstock production

Critical Success Factors

Success Factors:

- Results will evaluate the sustainability of intensive short-rotation pine for bioenergy by assessing whether forestry BMPs minimize impacts to hydrology and water quality, and therefore provide a high degree of protection of waters in the Southeastern U.S.
- Results advance understanding of hydrologic and chemical processes and can be generalized and interpreted in a modeling framework
- Results are published in peer-reviewed journals acceptable to Federal/State regulators and accessible to extension personnel

Challenges:

- Extreme climate events that could constrain interpretation of results
- Integration of complex operational treatments within study design

Advancement of Technology:

- Results are predicted to validate environmental sustainability of high-yield woody crop production technology and provide a baseline for this technology relative to current BMPs based on existing studies

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Future Work

- Harvesting and intensive silviculture practices:
  - Finalize silviculture plan by June 2011, and commence harvest in December 2011. Site preparation in summer and fall 2012
- Hydrology:
  - Install plot-scale N-cycling study
  - Install 5 additional groundwater wells in study watersheds
  - Conduct pre-harvest surveys for the presence of overland flow tracts
- Hydrologic modeling:
  - Extend catchment modeling framework to the Upper 4 Mile catchment
  - Incorporate residence time calculations
- Water quality:
  - Begin sampling water for herbicides and ^{15}N and ^{18}O in nitrate in FY11 to establish baseline concentrations and elucidate valley nitrogen cycling processes
  - Continue to measure key water quality parameters representative of different flowpaths and spatial scales to determine impacts from converting to and managing short-rotation pine (through FY15)

Summary

- Our work combines experimental and modeling approaches at the watershed scale to determine the effects of managing short-rotation woody crops for bioenergy feedstocks in S.E. US. Our project directly assesses the environmental sustainability (water quantity and quality) of high-intensity, short-rotation woody crops for bioenergy
- The silvicultural plan for the treatments is 75% complete. Harvest is set to begin December 2011
- Hydrologic monitoring provided time series data on soil moisture, shallow groundwater, interflow, and deep groundwater to develop and parameterize the hydrologic model. Extensive topographic, soils, and vegetation data have been collected to characterize watersheds
- Detailed models at hillslope and watershed scales have been developed based upon hydrometric data and watershed characterization
- The first year of watershed-scale water quality measurements to determine and compare baseline conditions in reference and two treatment watersheds is completed

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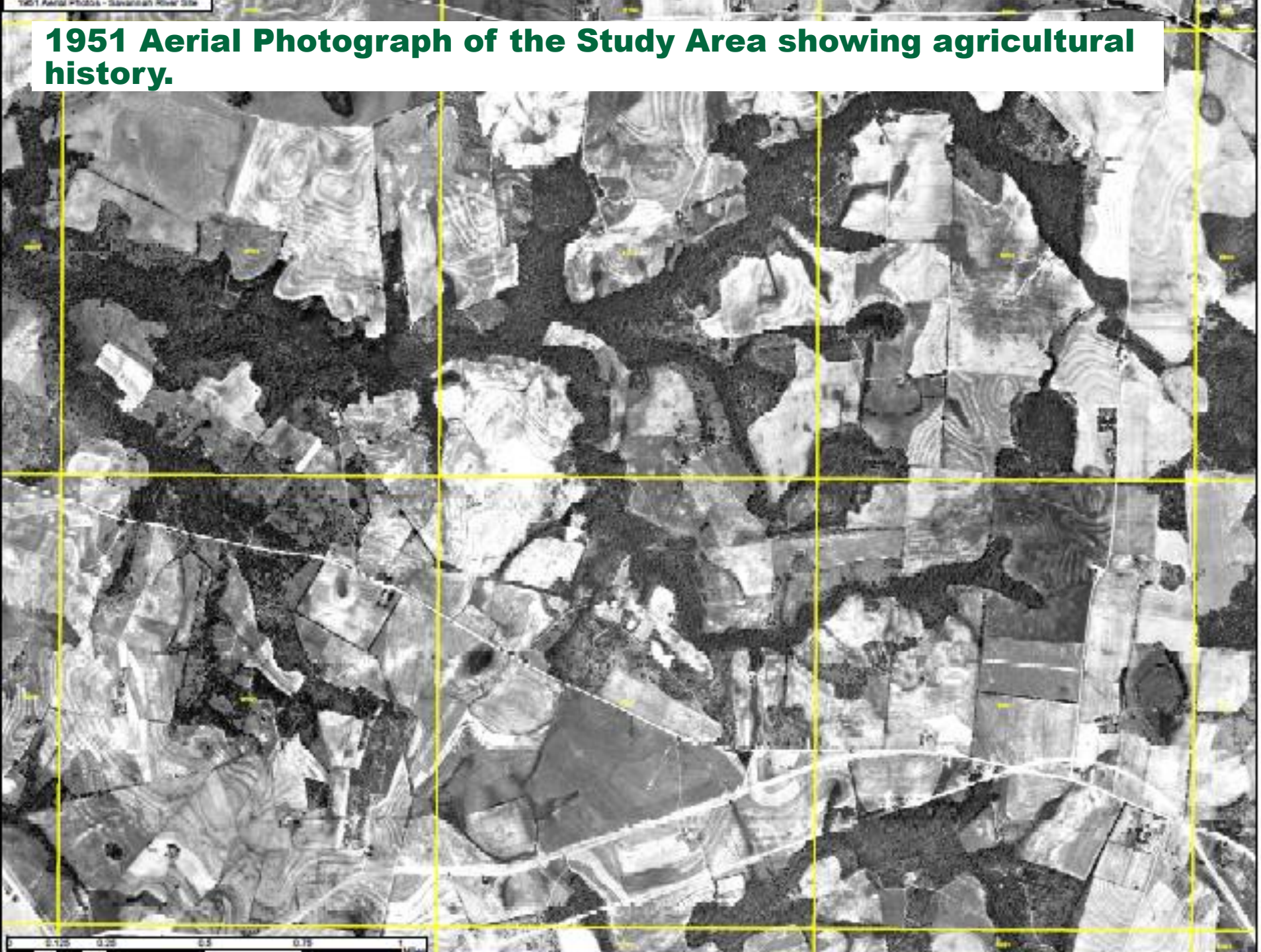
Additional Slides

Publications and Presentations

- Jackson, C.R. 2010. Water quality, flowpath, and hydrologic modeling issues related to intensified forestry for producing cellulosic biofuels. Watershed Perspective on Bioenergy Sustainability Workshop, Oak Ridge National Laboratory, February 3-4, Oak Ridge, TN.
- Jackson, C.R., L. Hopp, J.J. McDonnell, J. Greco, and J.I. Blake. 2010. Vadose zone hydrology in low relief terrain: The importance of lateral subsurface flow. POSTER. 2010 American Geophysical Union Conference, December 13-17, San Francisco, CA.
- Williamson, M.F., C.R. Jackson, J.C. Hale, and H.F. Sletten. 2010. In-situ hydraulic conductivities of soils and anomalies at a future biofuel production site. POSTER. 2010 American Geophysical Union Conference, December 13-17, San Francisco, CA.
- Jackson, C.R., Vache, K.B., Du, E., McDonnell, J.J., and Blake, J.I. 2011 (scheduled). Modeling issues in up-scaling field and small watershed biogeochemistry data from biomass production experiments. 2011 Annual Meeting of the Ecological Society of America, August 7-12, Austin, TX.
- Vache and Jackson are proposing a Fall AGU meeting session on relevant modeling issues.

1951 Aerial Photograph of the Study Area showing agricultural history.



Typical regenerated pine stand and hillslope in study area.

Loamy sand topsoil over sandy clay loam argillic layer, typical soil profile of study area hillslopes.

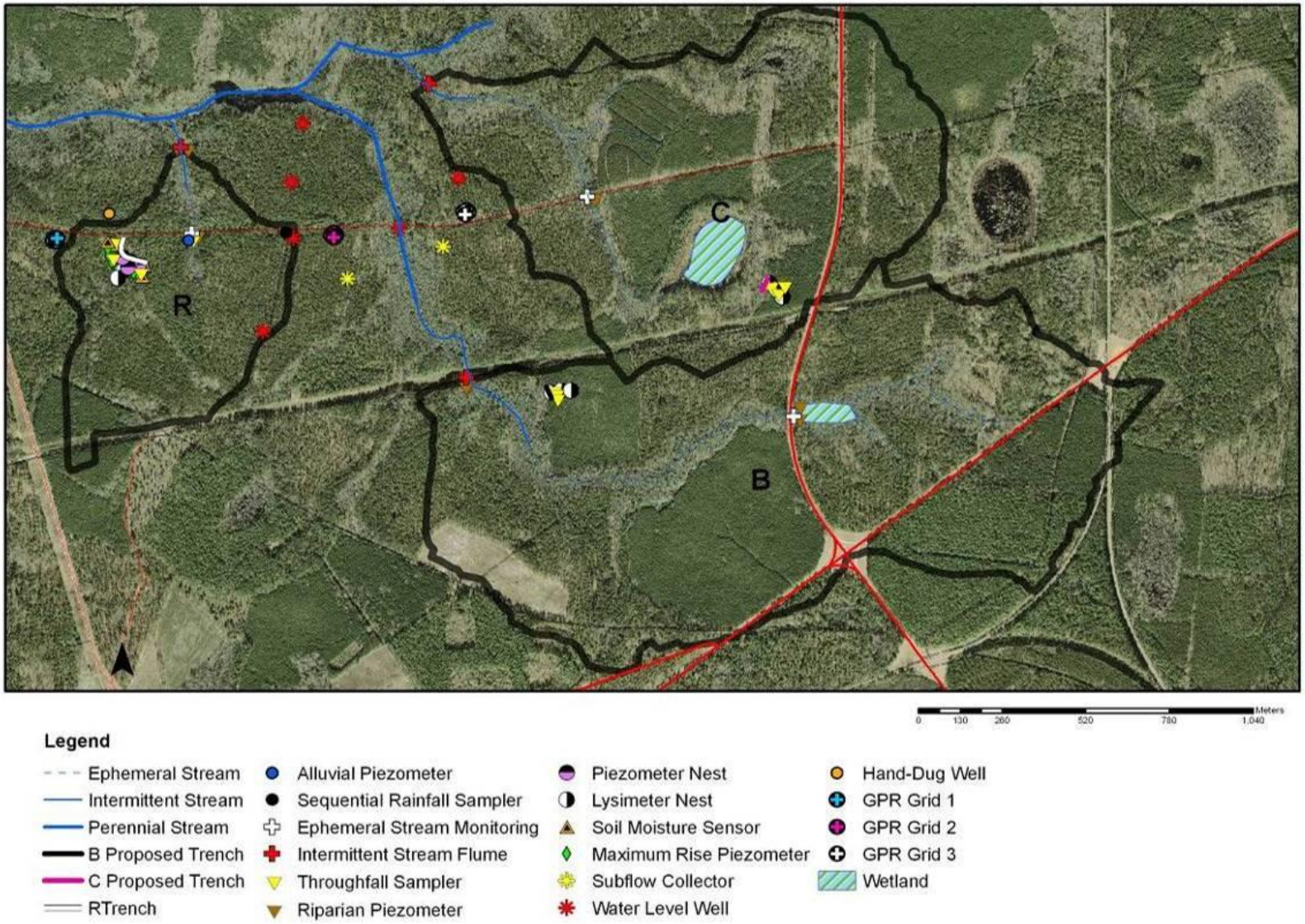
Typical stream valley. Photo from Watershed B. Each watershed includes an intermittent stream and long, flat valleys with indistinct channels characteristic of the SE Coastal Plain.

Open Interflow Interception Trench on Reference Watershed Hillslope

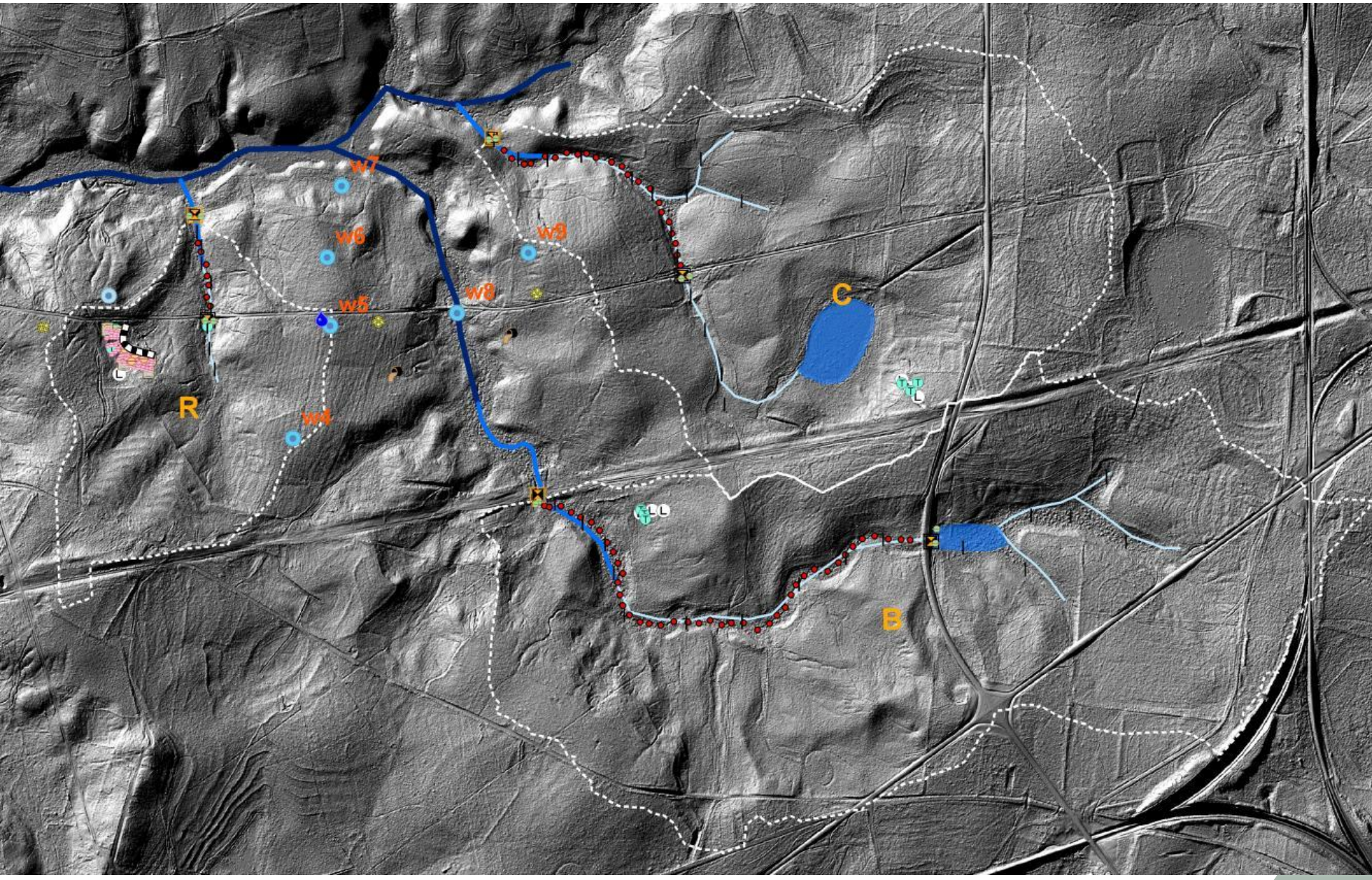
Roof over 120 m long interflow interception trench in reference watershed

Gravel-filled Interflow Interception Trench on Watershed C Hillslope

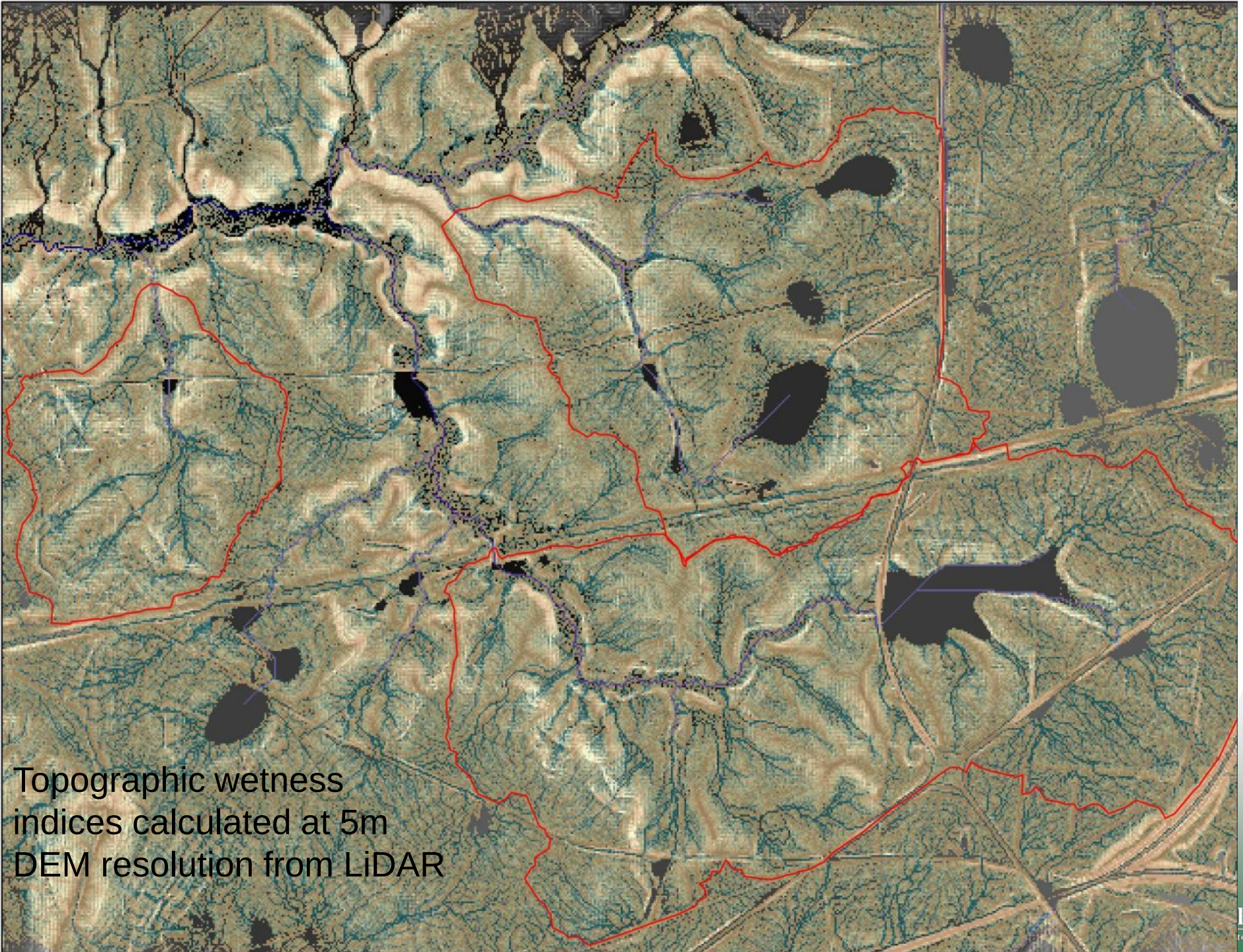
Experiment Site Equipment



Watershed monitoring system overlaid on aerial photography



Current Watershed monitoring system overlaid on shaded LiDAR

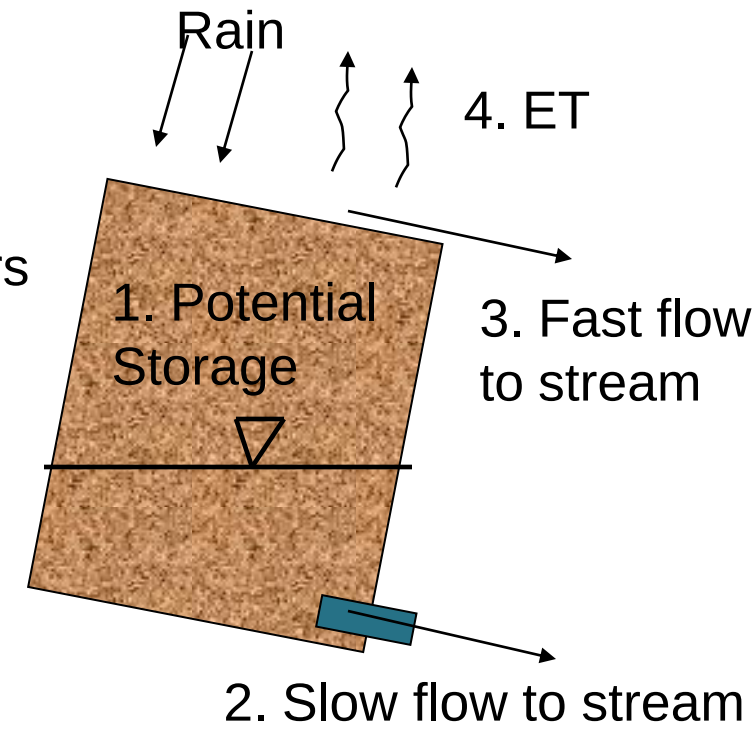


Topographic wetness indices calculated at 5m DEM resolution from LiDAR

Interplay Between Hillslope Monitoring and Modeling

Conceptualizing a hillslope as a simple bucket of soil (right), only 3 or 4 parameters are necessary to transform climate signal into streamflow (see bottom left). These parameters have little physical meaning.

To develop and validate hydrologic process models, data are needed on soil moisture, groundwater dynamics, and interflow occurrence. Chemistry and isotope data help elucidate pathways, travel times, and mixing.



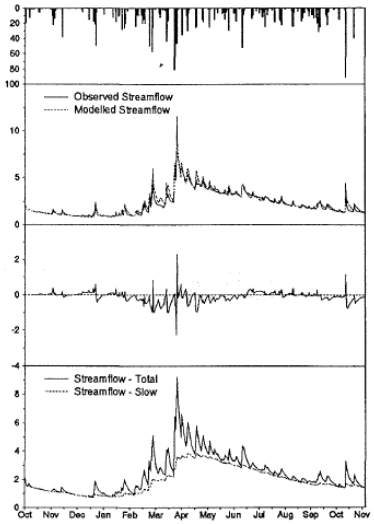


Fig. 7. Rainfall (millimeters), model fit, residuals and total/slow separation for daily streamflow (millimeters) at Coweeta watershed 34 in 1981–1982.

Jakeman and Hornberger, 1993, Water Resources Research.
- Shows agreement of simple bucket model simulations with measured flows in S. Appalachian streams.

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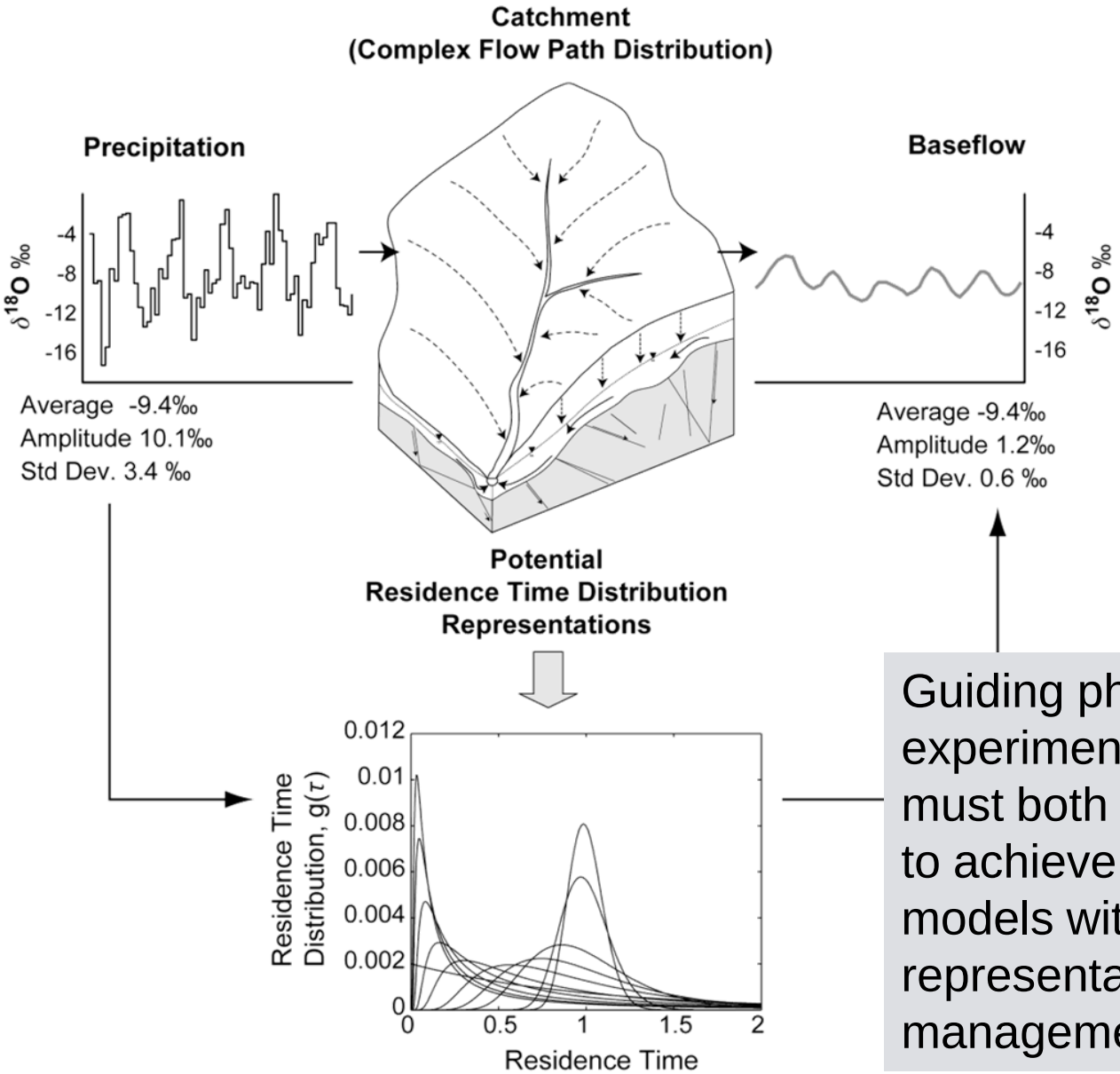

Guiding philosophy: experimentalist and modeler must both make concessions to achieve parsimonious models with sufficient process representation to address management decisions.

Site Hydrogeology – Existing information used to inform hydrologic model

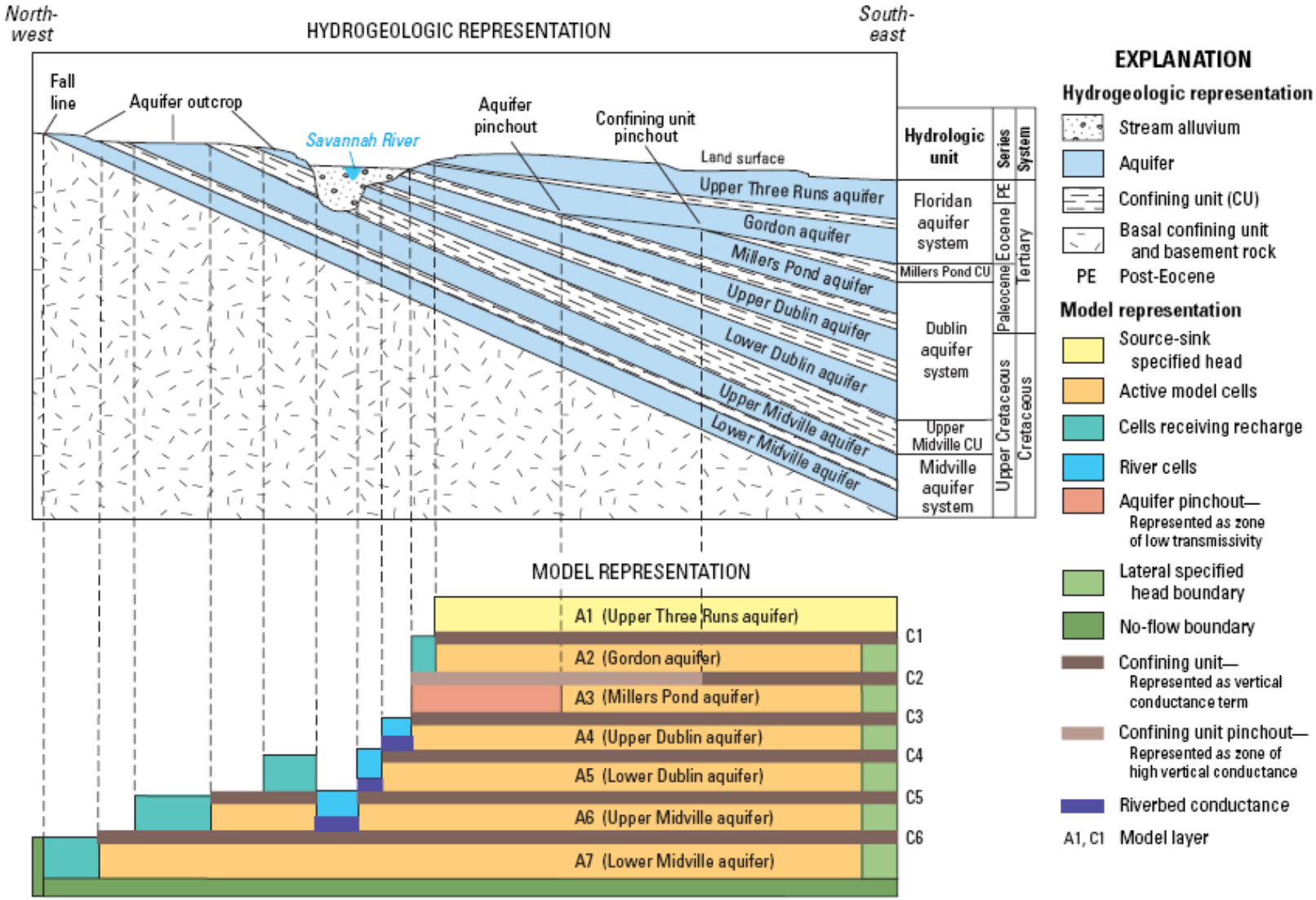

Figure 2. Schematic diagram showing hydrogeologic framework, model layers, and boundary conditions for the Vogtle Electric Generation Plant area, South Carolina (ground-water model modified from Clarke and West, 1998; Cherry, 2006).

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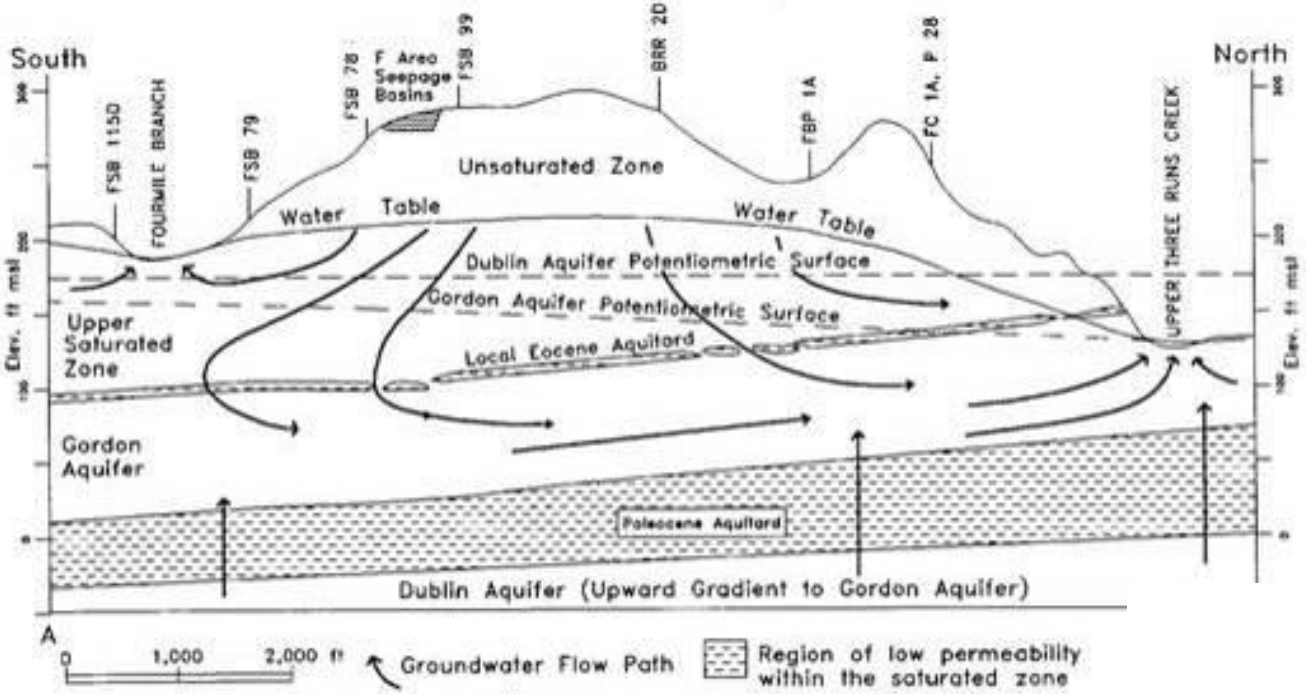
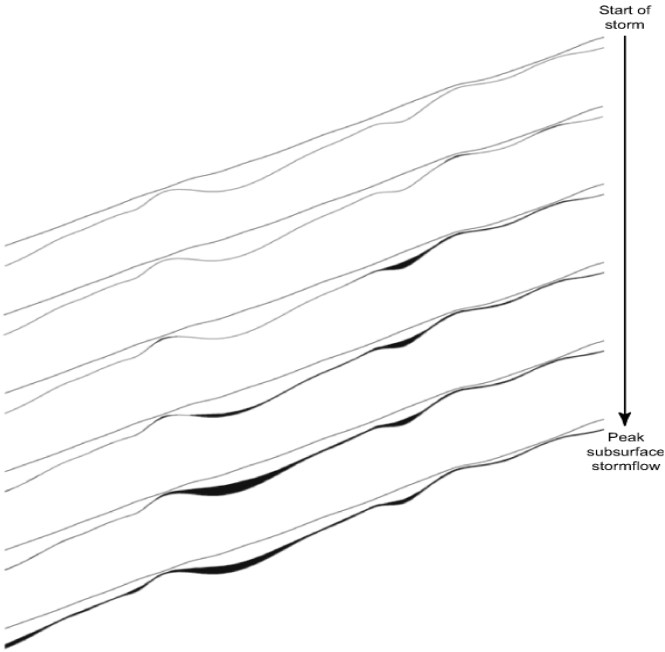
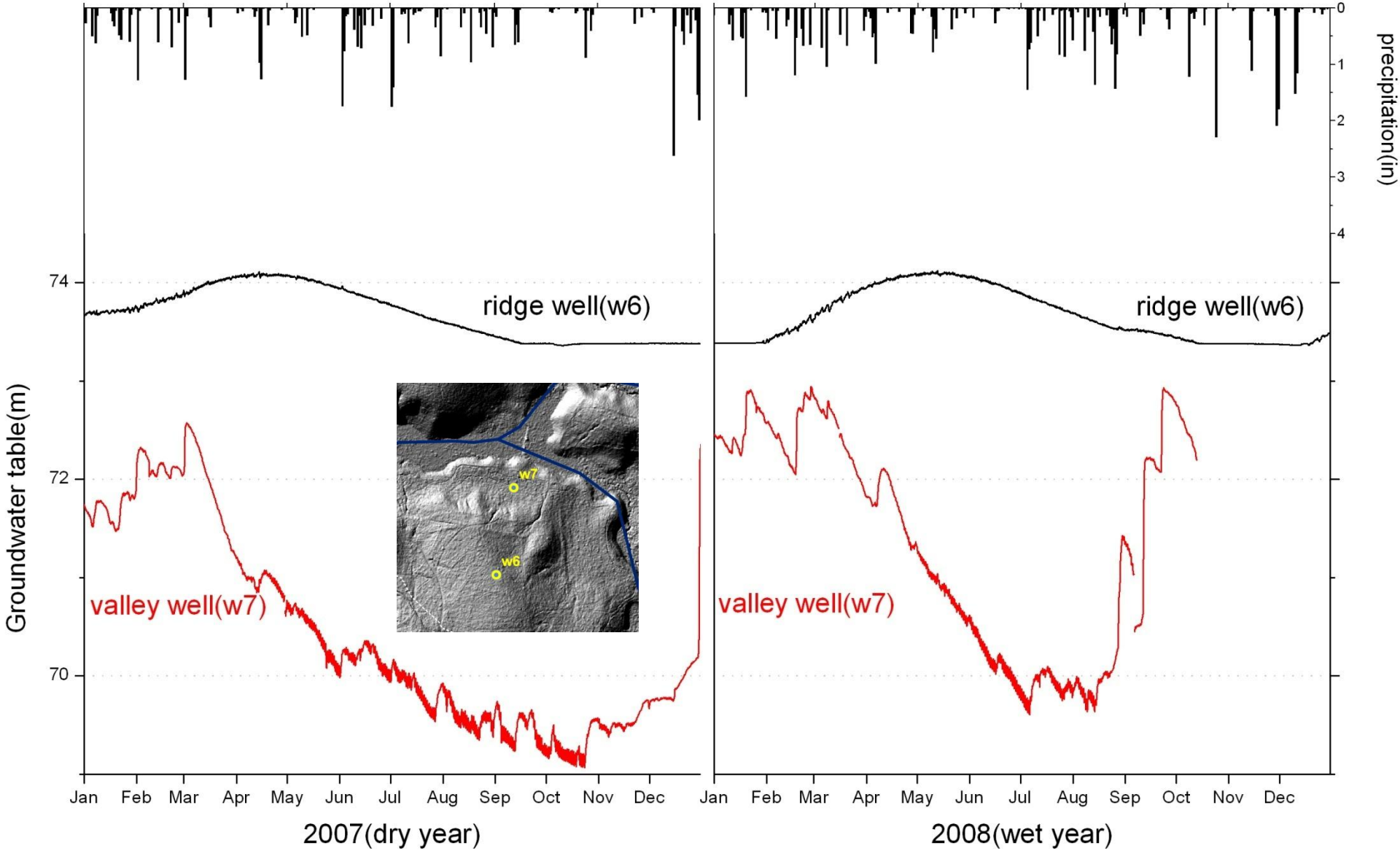


Figure 3. Cross-section showing generalized surface and groundwater flowpaths at the SRS.

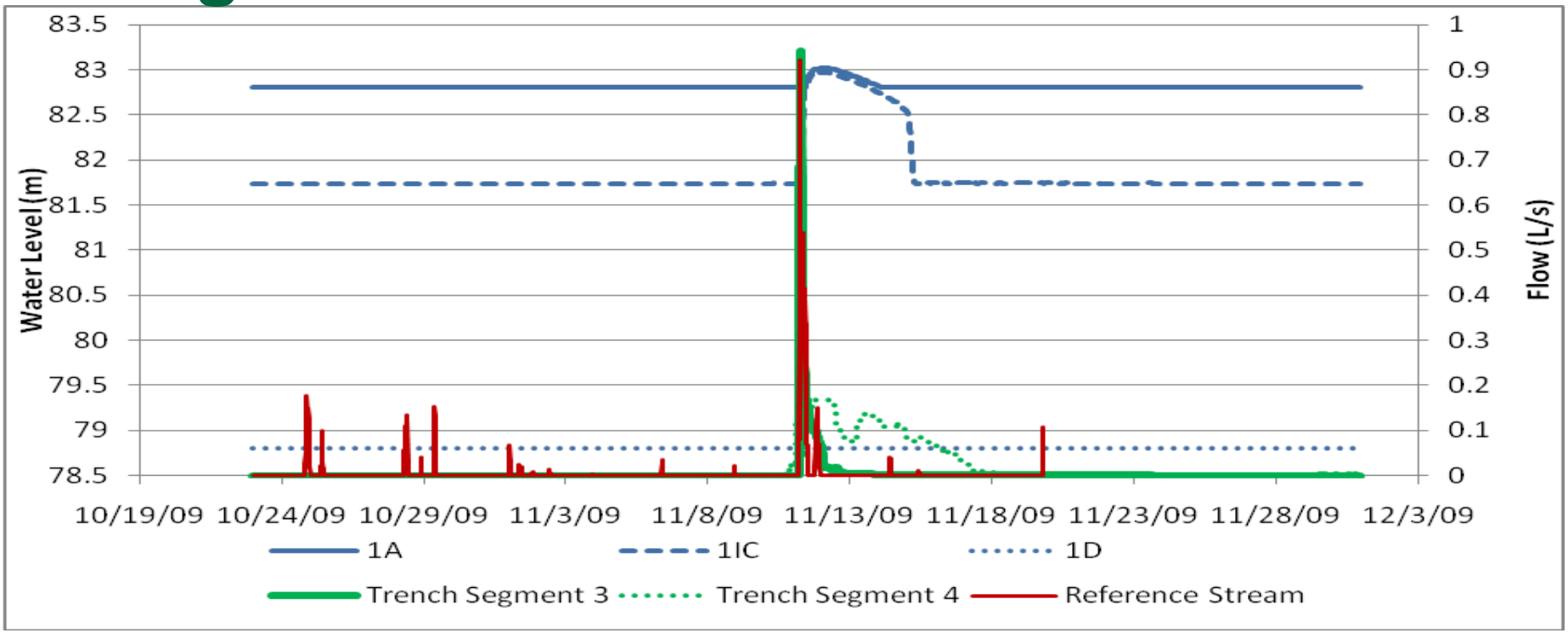


Fill and Spill concept of the initiation of downslope lateral flow (interflow) on hillslopes. (Tromp-van Meerveld and McDonnell, Water Resources Research, 2006)



Variation in deep well water level behavior between ridge top (well 006) and valley (well 007) and between dry and wet water years.

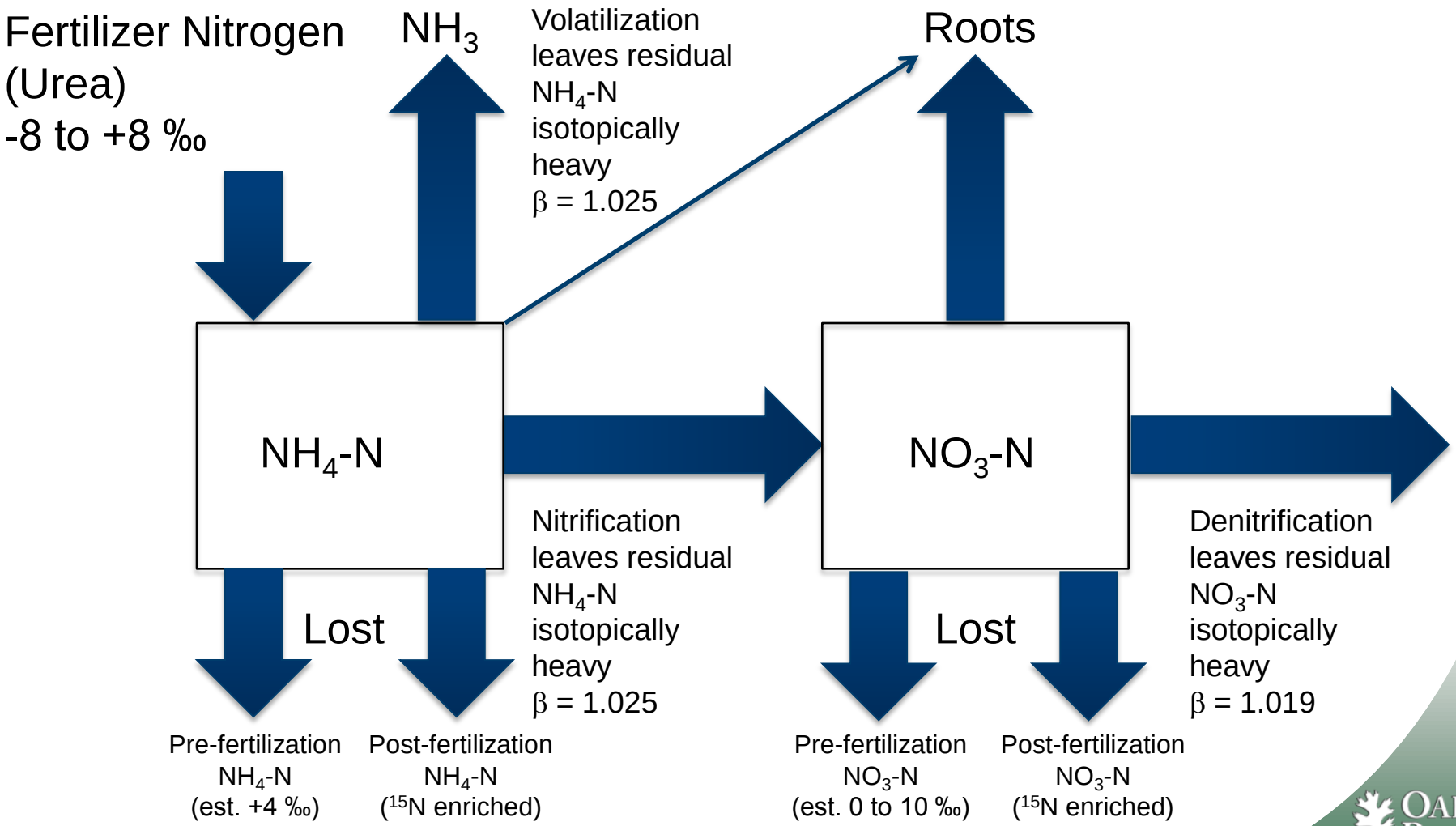
Hillslope and Small Watershed Behavior During Storms



Late fall/early winter 2009 hydrologic behavior of piezometers, trench flumes, and the reference stream. The three piezometers are above the clay, within the clay, or below the clay. During the large storm of November 10th, piezometric rise was rapid and coincident with rapid rise in some of the trench flume segments and stream discharge. The deep piezometer reveals that the saturation zone in and above the clay was perched. Some of the trench flumes did not respond in this period.

Isotopic Fractionations Following Fertilization

(for potential use of isotopic tracers in nitrate (^{15}N, ^{18}O) as evidence of fertilizer loss)



Impact of Weed Control, Fertilization, Advanced Genetics For Woody Crops from Seven Studies in S.E. U.S.

S.E . U.S. Pine Study	Stand Age	Yield tons/ac/yr
GA 1	12	13.6
GA 2	12	11.4
GA 3	10	9.9
GA 4	11	9.7
GA 5	11	9.7
GA 6	11	11.2
SC-SRS	10	10.6
Conventional	10	2 to 3