Use of a fully distributed triangulated irregular network hydrologic model in climate change and ecohydrological studies

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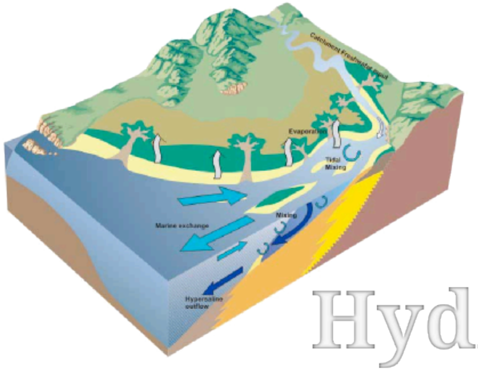

WRF
Hydro 2014

Outline

1. ***The tRIBS hydrologic model***

   ***Acknowledgments*:**
   Rafael Bras, Enrique R. Vivoni, Valeriy Ivanov, Sue Mniszewski, and Patricia Fasel

2. ***Study of climate change impacts in a Mediterranean basin***

   ***Acknowledgments*:**
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3. ***Ecohydrological study of a regional basin in northwest Mexico***

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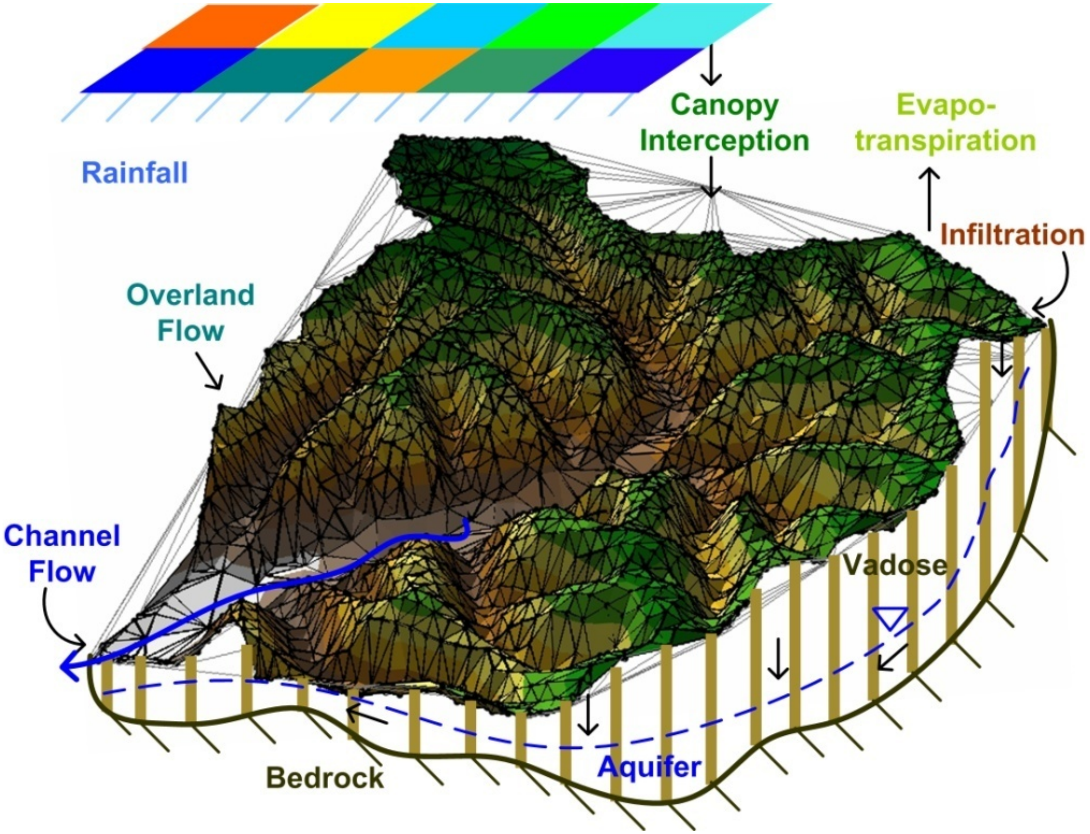
Hydrologic Model

*The **TIN-based Real-Time Integrated Basin Simulator (tRIBS)** distributed and physically-based hydrologic model*

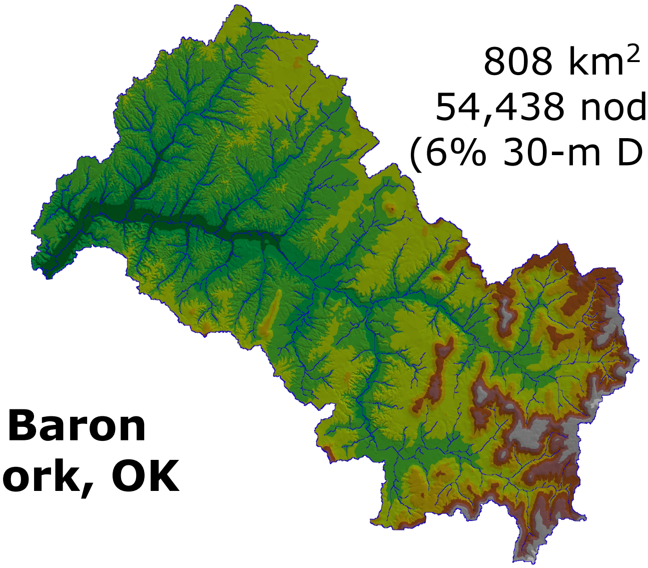


- ➡ Heritage from Real-time Integrated Basin Simulator (**RIBS**, *Garrote and Bras 1995*) and Channel-Hillslope Integrated Landscape Development (**CHILD**, *Tucker et al., 2001*).
- ➡ Coupled vadose and saturated zones with dynamic water table.
- ➡ Radiation and energy balance.
- ➡ Interception and evaporation.
- ➡ Hydrologic and hydraulic routing.
- ➡ C++ code.

Ivanov et al. (2004a,b), Vivoni et al. (2004)

Hydrologic Model

Terrain is represented through **Triangulated Irregular Networks** (TINs).

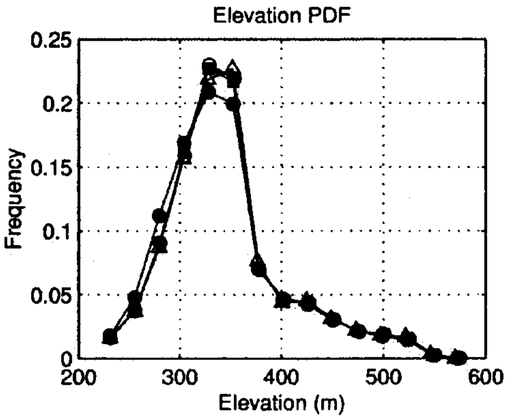


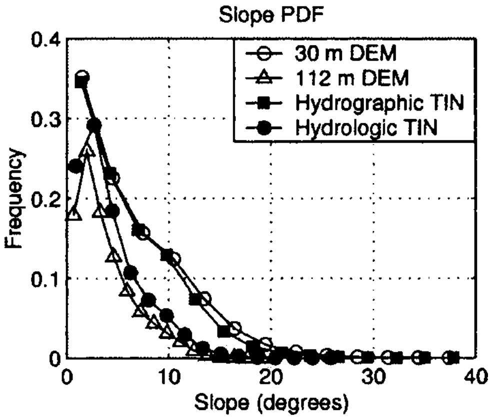
808 km^2
54,438 nodes
(6% 30-m DEM)

Baron Fork, OK

Advantages:

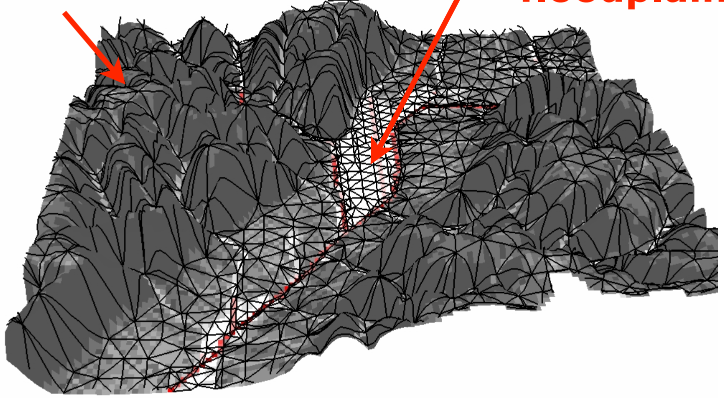
- Multiple-resolution terrain modeling.
- Conserves DEM statistical properties.
- Preserves linear features (boundary, stream network).
- Adds degrees of freedom in flow and transport.





Low-resolution in dry hillslopes

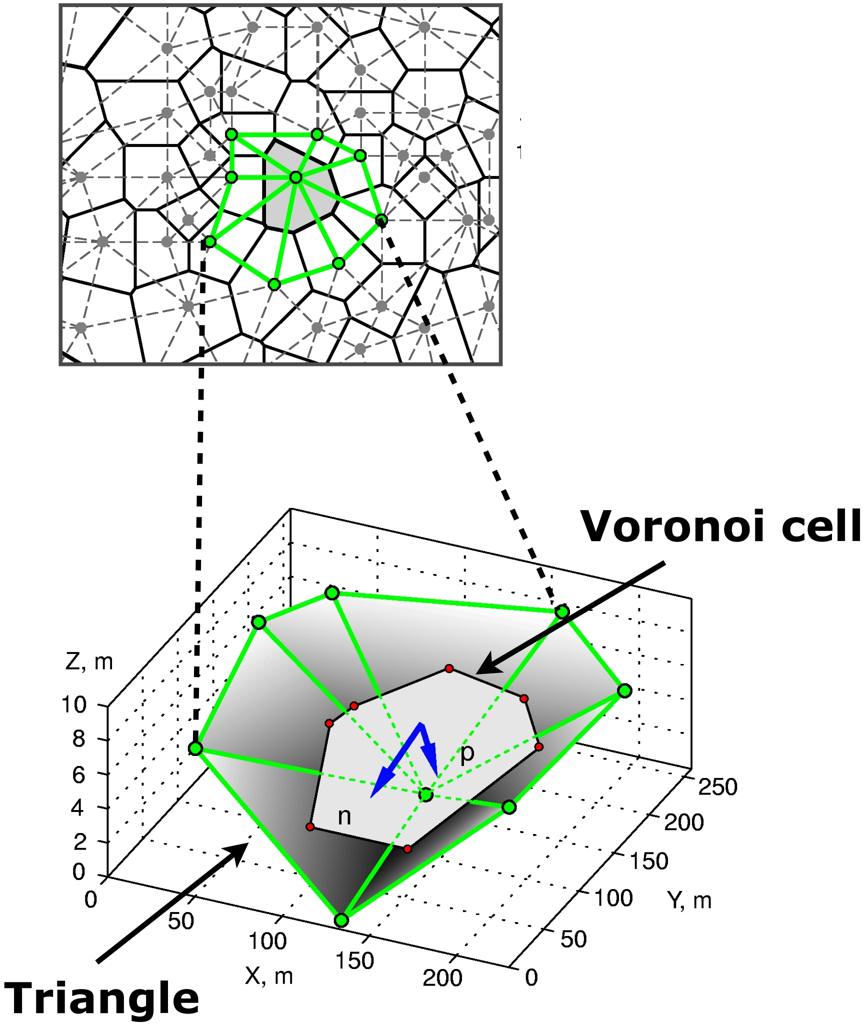
High-resolution in saturated floodplains



Vivoni et al. (2004; 2005)

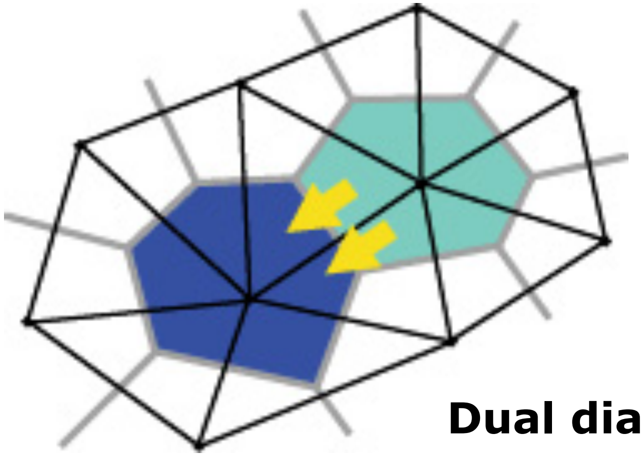
Hydrologic Model

The model domain consists of **Voronoi polygons** derived from the TIN.



Voronoi cell

Triangle

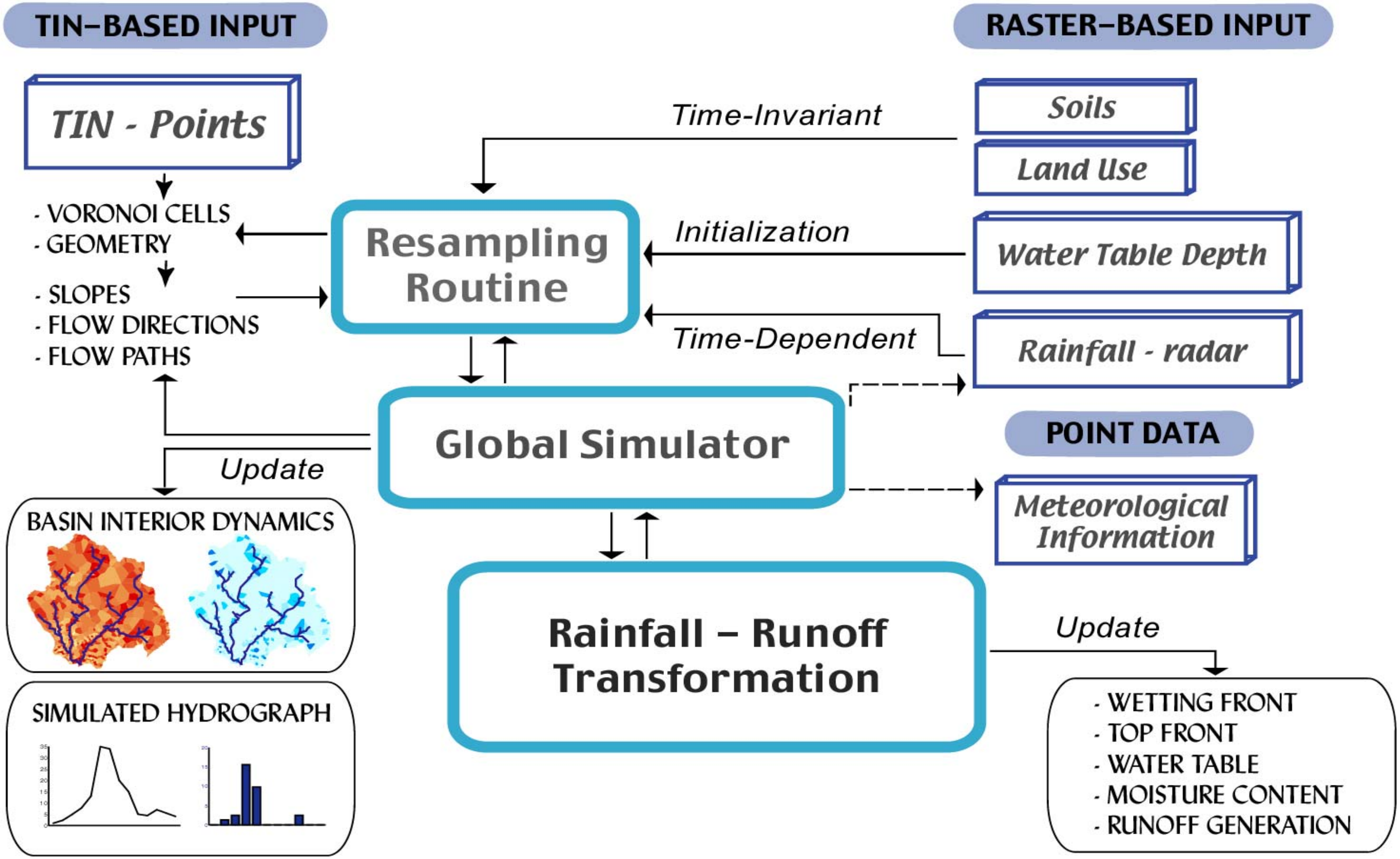


Dual diagram

- Hydrologic flow routing based on TIN node connectivity.
- Surface and subsurface fluxes over TIN edges and across Voronoi faces.
- Hydrologic mass balances computed for Voronoi polygon area.

Hydrologic Model

Schematic illustrating **tRIBS Data Flowchart and Capabilities**.



TIN–BASED INPUT

TIN - Points

- VORONOI CELLS
- GEOMETRY
- SLOPES
- FLOW DIRECTIONS
- FLOW PATHS

RASTER–BASED INPUT

Soils

Land Use

Water Table Depth

Rainfall - radar

Time-Invariant

Initialization

Time-Dependent

Resampling Routine

Global Simulator

POINT DATA

Meteorological Information

Update

BASIN INTERIOR DYNAMICS

SIMULATED HYDROGRAPH

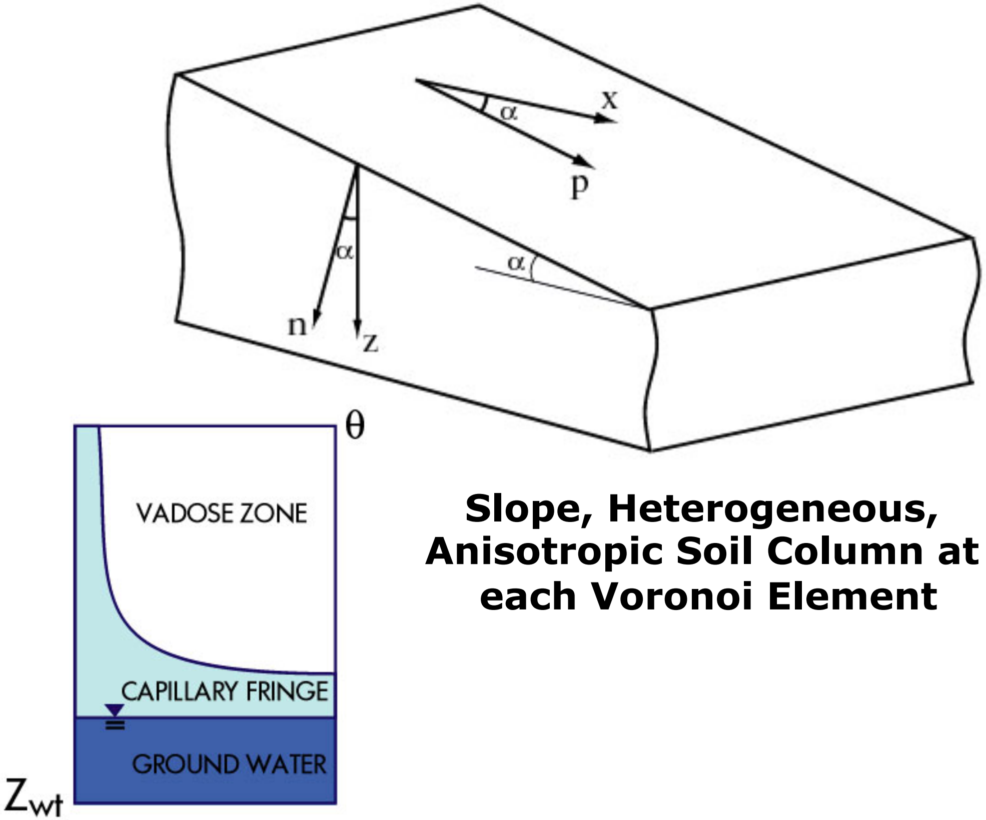
Rainfall – Runoff Transformation

Update

- WETTING FRONT
- TOP FRONT
- WATER TABLE
- MOISTURE CONTENT
- RUNOFF GENERATION

Hydrologic Model

Modified Green-Ampt scheme for sloped, anisotropic soil column developed by Cabral et al (1992) and Ivanov (2002).



Slope, Heterogeneous, Anisotropic Soil Column at each Voronoi Element

One-Dimensional Infiltration

- Saturated hydraulic conductivity decreases normally with depth:

$$K_s(n) = K_{on}(n)\exp(-fn)$$

- Brooks-Corey parameterization of unsaturated hydraulic conductivity:

$$K_u(n) = K_s(n)\frac{(\theta-\theta_r)^{\varepsilon}}{(\theta_s-\theta_r)}$$

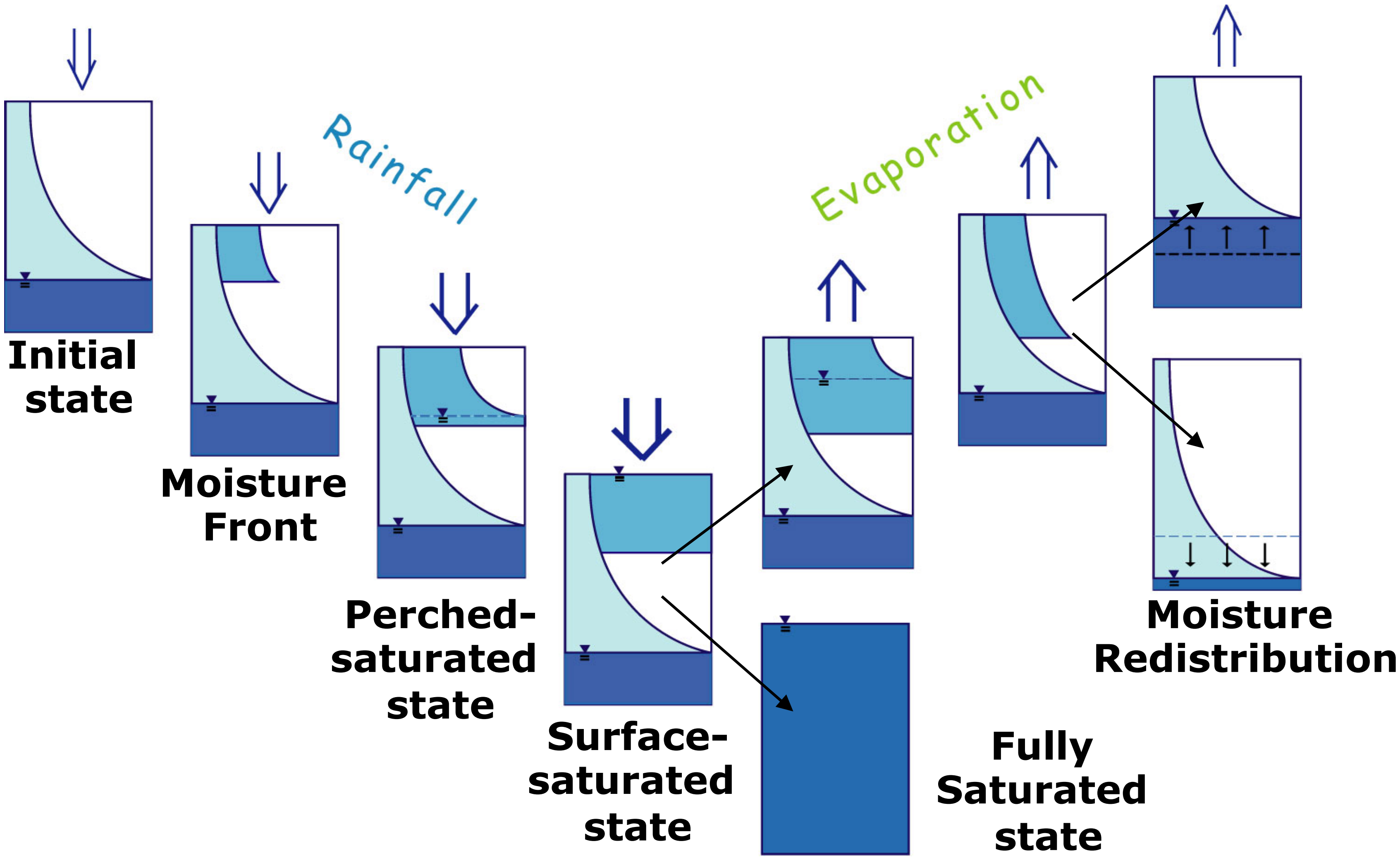
- Soil column considered anisotropic:

$$a_r = \frac{K_{op}}{K_{on}} > 1$$

- Gravity dominance assumed in unsaturated moisture profile.

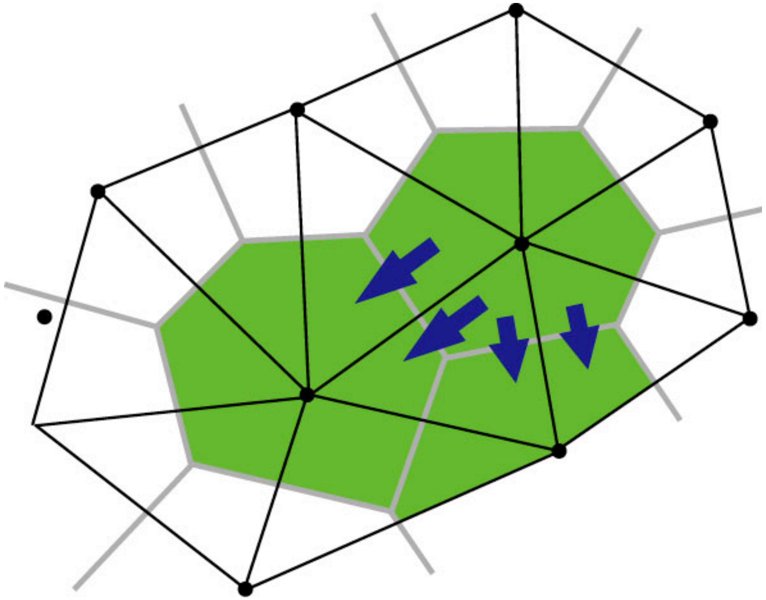
Hydrologic Model

Rainfall and evaporative forcing at the land-surface interact with pre-existing soil moisture profile and water table.



Hydrologic Model

Multiple direction flow in **groundwater component** allows moisture recharge in shallow aquifer to be redistributed.



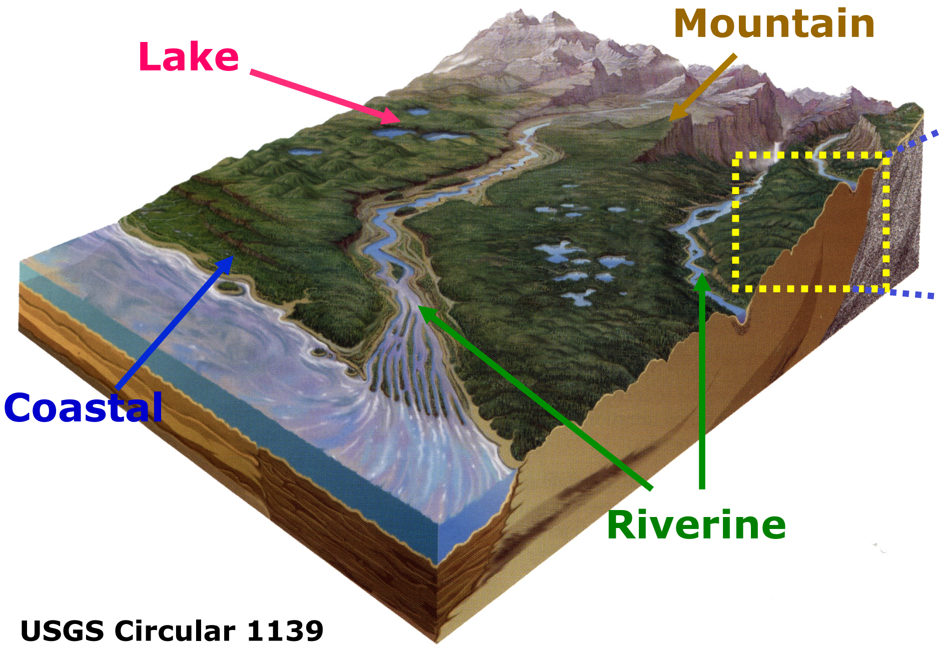
Variable, dynamic water table field

Shallow Groundwater

- Space/time variable groundwater table position.
- Single and multiple direction flow to downstream neighbors.
- Coupled to unsaturated zone to enable moisture mass balance.
- Bounded by a uniform or spatially-variable bedrock surface.
- Transmissivity is a function of depth to bedrock, depth to water table, and aquifer hydraulic properties.

Hydrologic Model

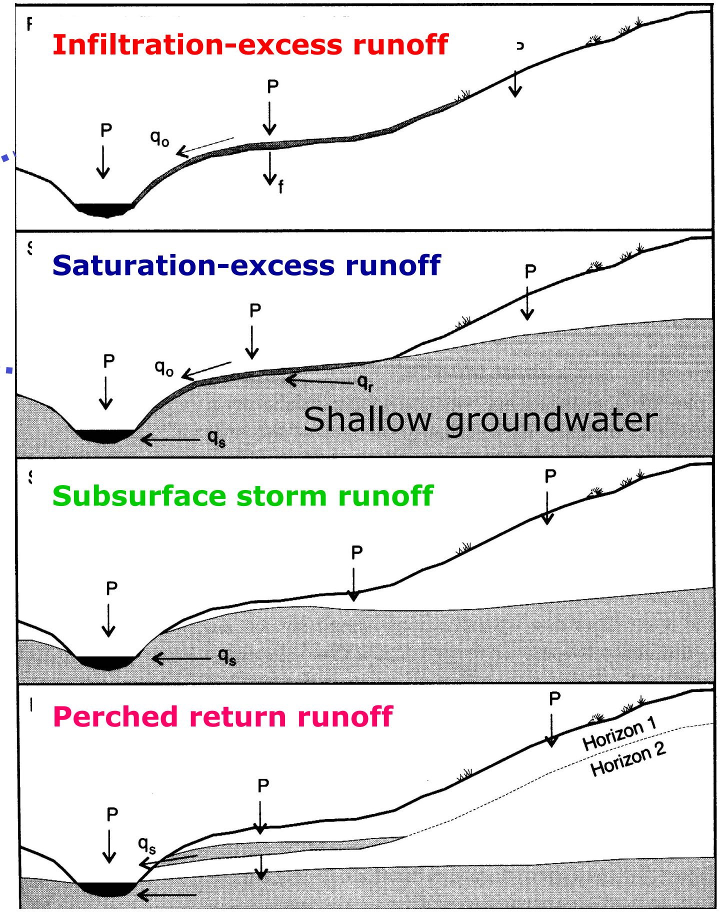
A range of runoff generation mechanisms is represented in the model as a result of the **unsaturated-saturated dynamics**.



USGS Circular 1139

Surface-Groundwater Interactions in different Landscapes and Scales

Hillslope runoff processes

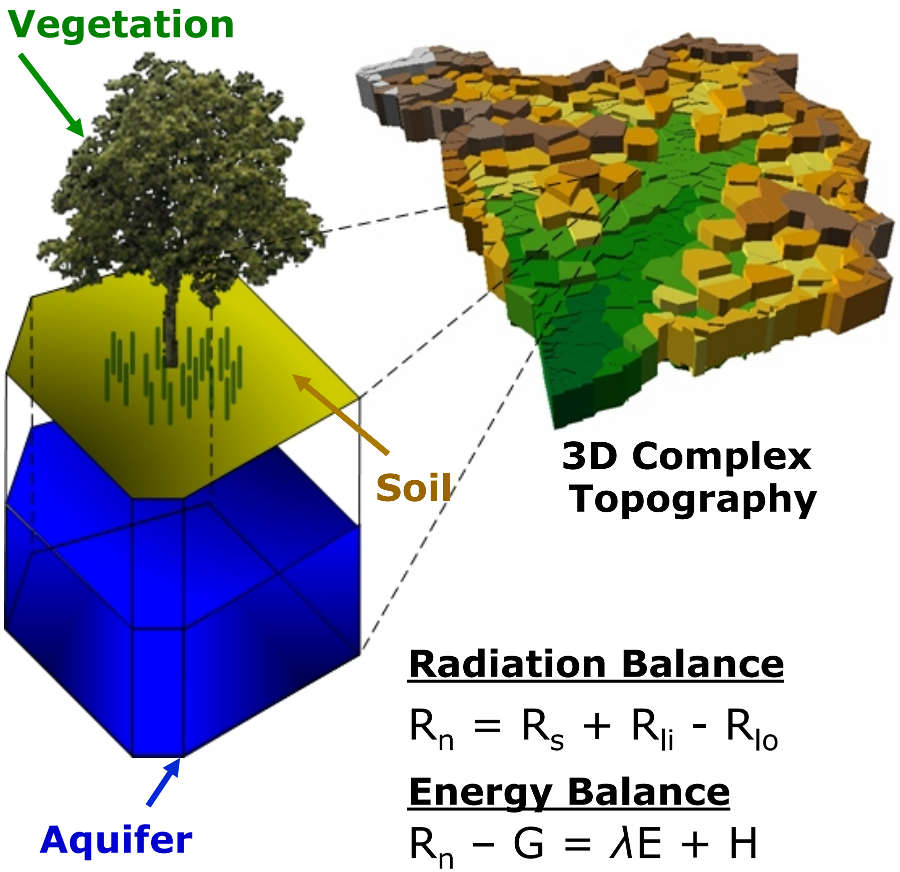


Beven (2001) Rainfall-Runoff Modeling

Hydrologic Model

The model solves the **coupled energy and hydrologic balance**.

Atmosphere-Land-Aquifer Interactions



Radiation Balance

$$R_n = R_s + R_{li} - R_{lo}$$

Energy Balance

$$R_n - G = \lambda E + H$$

Coupled Energy and Hydrology Processes on Complex Terrain

Radiation: Incoming short-wave and long-wave, outgoing long-wave radiation including effects of terrain.

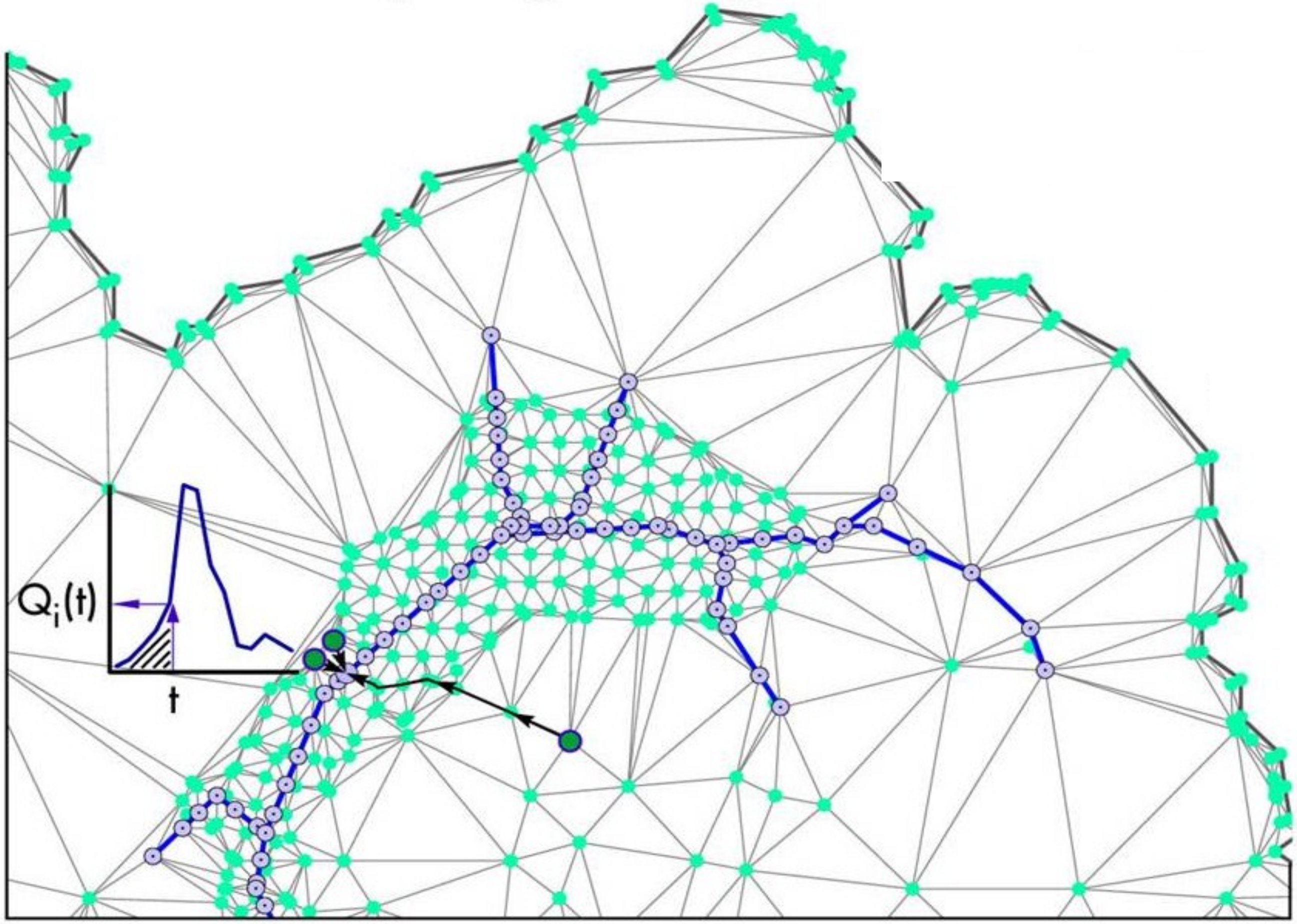
Vegetation: Canopy interception, drainage, throughfall and evaporation using vegetation functional type.

Energy Balance: Net radiation, ground heat, sensible heat and latent heat fluxes.

Evapotranspiration: Soil-moisture controls bare soil evaporation and canopy transpiration in root zone.

Hydrologic Model

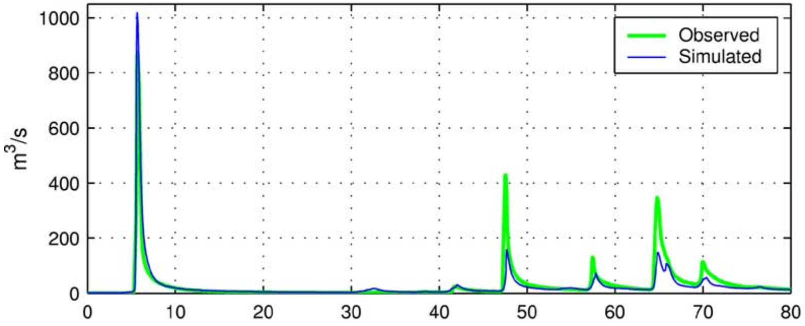
Hydrologic routing on **hillslopes** is tied to channel node discharge where a **1-D hydraulic channel routing** scheme is used.



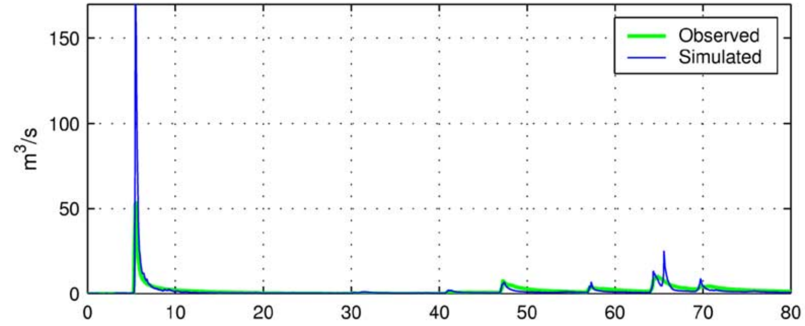
Hydrologic Model

Model outputs include time series at distributed locations and spatial maps

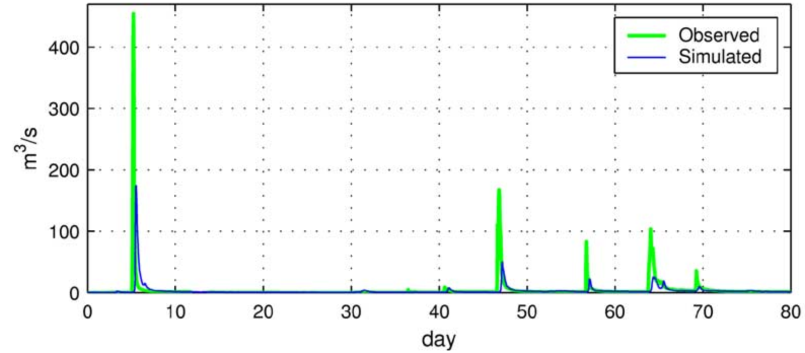
Baron Fork at Eldon

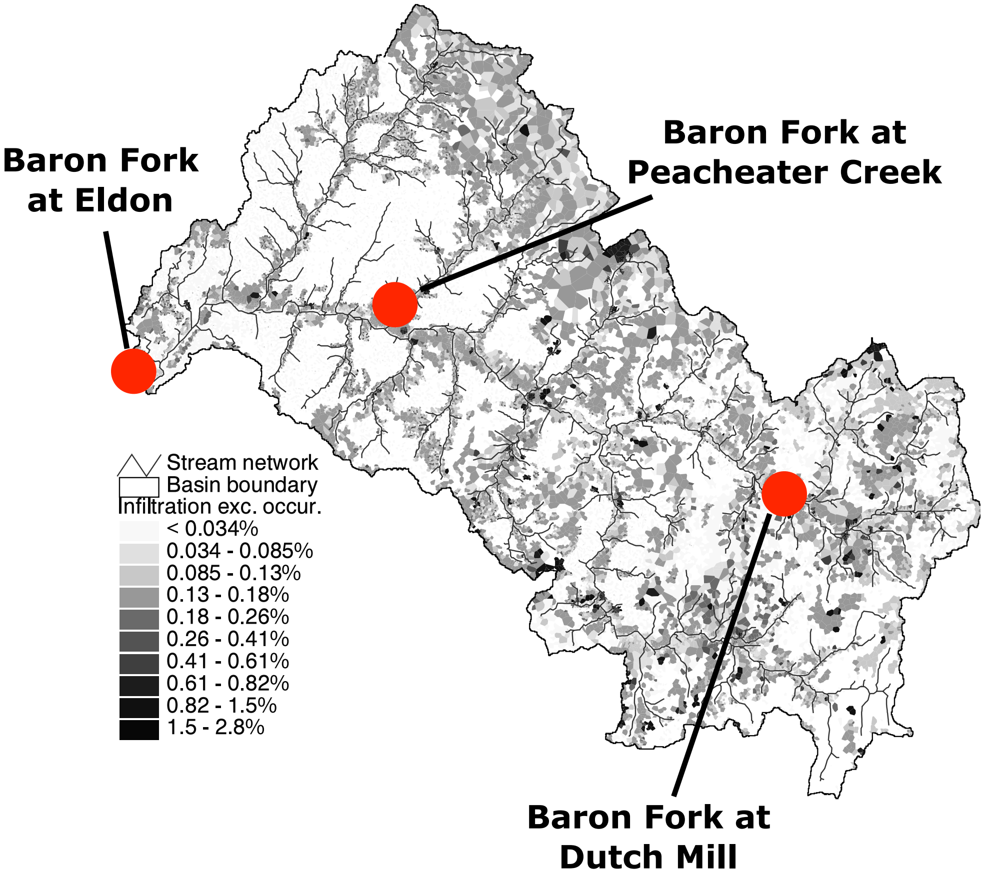


Baron Fork at Peacheater Creek



Baron Fork at Dutch Mill

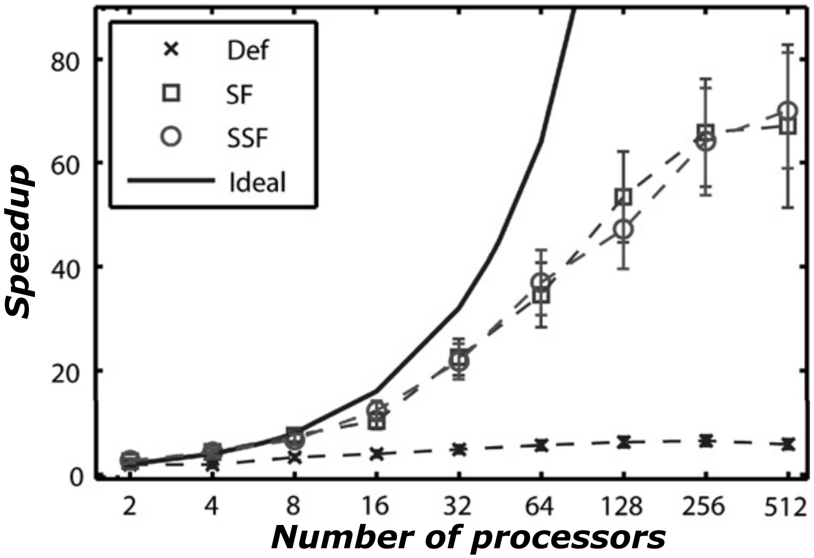


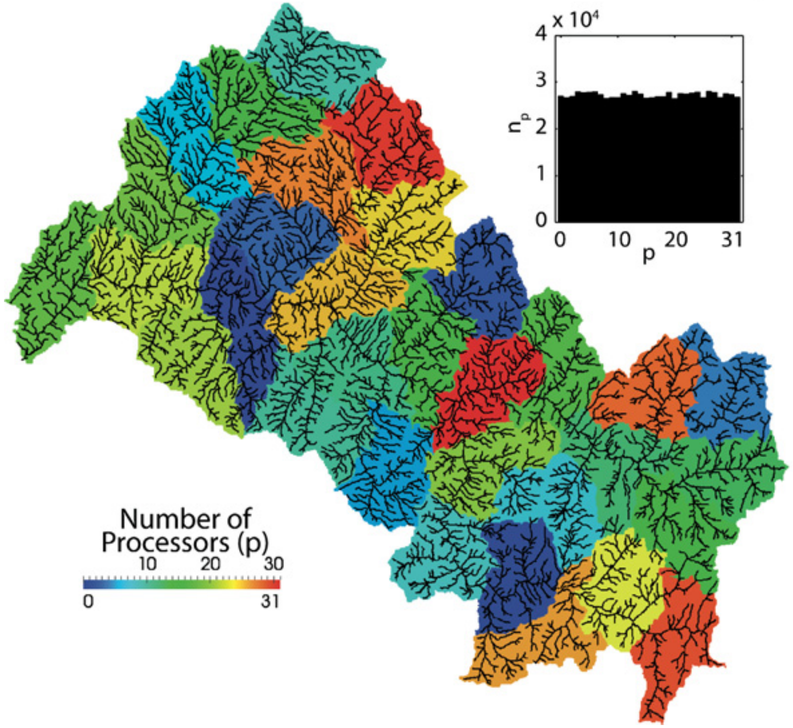


Ivanov et al. (2004a,b)

Hydrologic Model

Recent improvement: use of **High Performance Computing** for high-resolution distributed hydrological modeling





Surface-subsurface flow partitioning

Test the speedup in real-world simulations as a function of the number of processors, basin size and variability of forcing.

Identify the best domain partitioning to optimize allocation of computational resources.

Vivoni et al. (2011)

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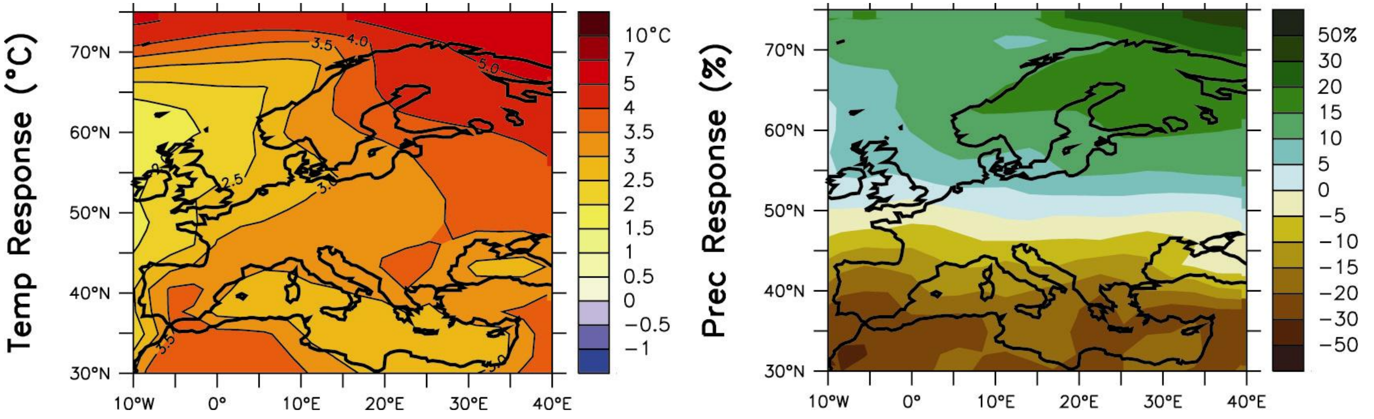
Motivation of Climate Change Study

- ★ **Mediterranean areas** are highly sensitive to climate variability and this vulnerability has significant impacts on water resources and hydrologic extremes.

- ★ **Future climate projections** depict a further decrease of water availability, with impact on agriculture.



MMD-A1B simulations. Annual mean. IPCC 2007

Hydrologic Impacts of Climate Change

*We quantify the **impacts of climate change** on water resources and hydrologic extremes of Mediterranean basins*

Hydrologic Impacts of Climate Change

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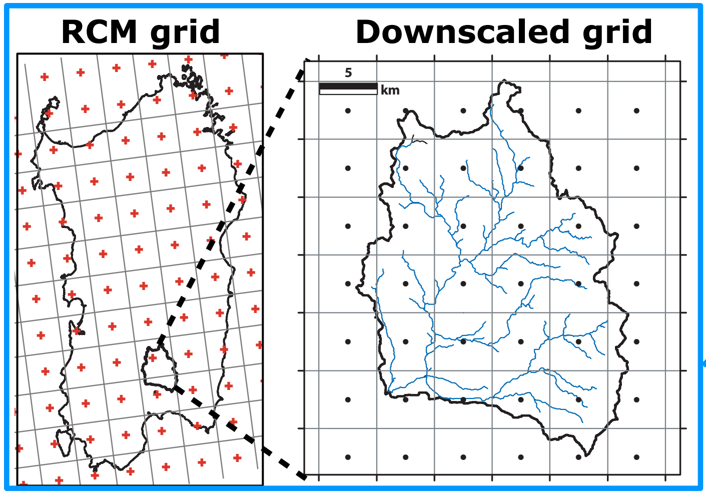

GCM and RCM Auditing and Downscaling

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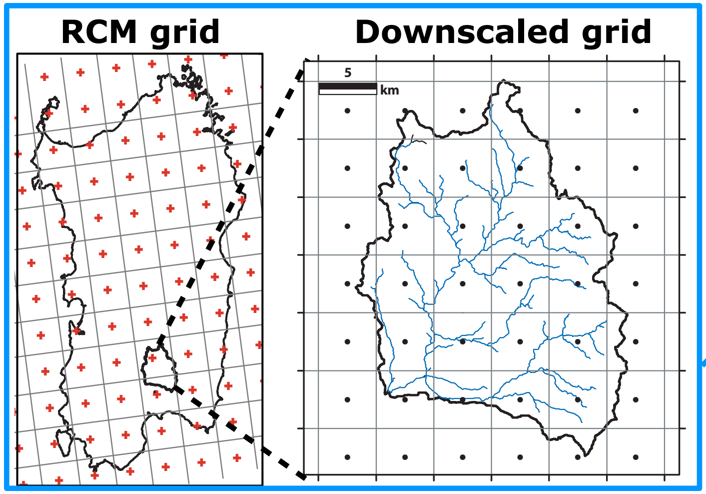
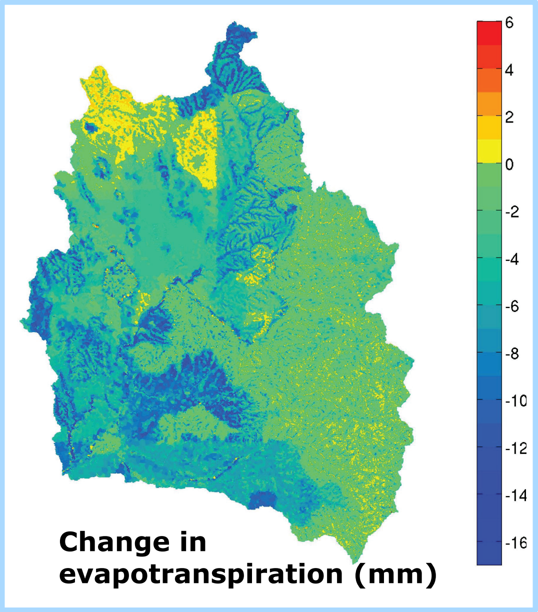


GCM and RCM Auditing and Downscaling

Process-based Distributed Hydrological Modeling

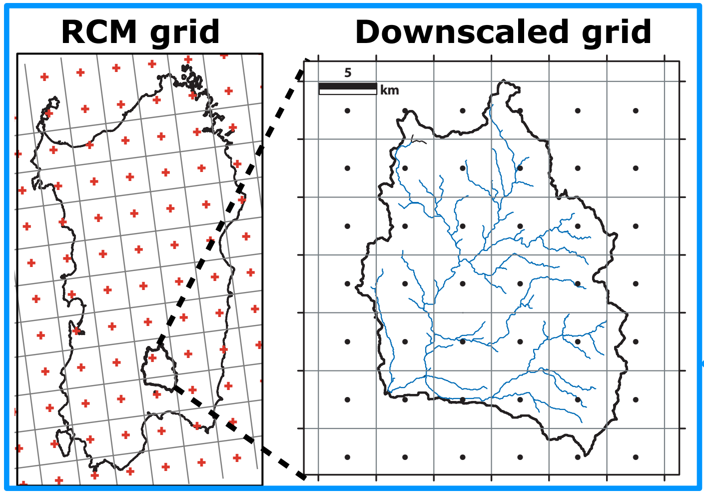


Change in evapotranspiration (mm)

Hydrologic Impacts of Climate Change

*We quantify the **impacts of climate change** on water resources and hydrologic extremes of Mediterranean basins*

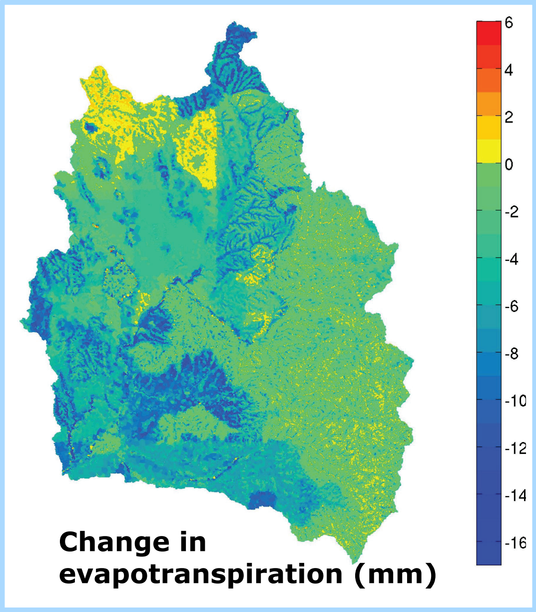
CLIMB
Climate Induced Changes on the Hydrology of Mediterranean Basins



GCM and RCM Auditing and Downscaling

Study Site Characterization and Monitoring

Process-based Distributed Hydrological Modeling



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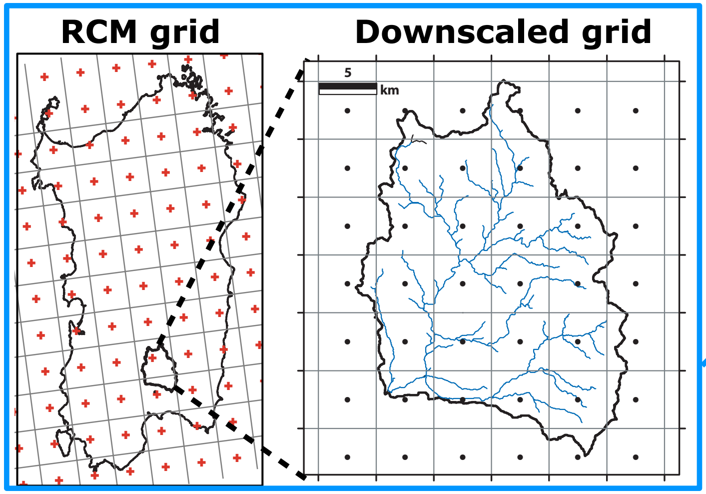

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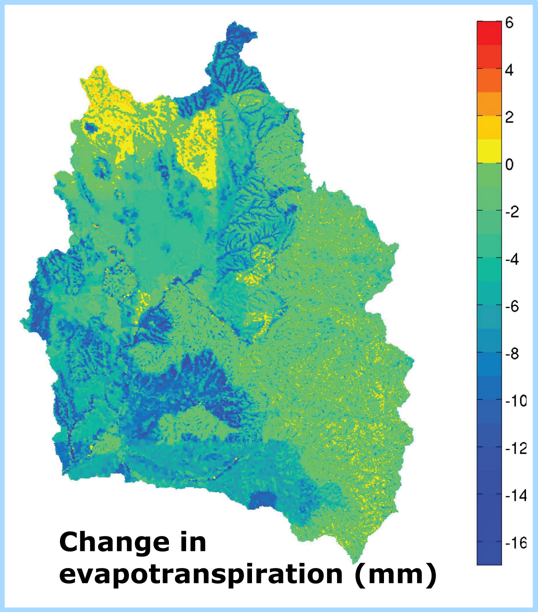


Change in evapotranspiration (mm)

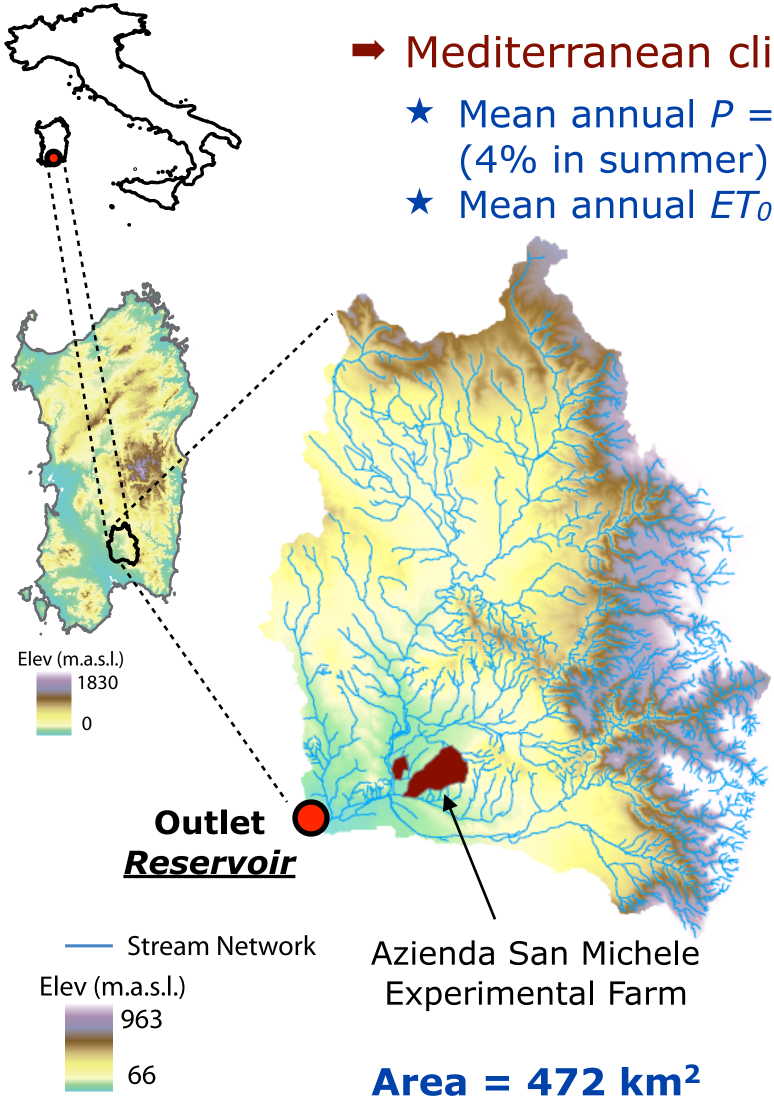
Vulnerability and Risk Assessment

Dissemination and Interaction with Stakeholders

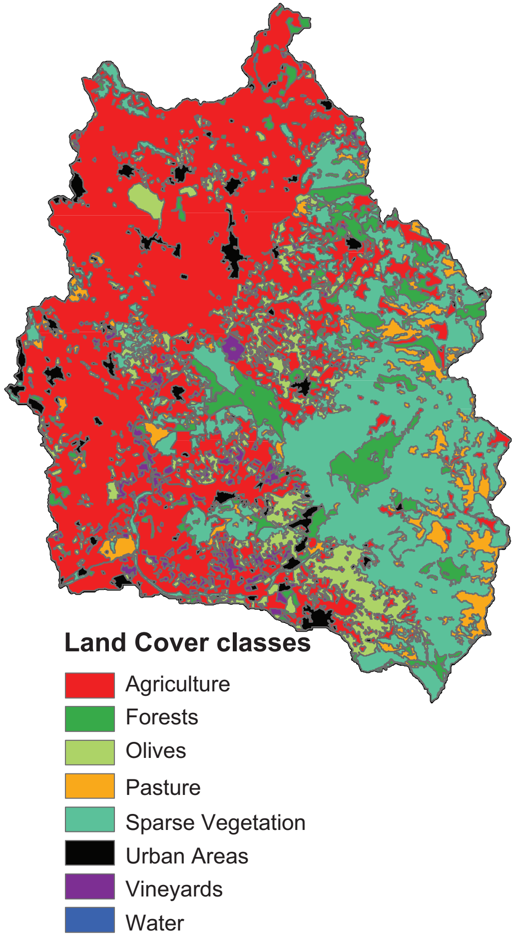
Hydrologic Impacts of Climate Change

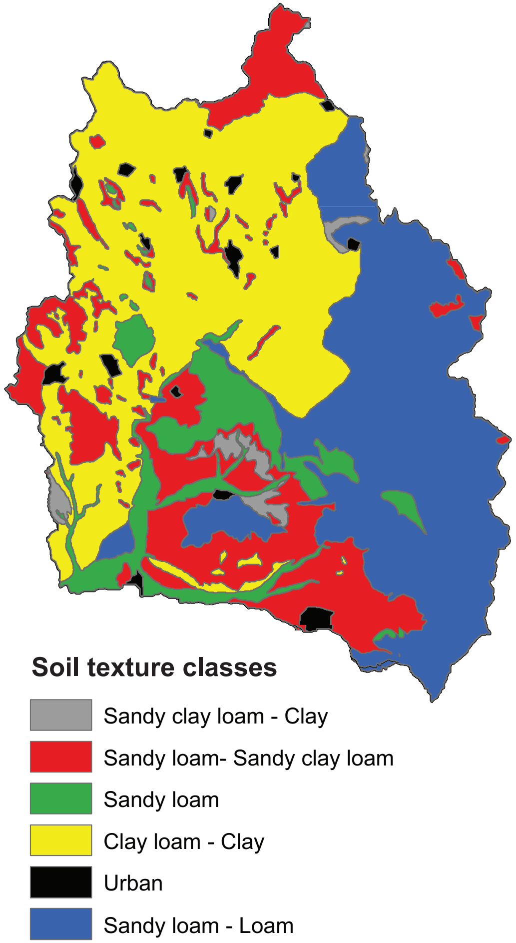
Our study site is the ***Rio Mannu basin (RMB), Sardinia, Italy***

- ➡ Mediterranean climate:
  - ★ Mean annual *P* = 680 mm (4% in summer).
  - ★ Mean annual ET_0 = 750 mm.
- ➡ Affected by prolonged drought period with water restrictions for agriculture.



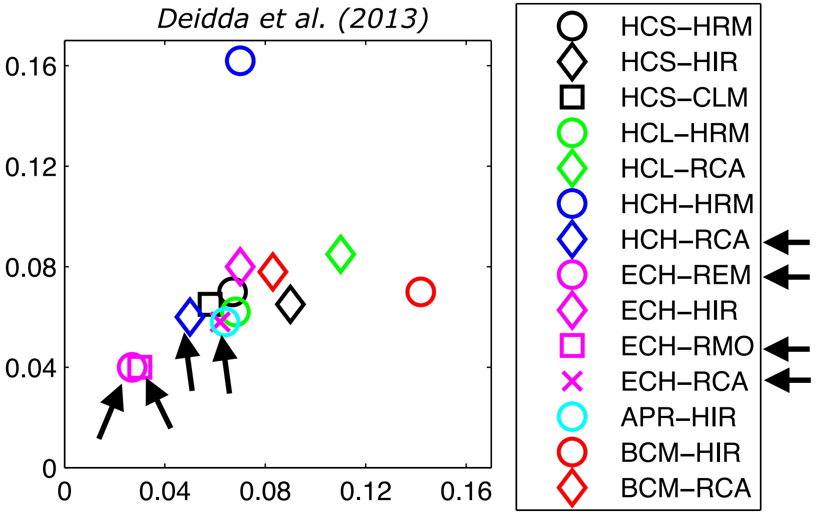
Area = 472 km²





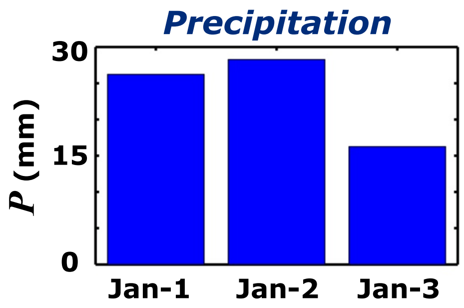
Hydrologic Impacts of Climate Change

Problem: ***Scale gap between resolution of climate model outputs and resolution required by the hydrological model.***

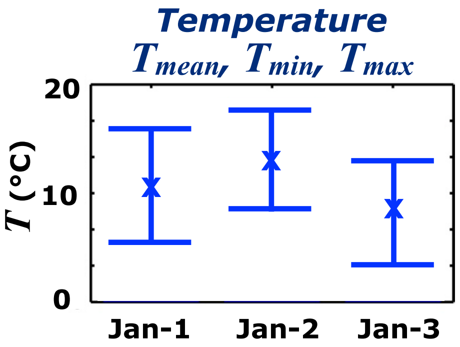


GCM	Hadley Centre for Climate Prediction, Met Office, UK	HCH
GCM	Max Planck Institute for Meteorology, Germany ECHAM5 / MPI OM	ECH
RCM	Swedish Meteorological and Hydrological Institute (SMHI), SwedenRCA Model	RCA
RCM	Max Planck Institute for Meteorology, Hamburg, Germany- REMO Model	REM
RCM	Koninklijk Nederlands Meteorologisch Instituut (KNMI), Netherlands RACMO2 Model	RMO

Daily model outputs



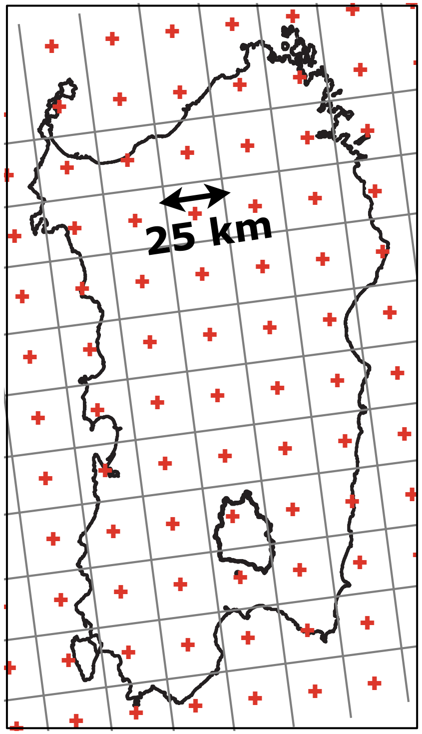
Precipitation



Temperature

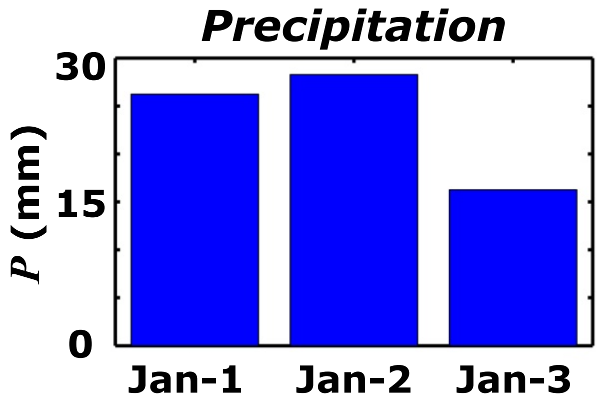
$T_{mean}, T_{min}, T_{max}$

25-km grid

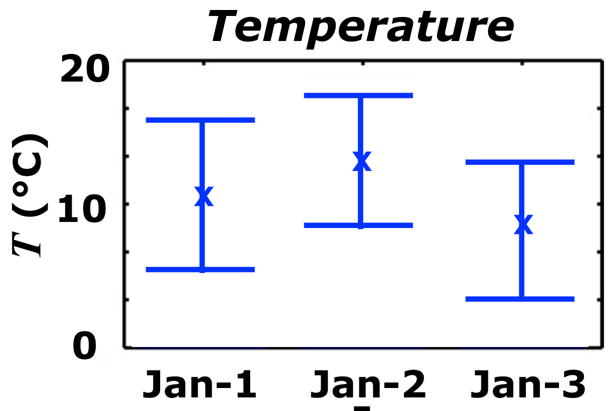


Hydrologic Impacts of Climate Change

Solution: *Use of two downscaling techniques for P and ET_0.*

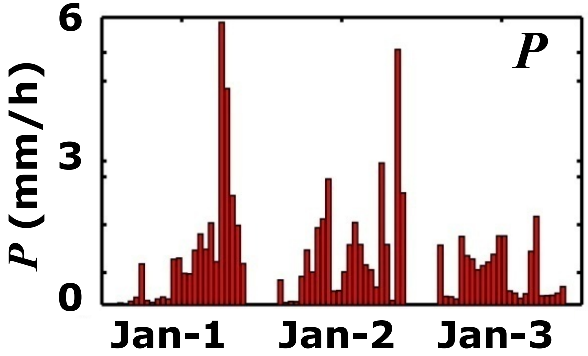

Precipitation

Daily climate model outputs

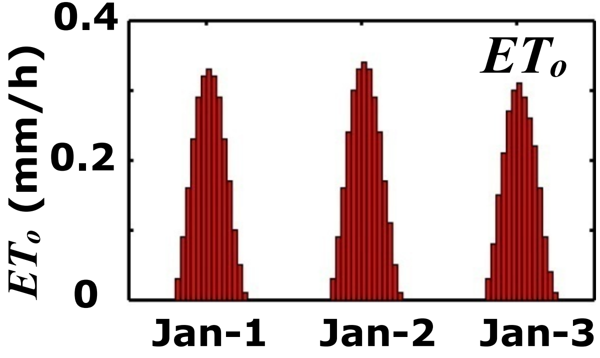

Temperature

Multifractal downscaling technique to disaggregate P in space and time

Generation of hourly grids of ET_o from T_{min} and T_{max}.



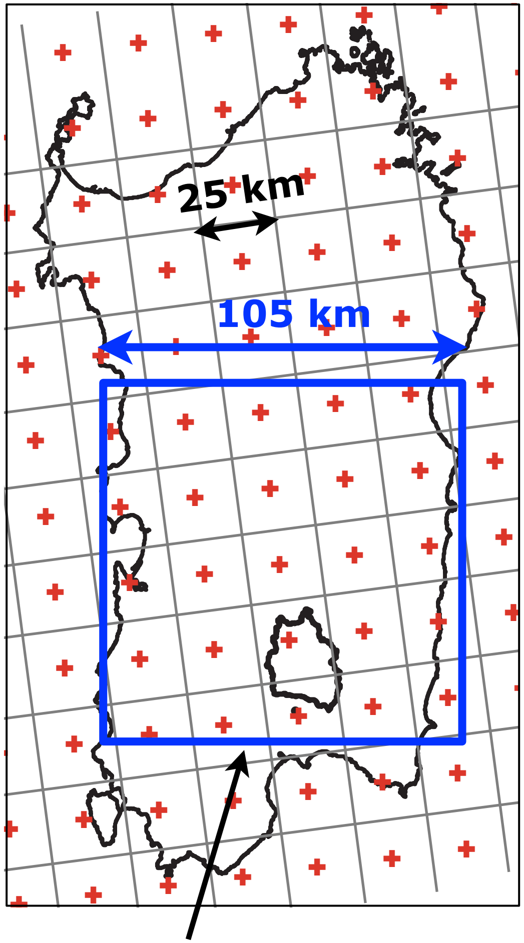
Hourly data needed to force the hydrologic model



Precipitation Downscaling

Precipitation downscaling with a multifractal model

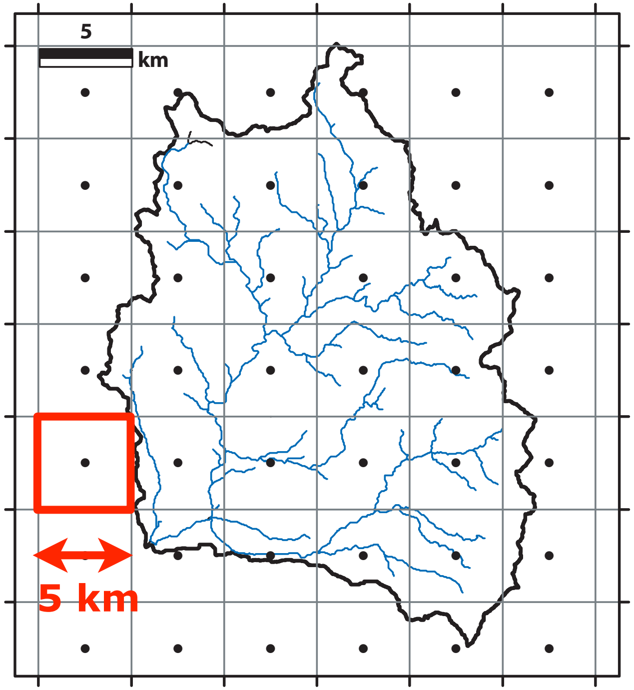
RCM grid - Daily resolution



Calibration dataset:
data at 1-min res from 204 gages (1986-1995).

Downscaling in 2-steps:
(1) Time;
(2) Space and Time.

Downscaled grid - Hourly resolution



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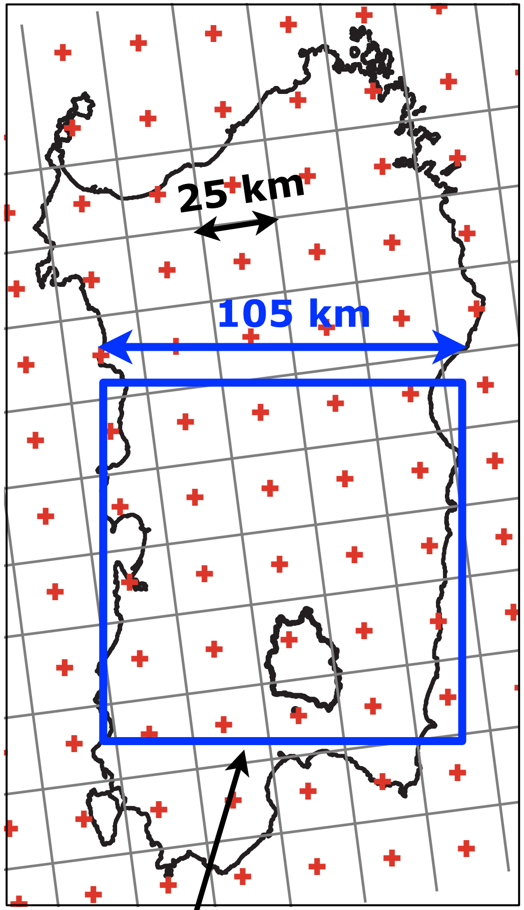

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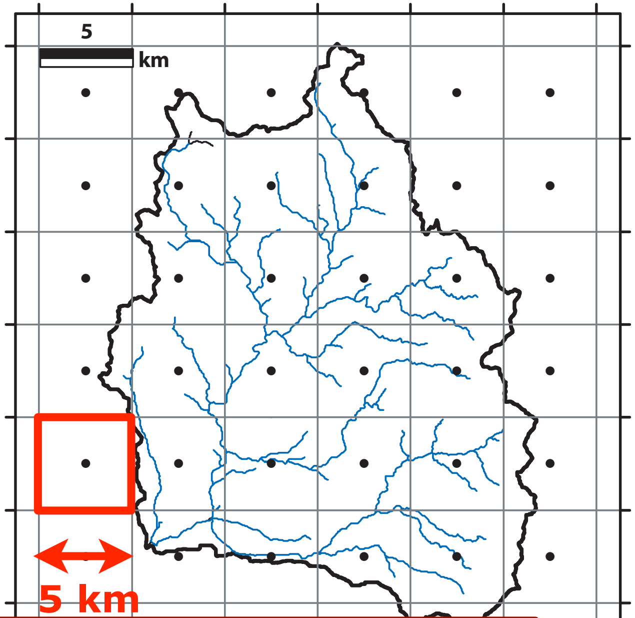
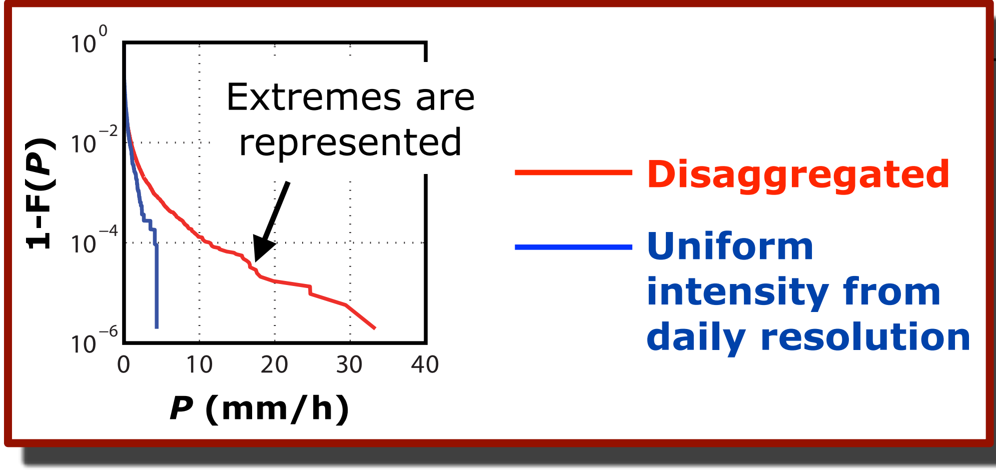




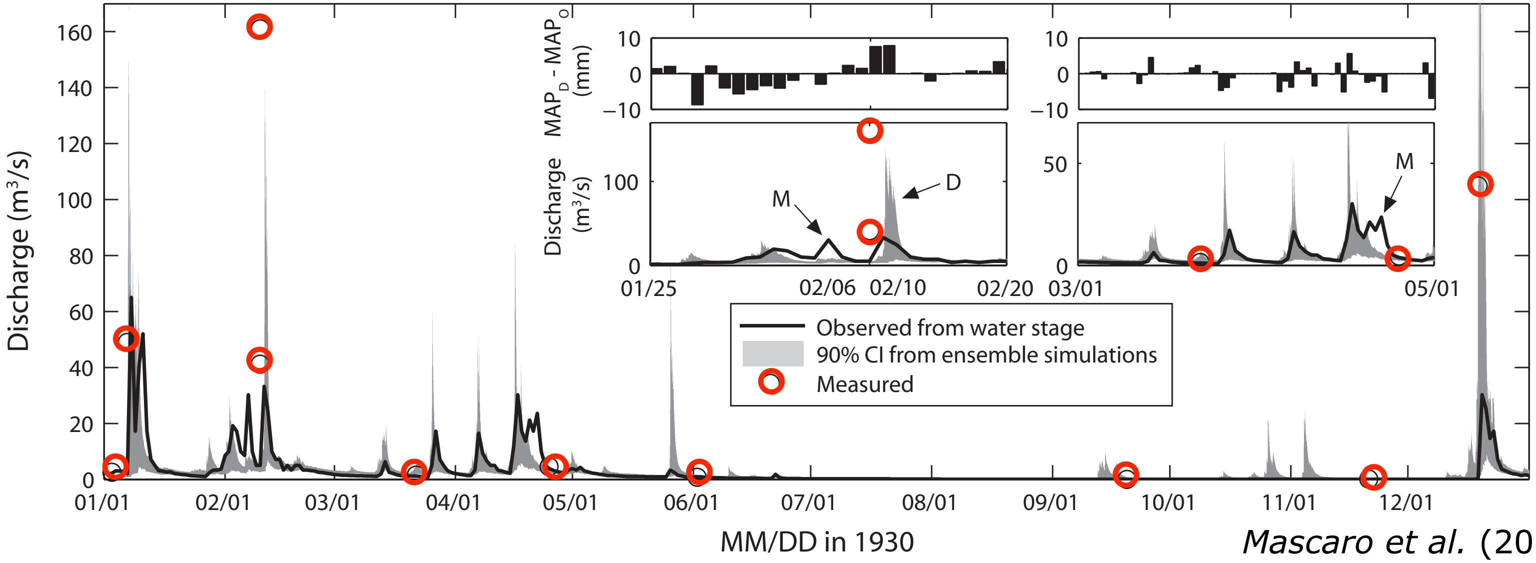
Extremes are represented

Hydrologic Impacts of Climate Change

★ ***The tRIBS hydrologic model was calibrated with historical daily observations using two downscaling tools.***

- ➡ **Calibration** in 1930 and **validation** in 1931-1932 (spin-up interval of 2 years).
- ➡ Model parameters, with focus on K_s and f, were manually tuned. Most values were derived from the literature.

Calibration (1930)



Mascaro et al. (2013), HESS

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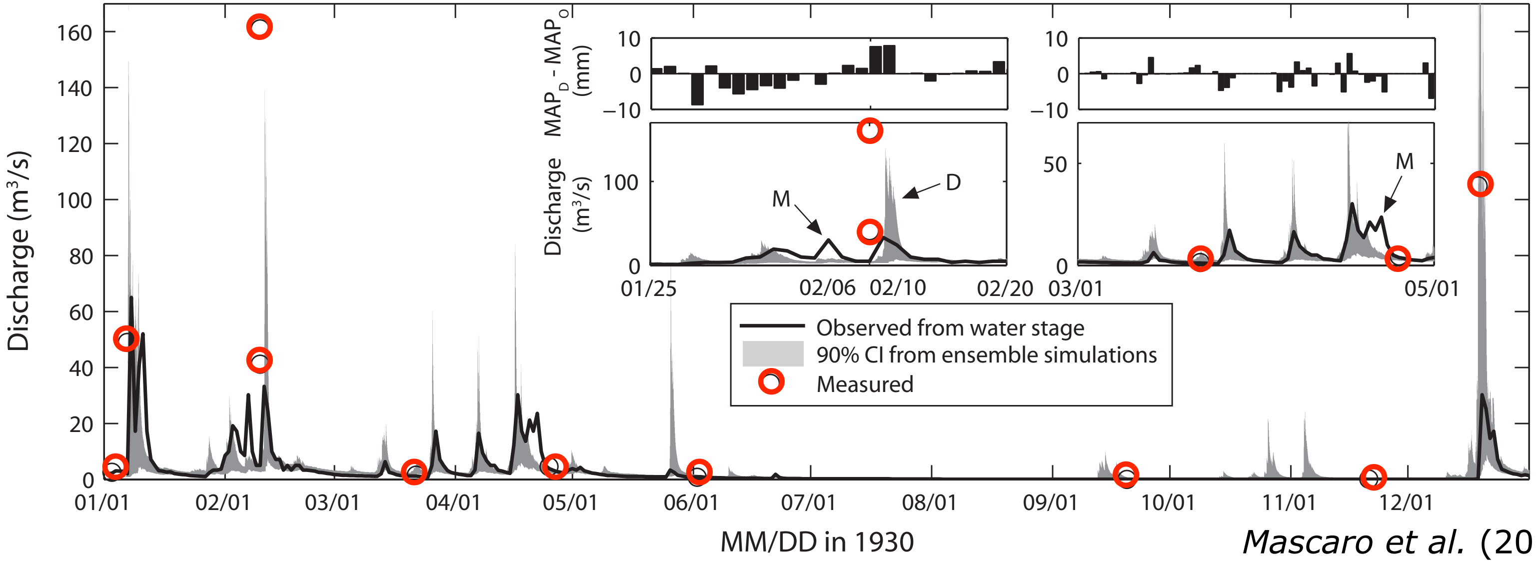
Calibration (1930)



Mascaro et al. (2013), HESS

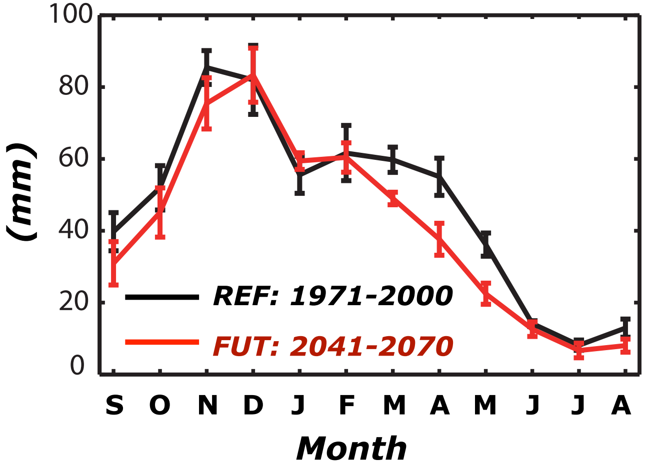
★ ***The climate simulations were carried out in a reference (REF, 1971-2000) and future (FUT, 2041-2070) period.***

- ➡ A total of 256 years of simulations were conducted with the **parallel code** in Saguaro **cluster** at ASU.

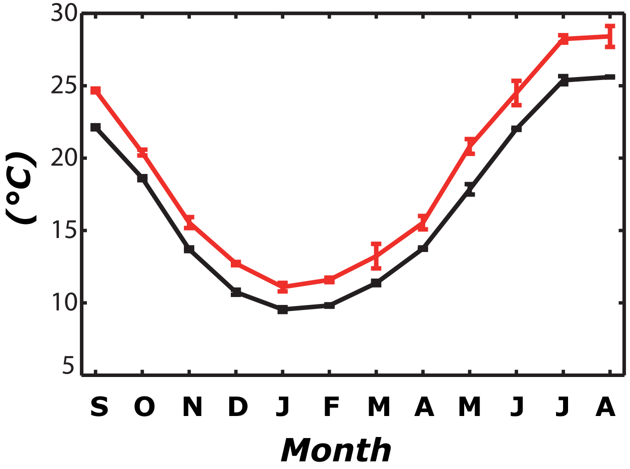
Change in P, T and Q

Change in climate forcings:

Precipitation (P)



Temperature (T)



Mean annual change:

	ΔP (%)	ΔT (°C)
ECH-RCA	-12	+1.9
ECH-REM	-7	+1.9
ECH-RMO	-10	+1.9
HCH-RCA	-21	+3.0

Change in P, T and Q

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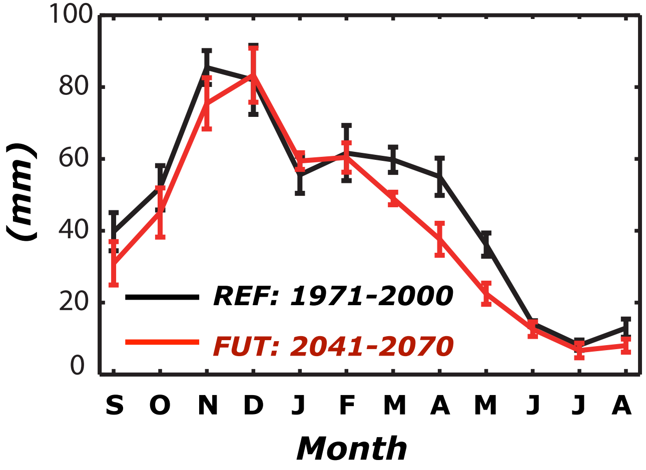
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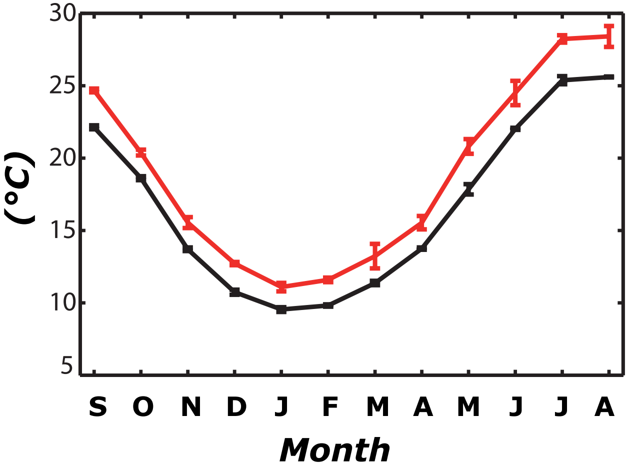
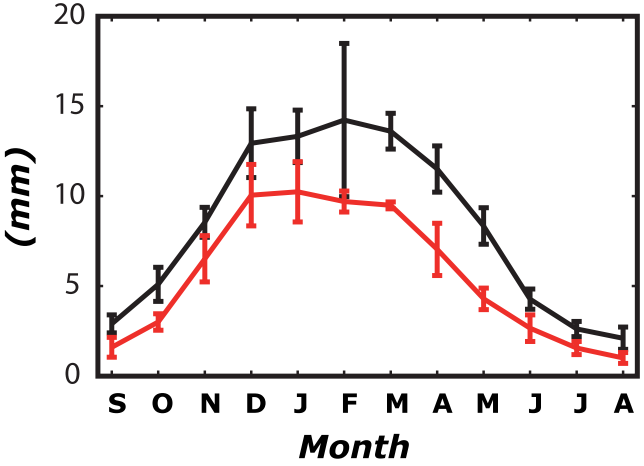

Temperature (T)

Mean annual change:

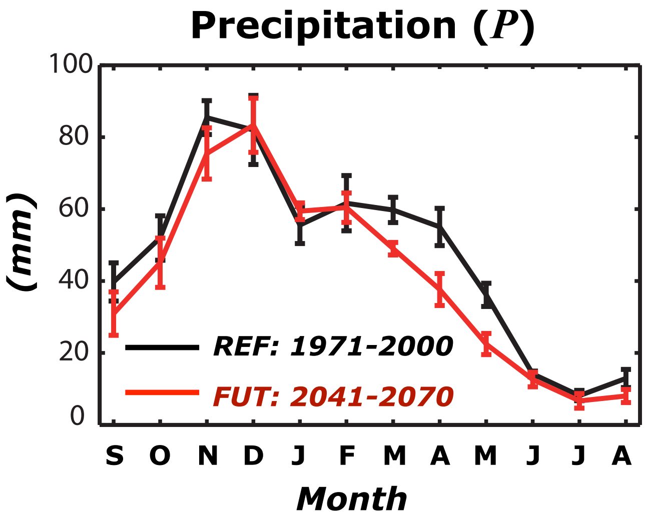
	ΔP (%)	ΔT (°C)	ΔQ (%)
ECH-RCA	-12	+1.9	-33
ECH-REM	-7	+1.9	-17
ECH-RMO	-10	+1.9	-26
HCH-RCA	-21	+3.0	-50

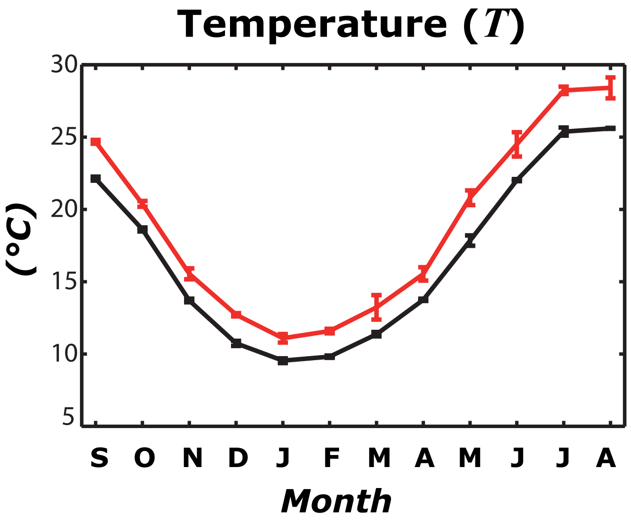
Change in runoff and its generation mechanisms:


Runoff (Q)

Change in P, T and Q

Change in climate forcings:


Precipitation (P)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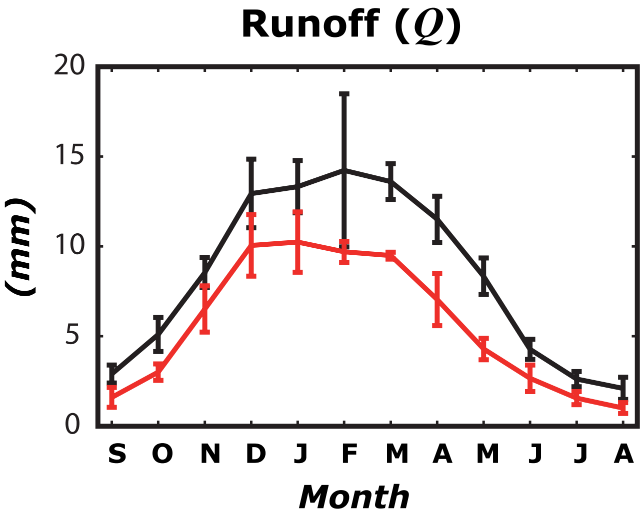
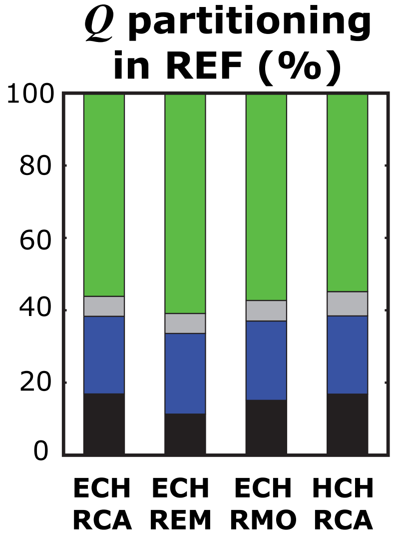
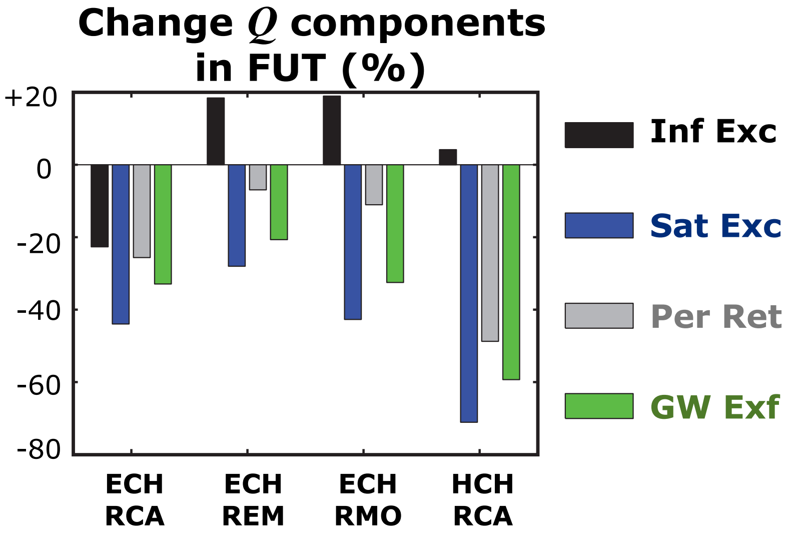
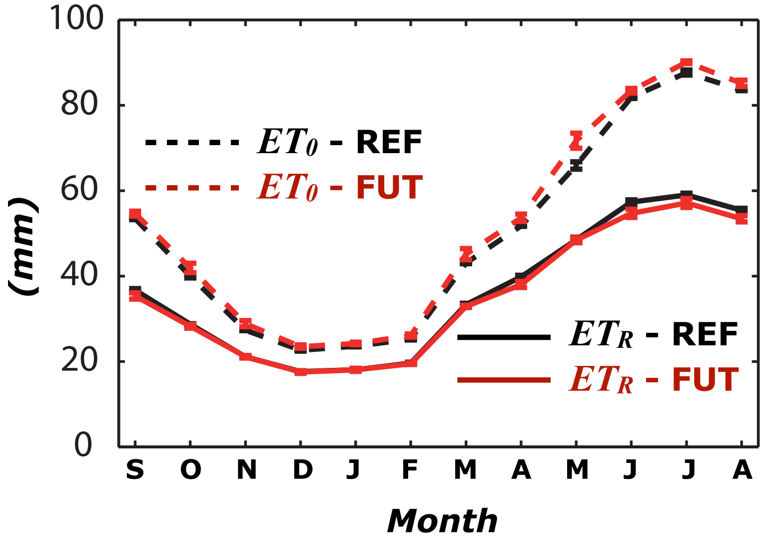

Runoff (Q)


Q partitioning in REF (%)


Change Q components in FUT (%)

Change in ET_0, ET_R, and SWC

Change in potential (ET_0) and real evapotranspiration (ET_R), and soil water content (SWC) in the root zone:



★ Increasing ET_0 (annual mean of +3.7%), due to higher T.

★ Decreasing ET_R (mean of -2.0%).

Change in ET_0, ET_R, and SWC

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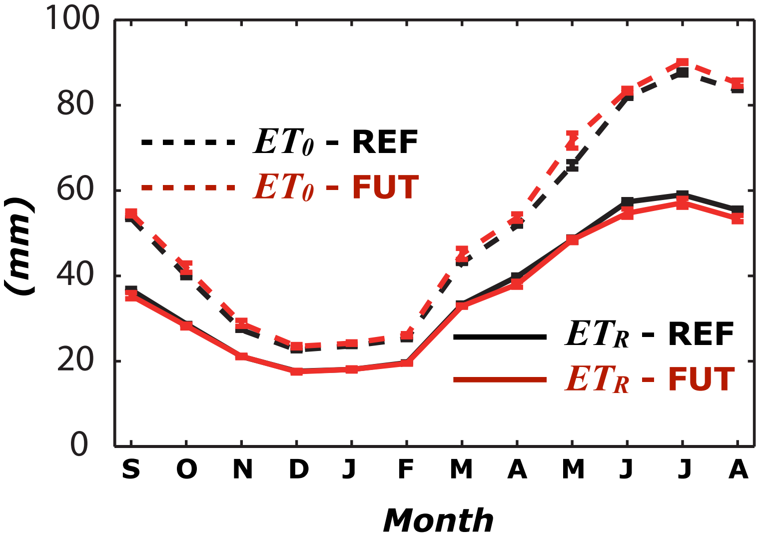
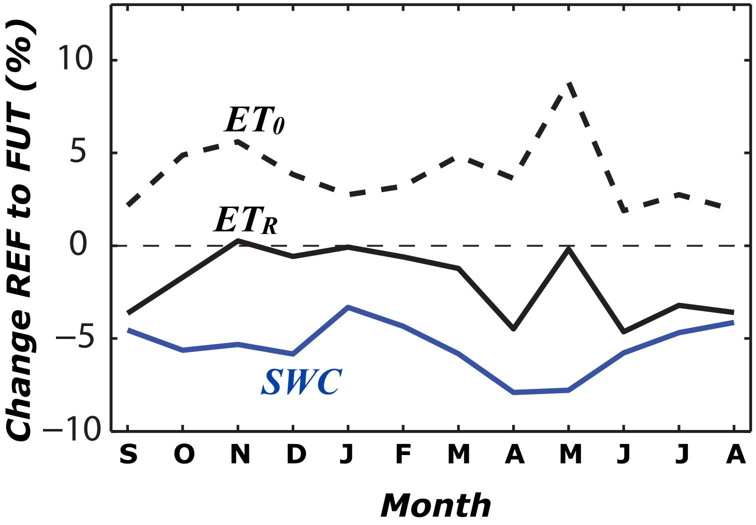
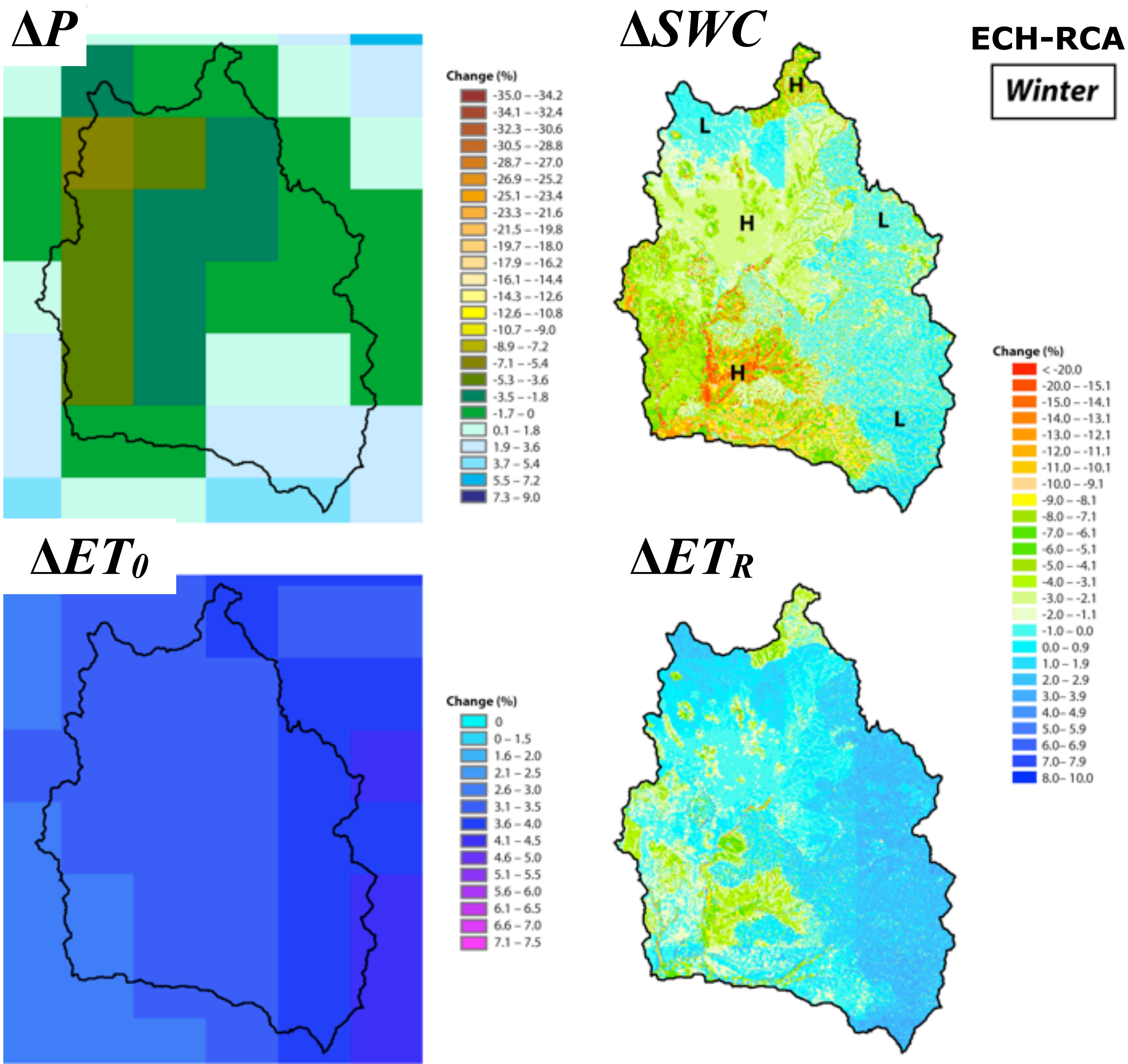




- Increasing ET_0 (annual mean of +3.7%), due to higher T.
- Decreasing ET_R (mean of -2.0%).
- Decreasing ET_R due to diminishing SWC (-5.1%).
- Diminishing SWC due to decreasing P.
- Results consistent with *Senatore et al.* 2011 (JH).

Change in ET_0, ET_R, and SWC

Smallest variability of P (positive or slightly negative ΔP)



Change in ET_0, ET_R, and SWC

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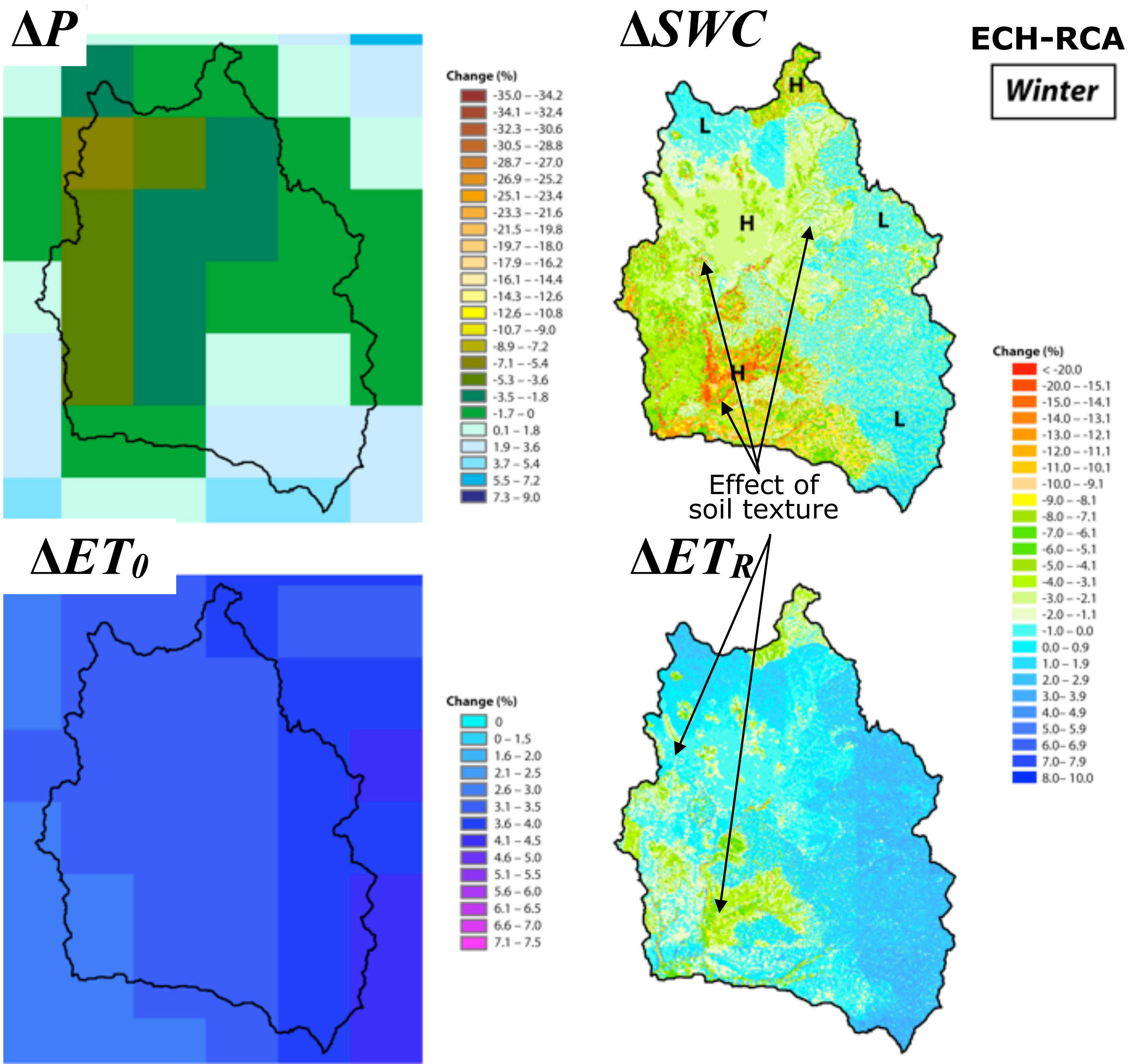


ECH-RCA

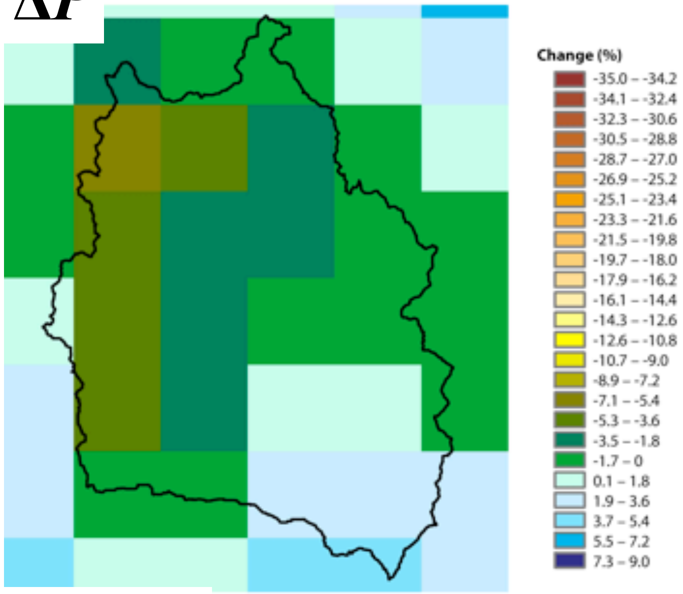
Winter

Effect of soil texture

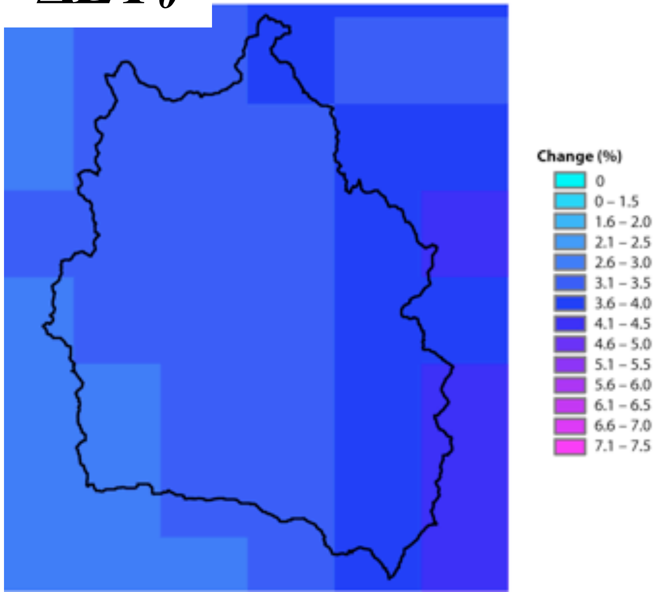
Change in ET_0, ET_R, and SWC

Smallest variability of P (positive or slightly negative ΔP)

ΔP



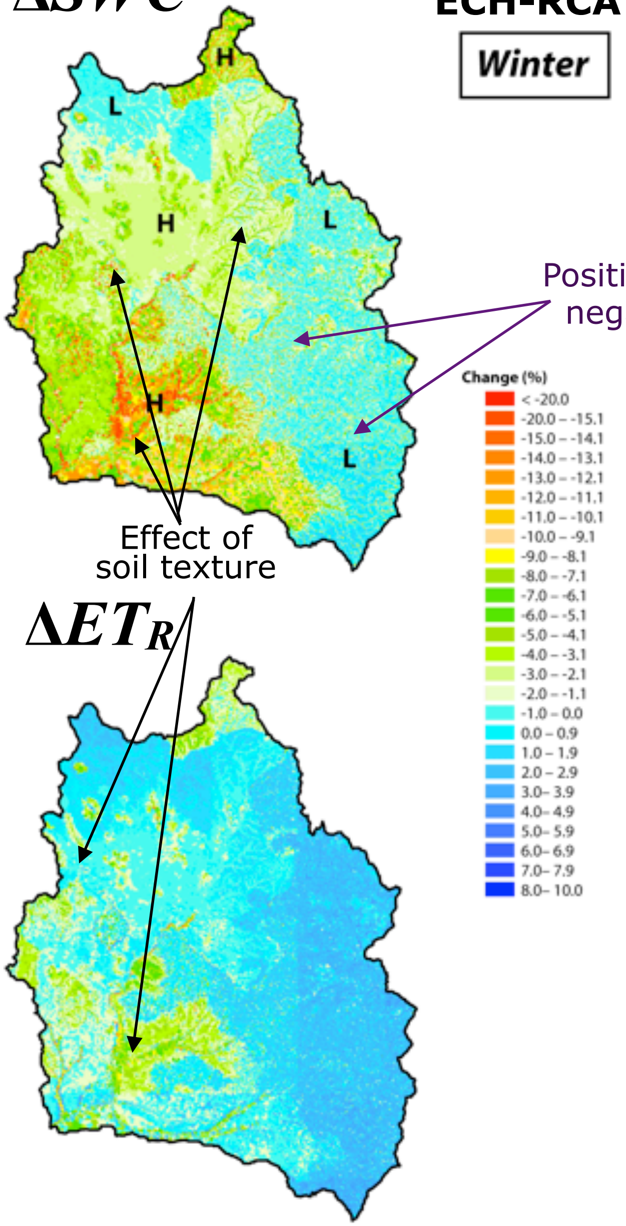
ΔET_0



ΔSWC

ECH-RCA

Winter



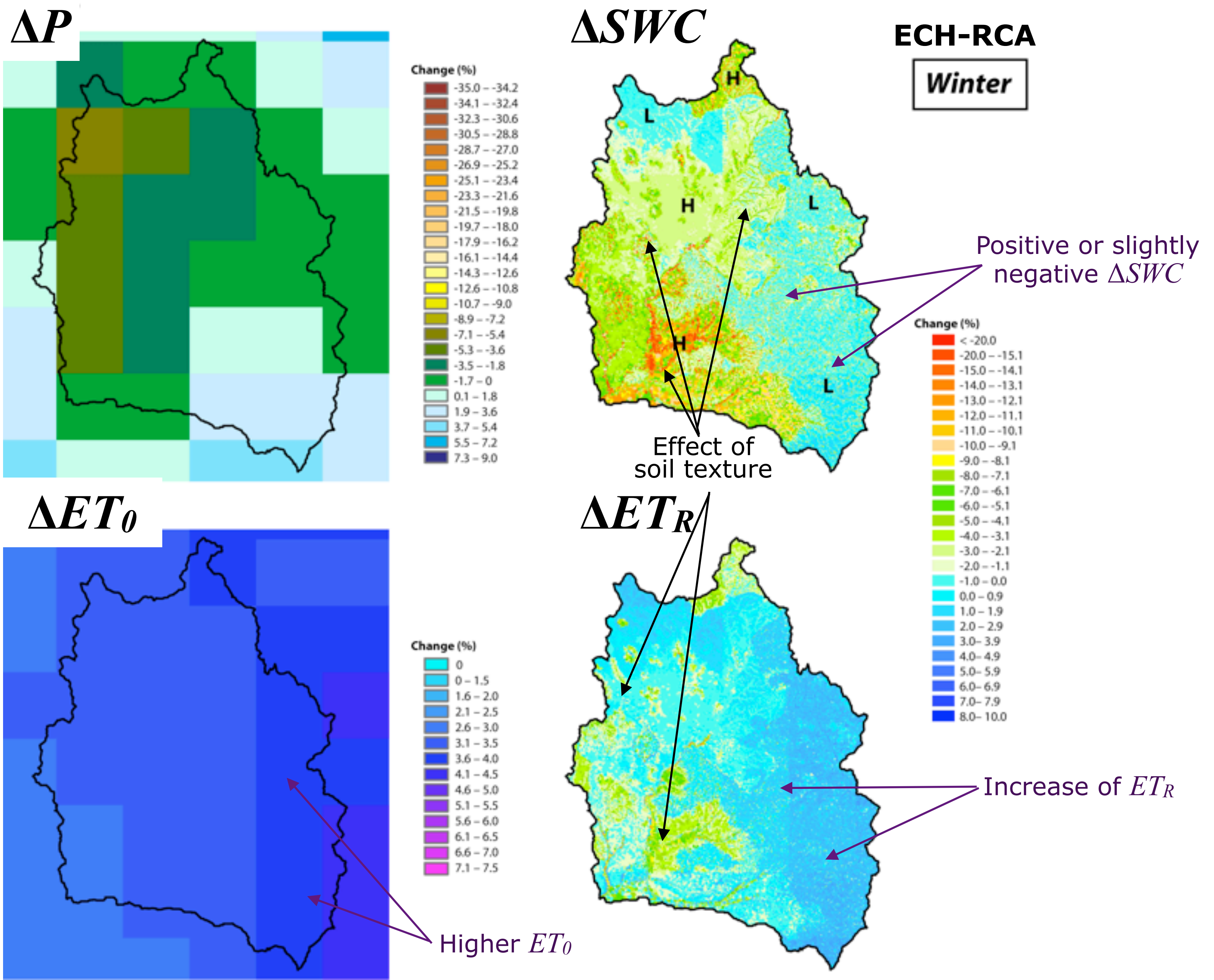
Positive or slightly negative ΔSWC

Effect of soil texture

ΔET_R

Change in ET_0, ET_R, and SWC

Smallest variability of P (positive or slightly negative ΔP)



Positive or slightly negative ΔSWC

Effect of soil texture

Increase of ET_R

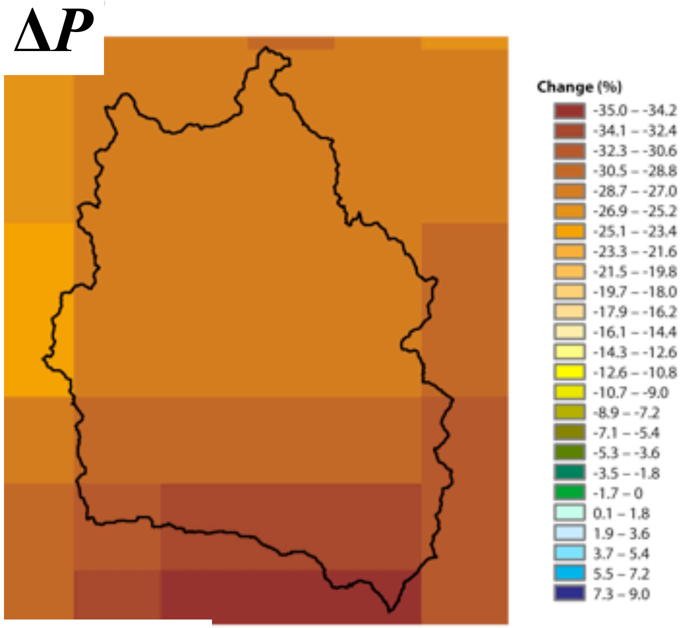
Higher ET_0

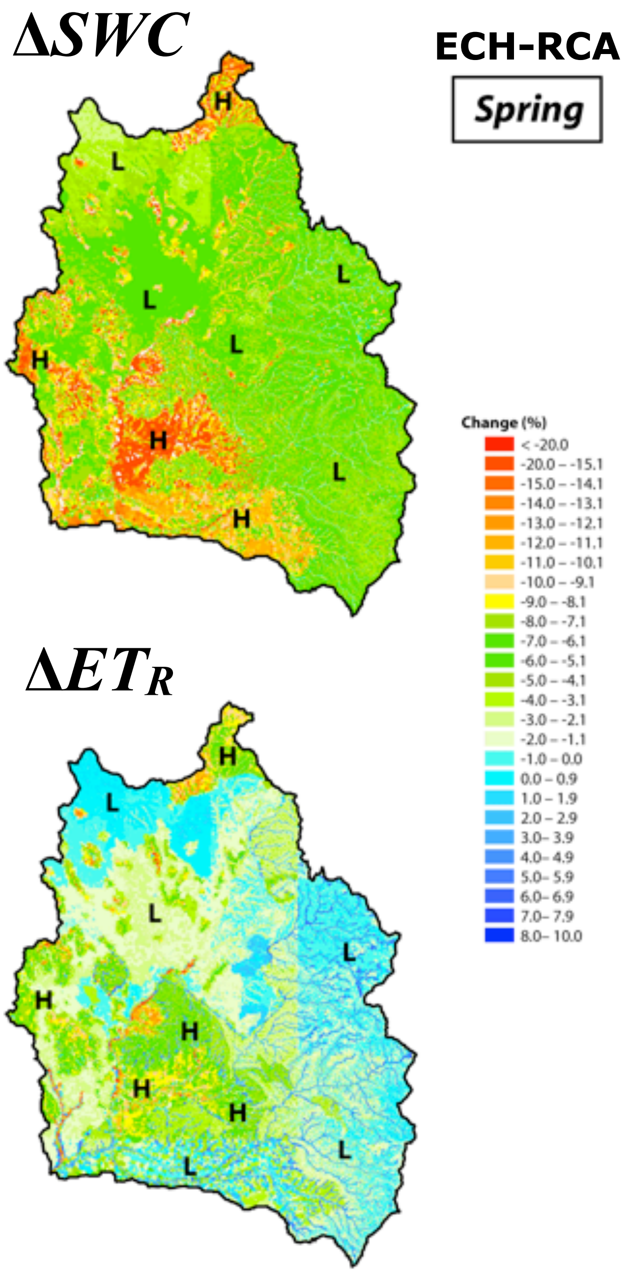
Change in ET_0, ET_R, and SWC

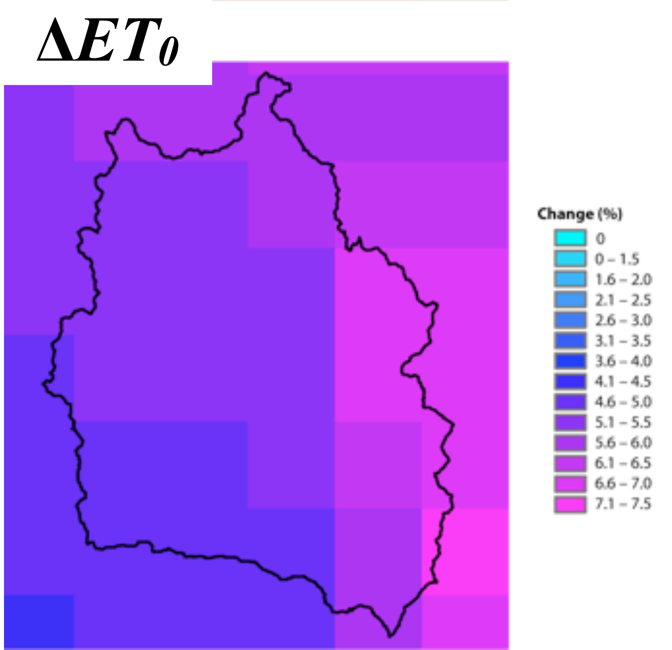
ECH-RCA

Spring

Largest decrease of P (negative ΔP)

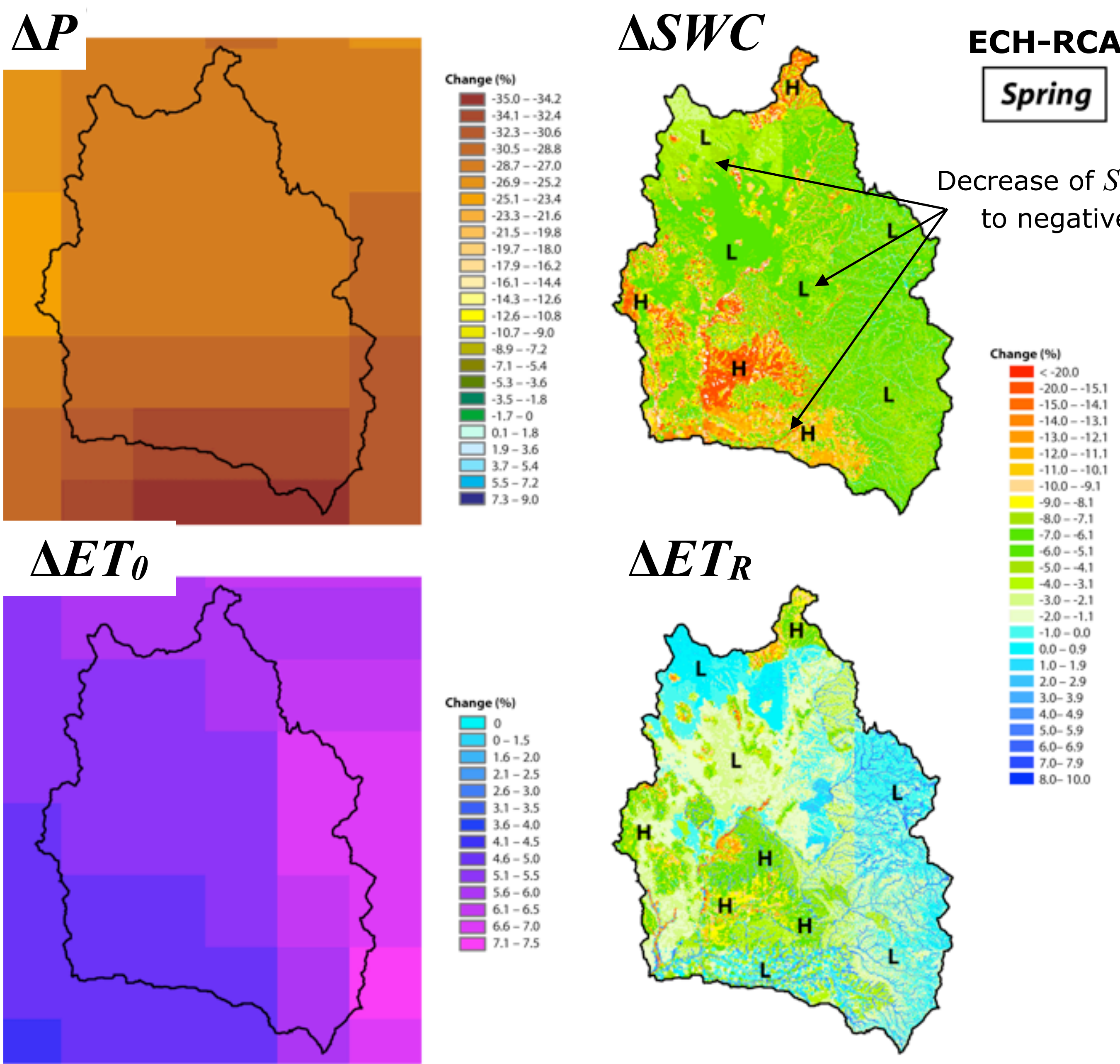






Change in ET_0, ET_R, and SWC

Largest decrease of P (negative ΔP)



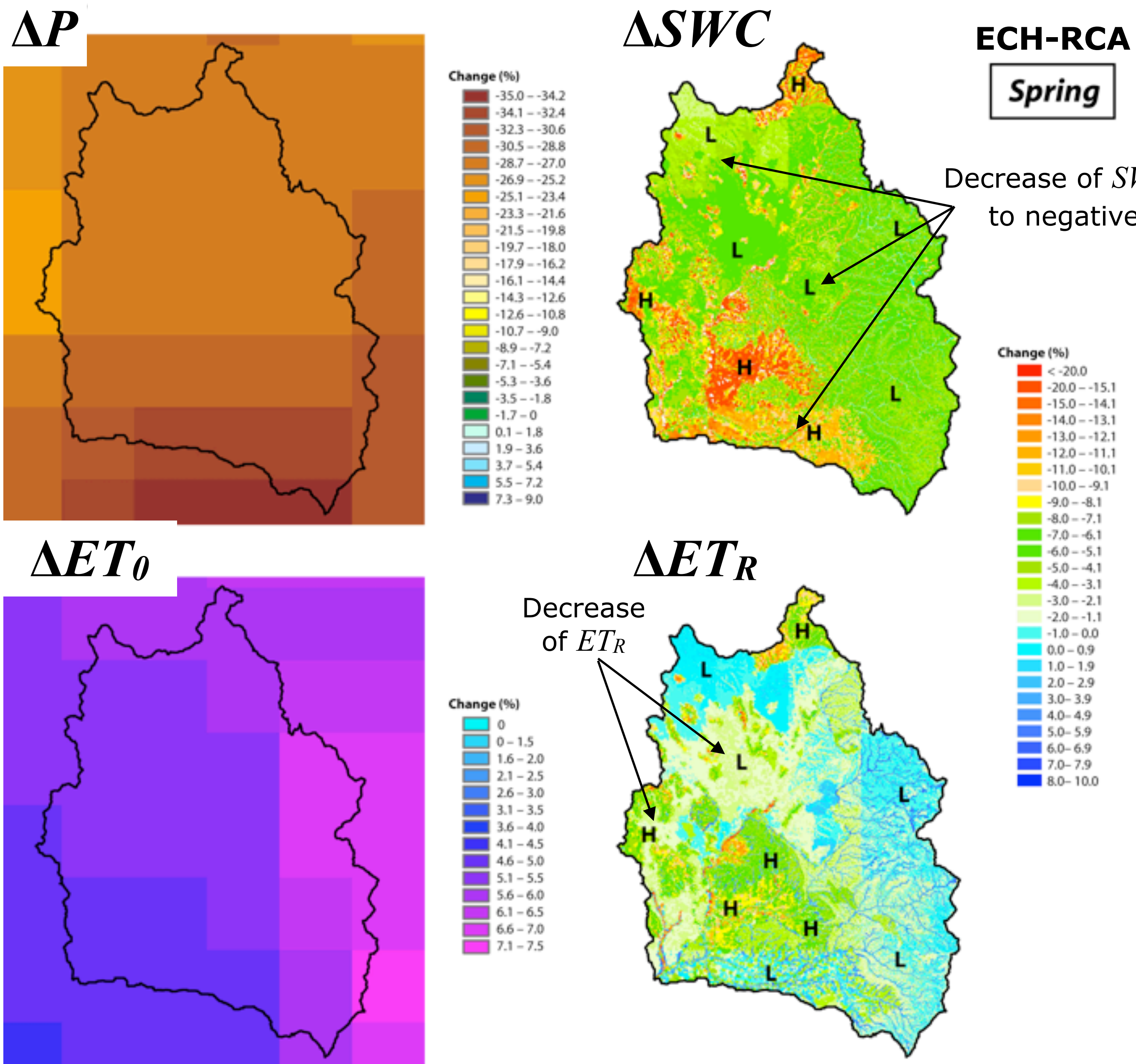
ECH-RCA

Spring

Decrease of SWC due to negative ΔP

Change in ET_0, ET_R, and SWC

Largest decrease of P (negative ΔP)



ECH-RCA

Spring

ΔP

ΔSWC

Decrease of SWC due to negative ΔP

ΔET_0

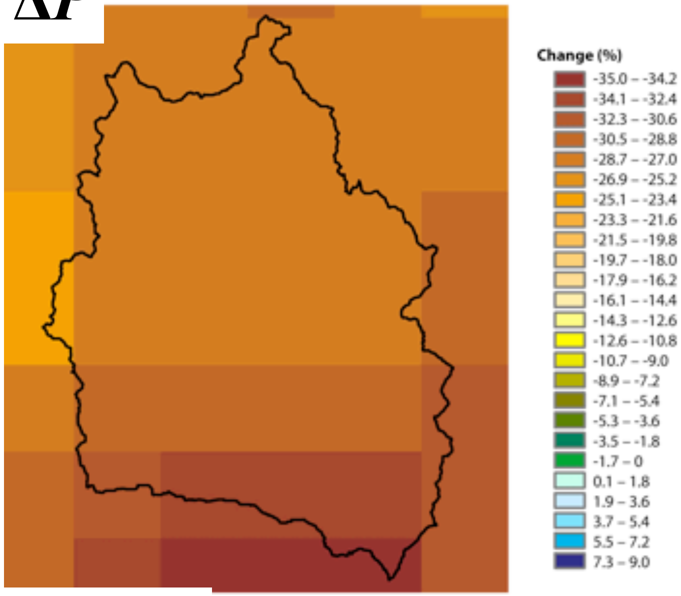
ΔET_R

Decrease of ET_R

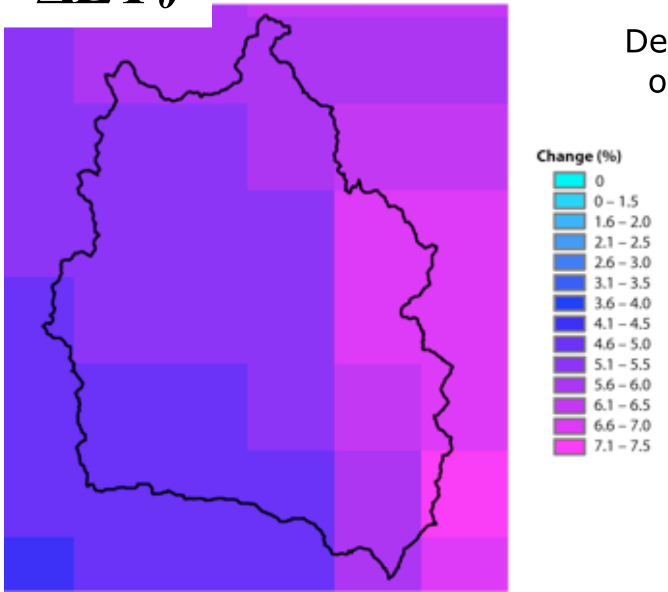
Change in ET_0, ET_R, and SWC

Largest decrease of P (negative ΔP)

ΔP



ΔET_0

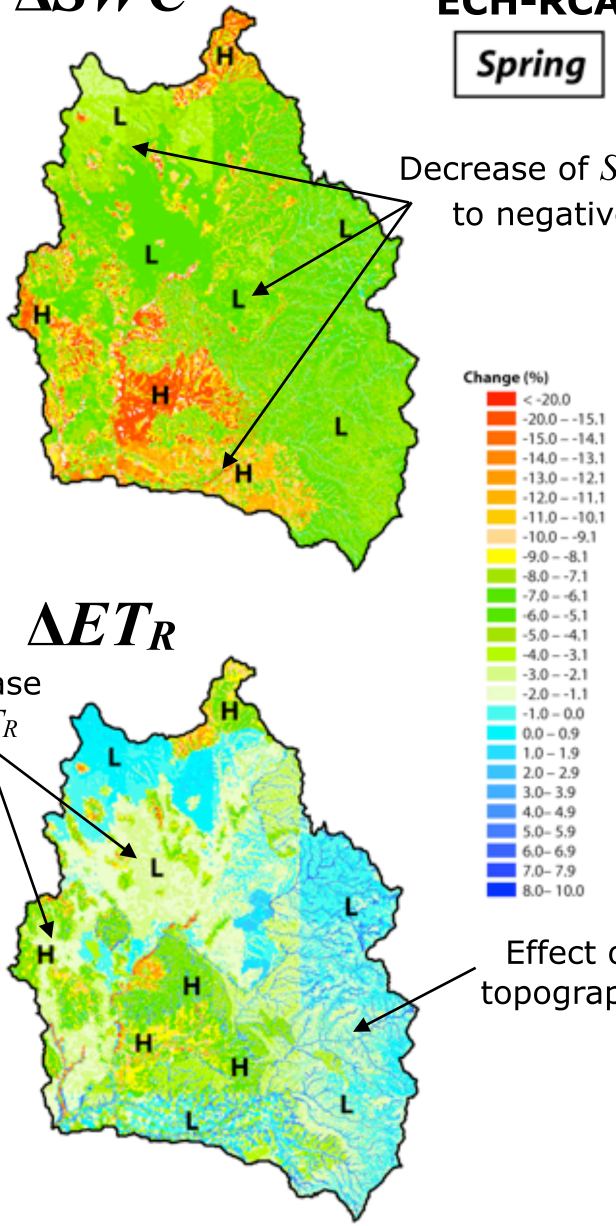


ECH-RCA

Spring

ΔSWC

ΔET_R



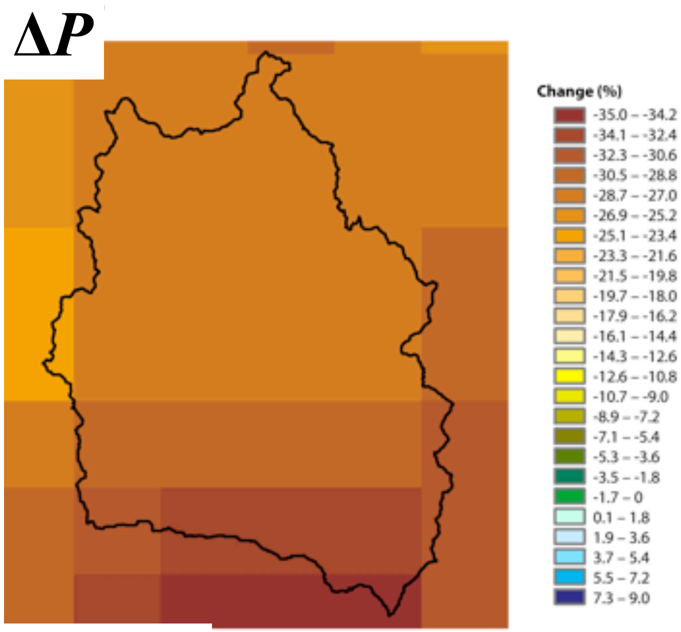
Decrease of SWC due to negative ΔP

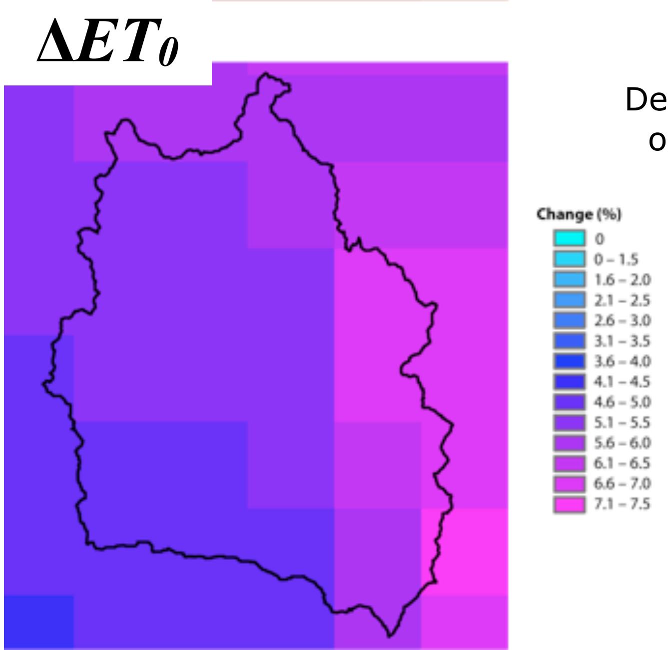
Decrease of ET_R

Effect of topography

Change in ET_0, ET_R, and SWC

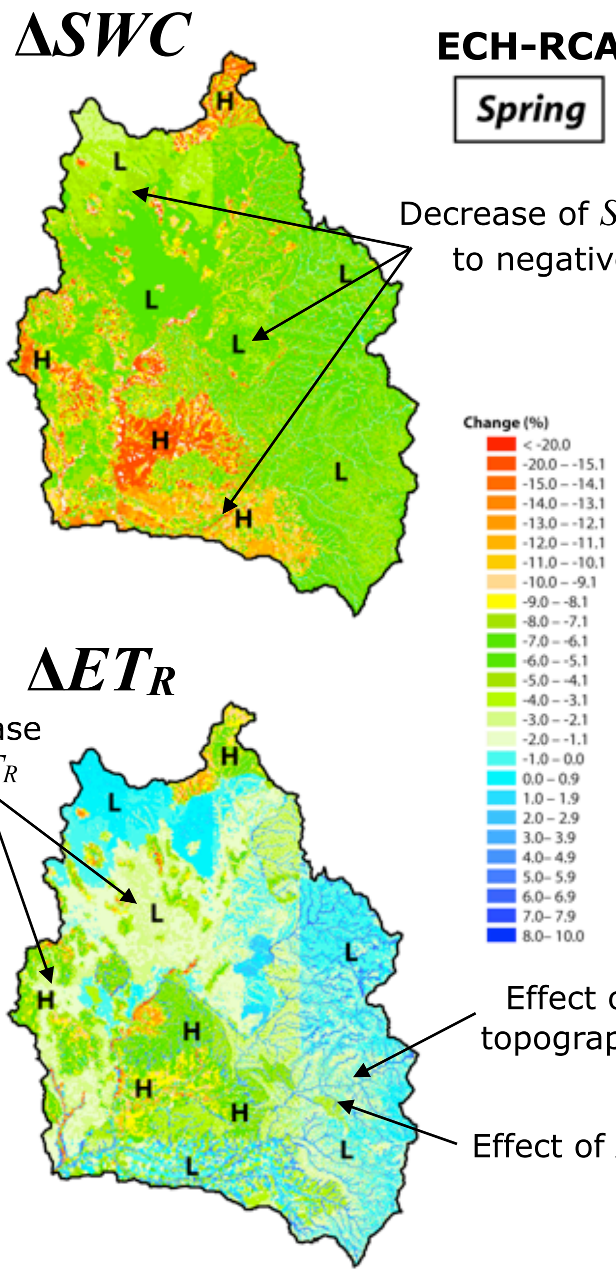
Largest decrease of P (negative ΔP)





ECH-RCA

Spring



Decrease of SWC due to negative ΔP

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Effect of topography

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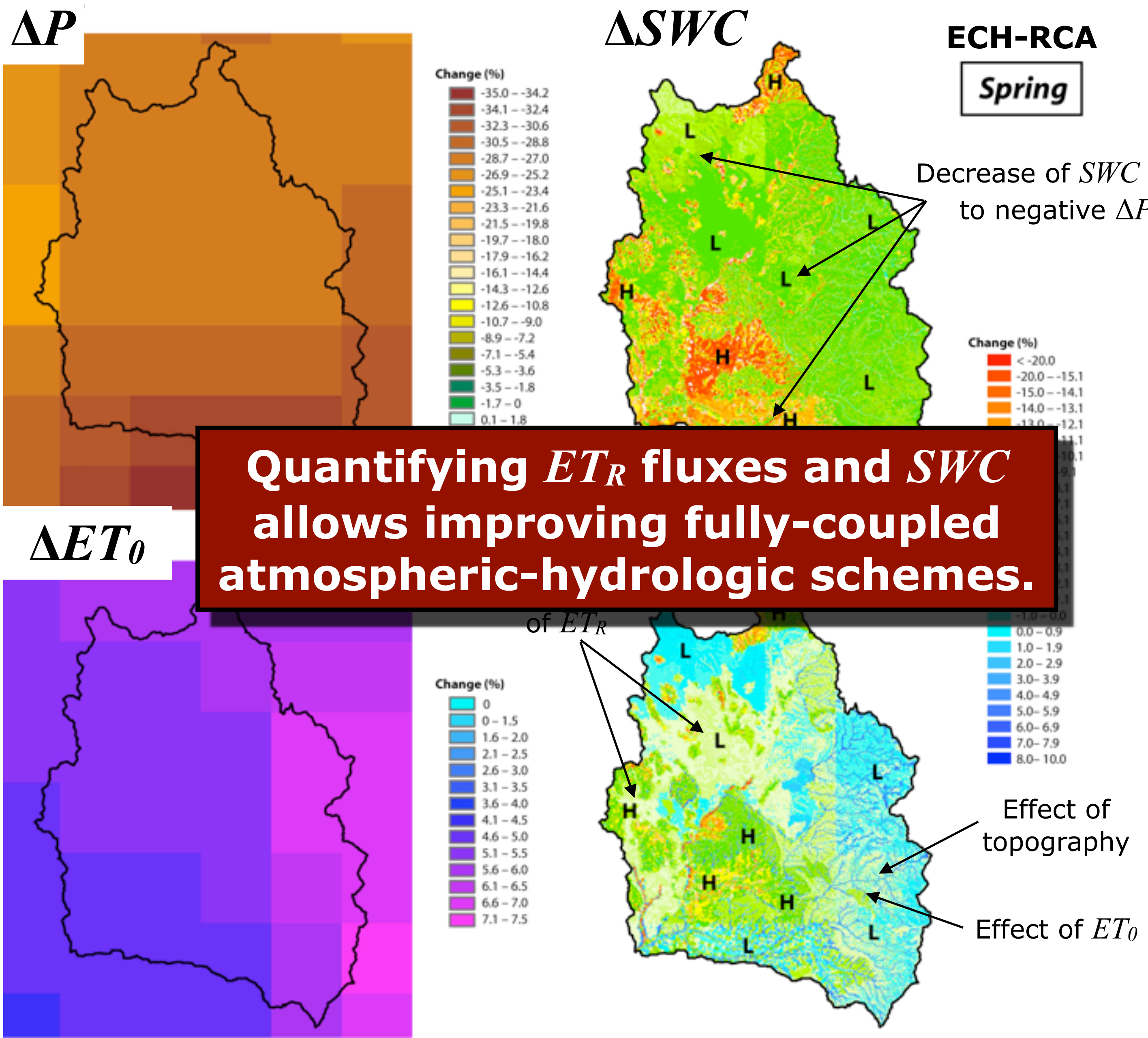

Decrease of SWC due to negative ΔP

of ET_R

Effect of topography

Effect of ET_0

Quantifying ET_R fluxes and SWC allows improving fully-coupled atmospheric-hydrologic schemes.

Key-Points of Climate Change Study

- ★ Multiple climate scenario allowed characterizing **uncertainty of future climate projections**.

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- ★ Expected **impacts** due to future climate on **water resources and hydrology**:
  - ➡ Reduction of runoff volume.
  - ➡ Intensification of extremes.
  - ➡ Spatially-variable decreasing SWC and ET_R.

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  ➡ Reduction of runoff volume.

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  ➡ Spatially-variable decreasing SWC and ET_R.

★ **Utility for stakeholders**: estimation of agricultural productivity, design of infrastructures, land use planning, and touristic sector, among others.

Outline

1. ***The tRIBS hydrologic model***

   Acknowledgments:
   Rafael Bras, Enrique R. Vivoni, Valeriy Ivanov, Sue Mniszewski, and Patricia Fasel

2. ***Study of climate change impacts in a Mediterranean basin***

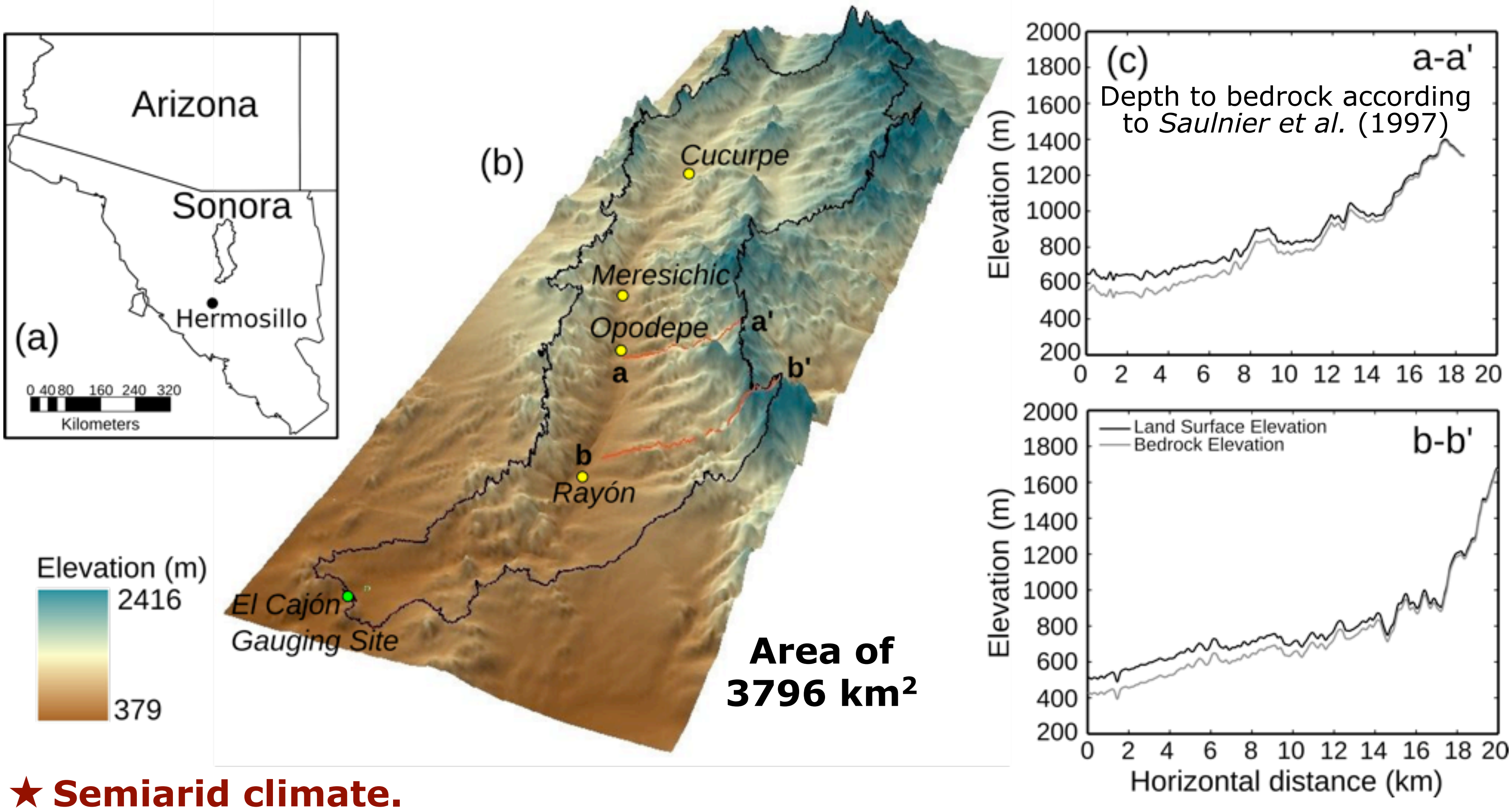
   Acknowledgments:
   Monica Piras, Roberto Deidda and Enrique R. Vivoni

3. ***Ecohydrological study of a regional basin in northwest Mexico***

   Acknowledgments:
   Luis Mendez-Barroso and Enrique R. Vivoni

Ecohydrological study

We used tRIBS to investigate the ecosystem control on hydrologic fluxes and states in the ***Rio San Miguel*** *(****RSM****) basin, Mexico.*

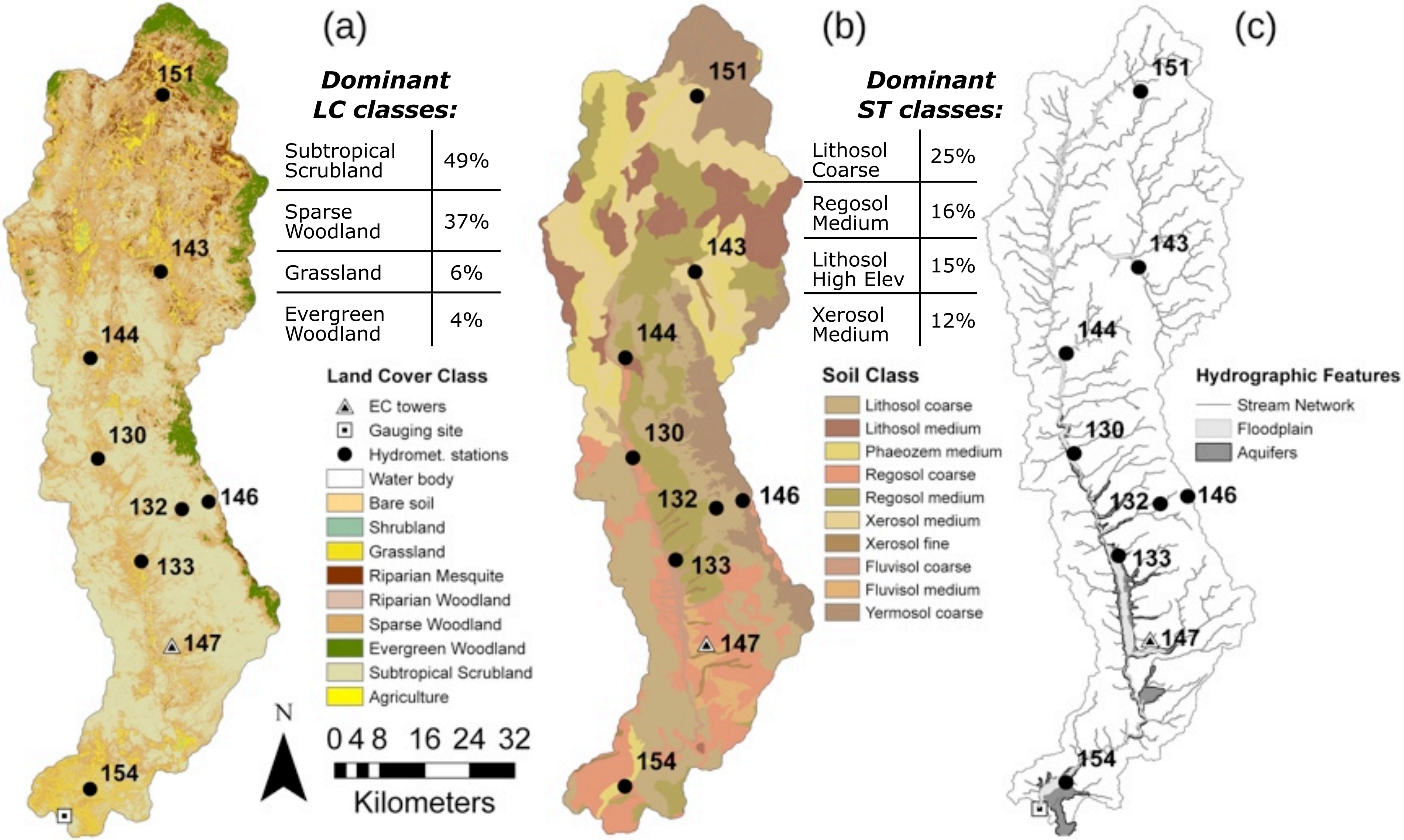


Depth to bedrock according to *Saulnier et al.* (1997)

Area of 3796 km²

★ Semiarid climate.
★ Complex topography.
★ Dramatic vegetation greening during the North American Monsoon (NAM).

Ecohydrological study



Dominant LC classes:

Subtropical Scrubland	49%
Sparse Woodland	37%
Grassland	6%
Evergreen Woodland	4%

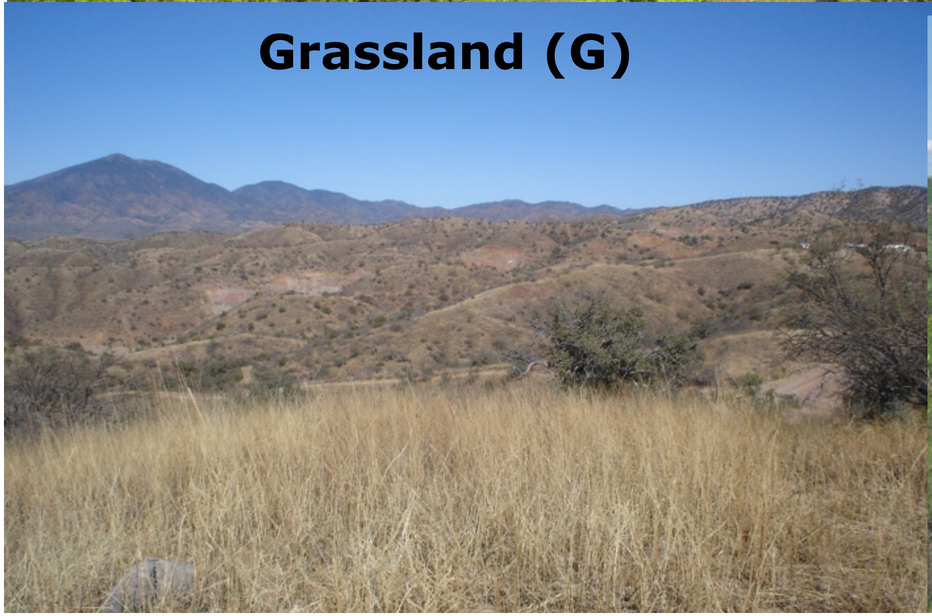
Dominant ST classes:

Lithosol Coarse	25%
Regosol Medium	16%
Lithosol High Elev	15%
Xerosol Medium	12%

Ecohydrological study

Evergreen Woodland (EW)

Subtropical Scrubland (SS)

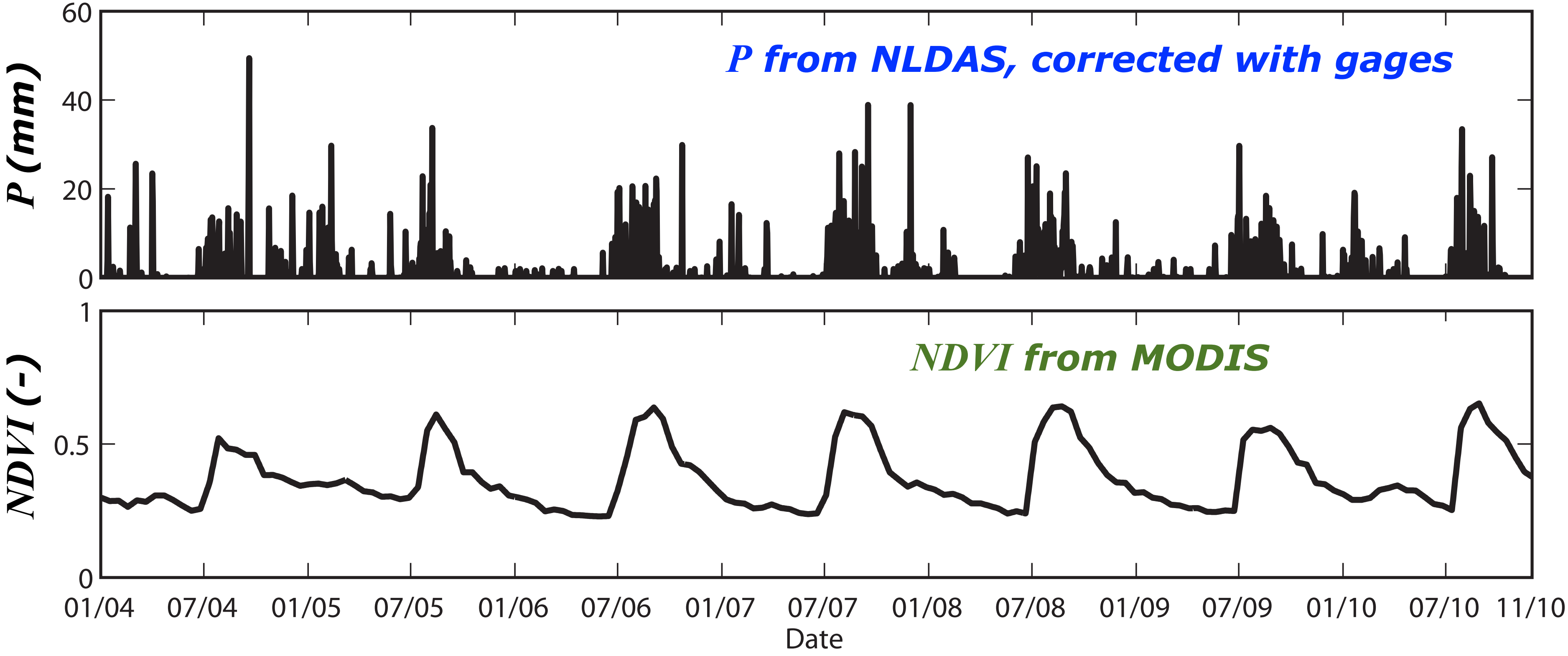


Grassland (G)

Sparse Woodland (SW)

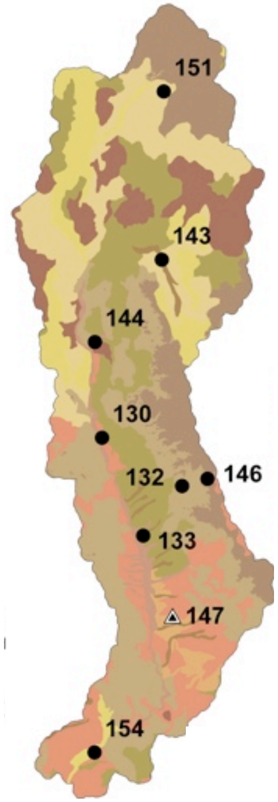
Dataset

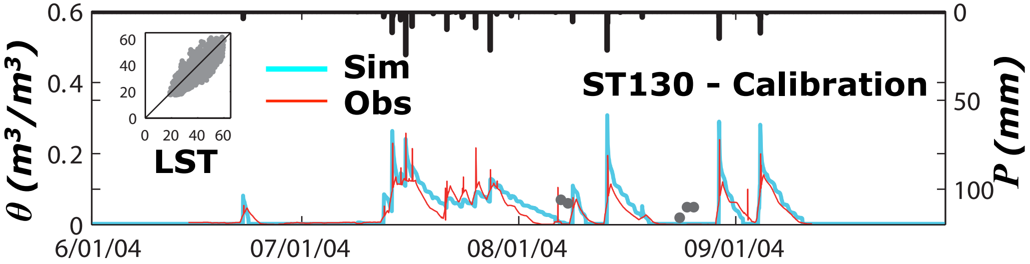
- Period of hydrologic simulation: **Jan 2004 - Dec 2010**.
- **Hydrometeorological forcing** from North American Land Data Assimilation Systems (**NLDAS**) at 12 km - 1 h; bias-corrected.
- **Time-varying vegetation parameters** derived from MODIS.
- **Cal-Val:** (i) **soil moisture** (θ) observations at 9 stations and 2D-STAR airborne-sensor; (ii) **Land Surface Temperature** (LST) from MODIS.



Model Calibration and Validation

- TIN of 624,716 nodes.
- Point **calibration** (summer 2004) of soil parameters against θ at the 9 stations.

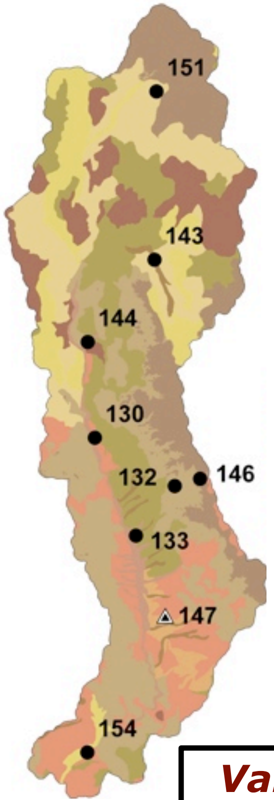


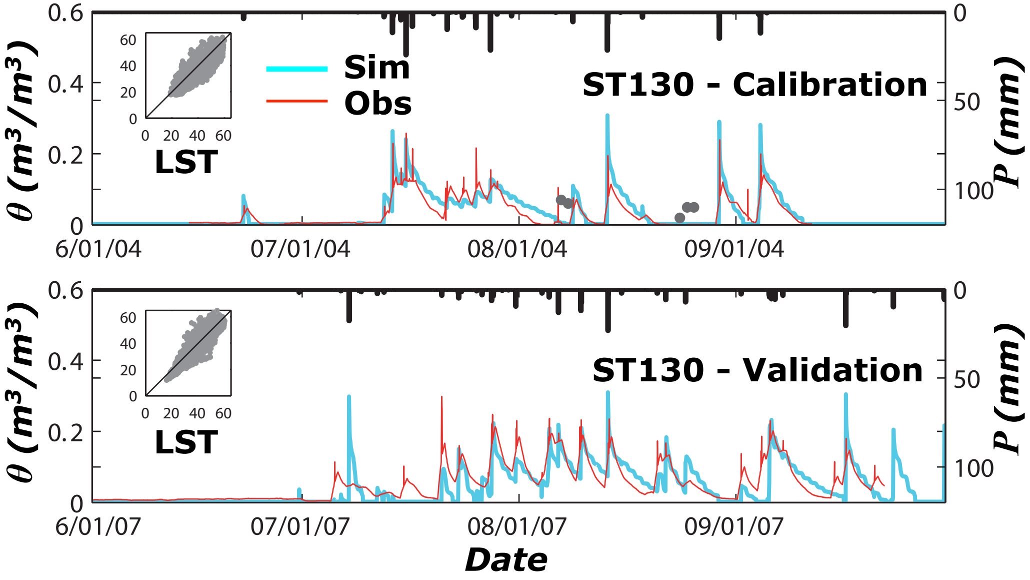


ST	BIAS (%)	MAE (m^3/m^3)	CC (-)
147	-2.6	0.012	0.91
130	17.9	0.013	0.94
132	5.1	0.016	0.91
133	5.8	0.015	0.95
144	-1.3	0.021	0.95
154	4.5	0.015	0.90
146	27.7	0.024	0.94
151	-10.8	0.026	0.91
143	-21.7	0.033	0.85

Model Calibration and Validation

- ★ <u>TIN of 624,716 nodes.</u>
- ★ Point **calibration** (summer 2004) of soil parameters against θ at the 9 stations.
- ★ **Validation** (summer 2007) at the stations with point and basin simulations.





				Validation Point Sim			*Validation Basin Sim*		
ST	**BIAS (%)**	**MAE (m^3/m^3)**	**CC (-)**	**BIAS (%)**	**MAE (m^3/m^3)**	**CC (-)**	**BIAS (%)**	**MAE (m^3/m^3)**	**CC (-)**
147	-2.6	0.012	0.91	12.1	0.012	0.95	51.3	0.036	0.69
130	17.9	0.013	0.94	-12.4	0.016	0.92	91.7	0.034	0.78
132	5.1	0.016	0.91	-17.4	0.017	0.88	56.6	0.034	0.76
133	5.8	0.015	0.95	-5.0	0.019	0.94	58.8	0.038	0.85
144	-1.3	0.021	0.95	-2.7	0.016	0.93	49.6	0.071	0.80
154	4.5	0.015	0.90	-23.8	0.026	0.89	9.0	0.027	0.89
146	27.7	0.024	0.94	17.7	0.029	0.84	72.8	0.060	0.70
151	-10.8	0.026	0.91	-18.2	0.038	0.84	16.0	0.025	0.95
143	-21.7	0.033	0.85	-40.4	0.062	0.94	42.5	0.076	0.59

Model Validation

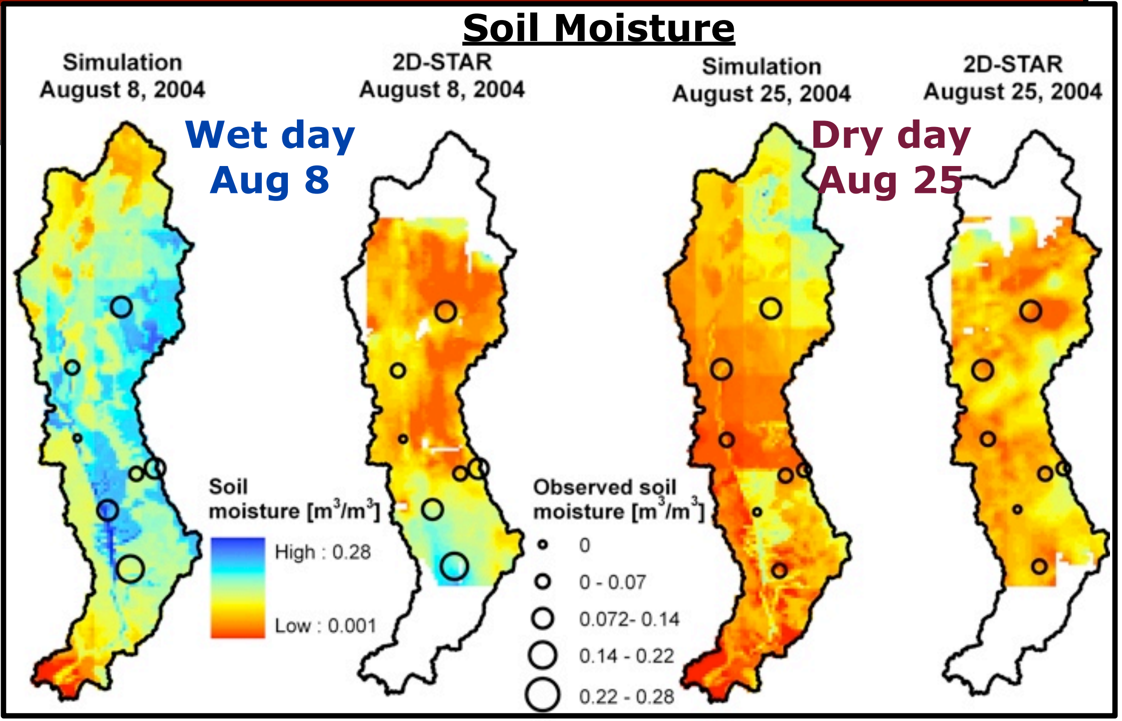
- ★ **Validation** against 2D-STAR θ and MODIS LST.

- ★ ***Wet day: Aug 8***

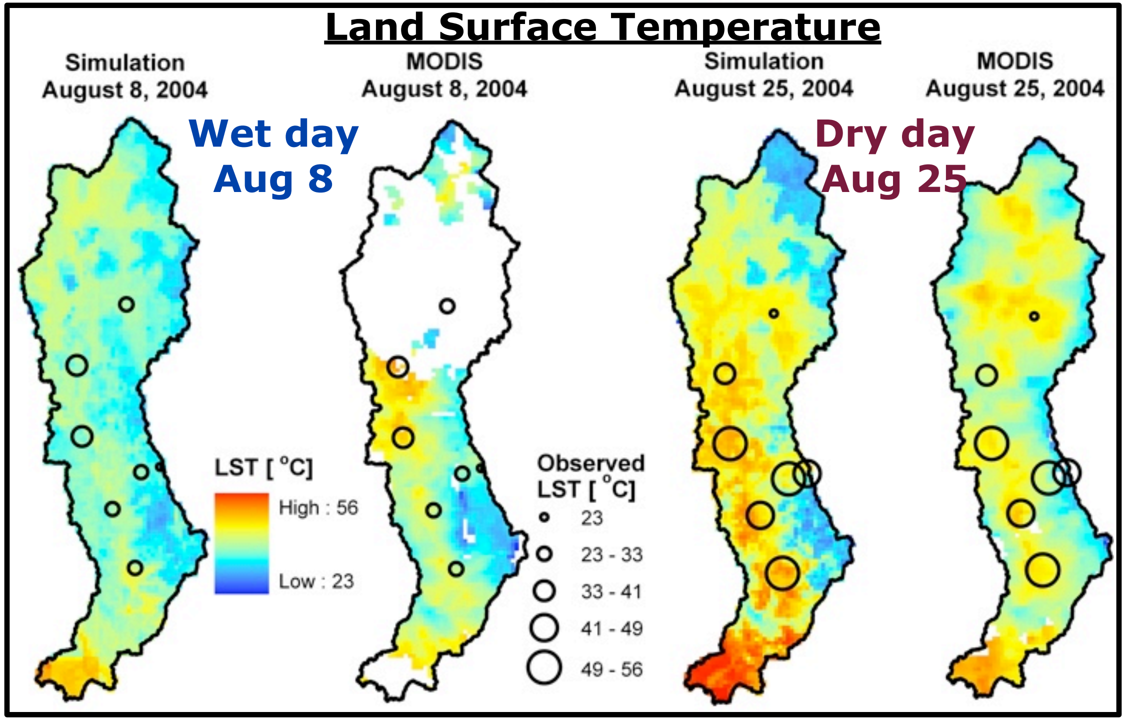
	RMSE **(m³/m³)**	***BIAS*** **(° C)**	***CC*** **(-)**
θ	0.10	0.08	0.02
LST	4.5	-1.7	0.52

- ★ ***Dry day: Aug 25***

	RMSE **(m³/m³)**	***BIAS*** **(° C)**	***CC*** **(-)**
θ	0.04	-0.006	0.08
LST	4.9	1.2	0.64



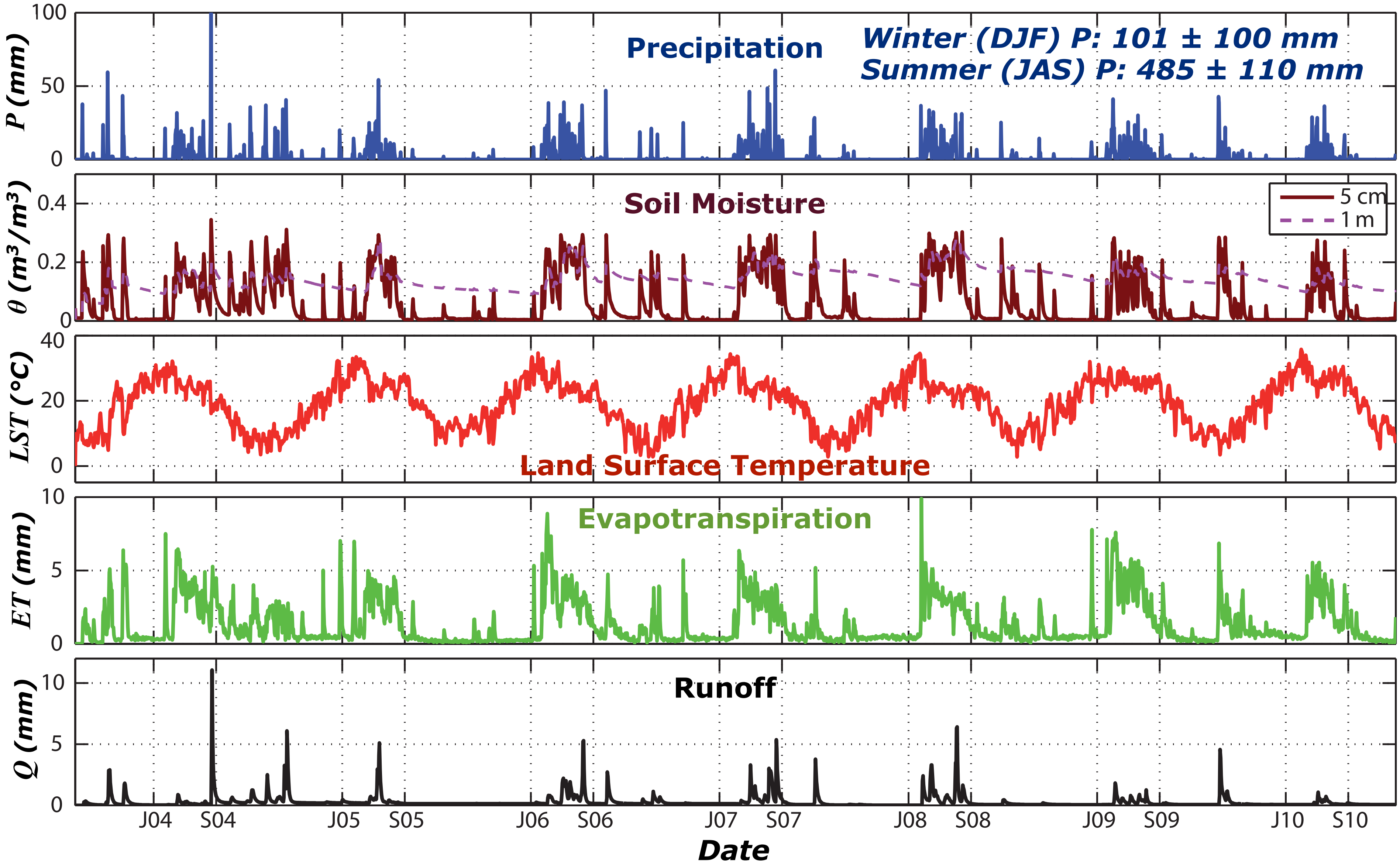
Soil Moisture



Land Surface Temperature

Ecohydrological study

Basin-averaged model outputs:



Ecohydrological study

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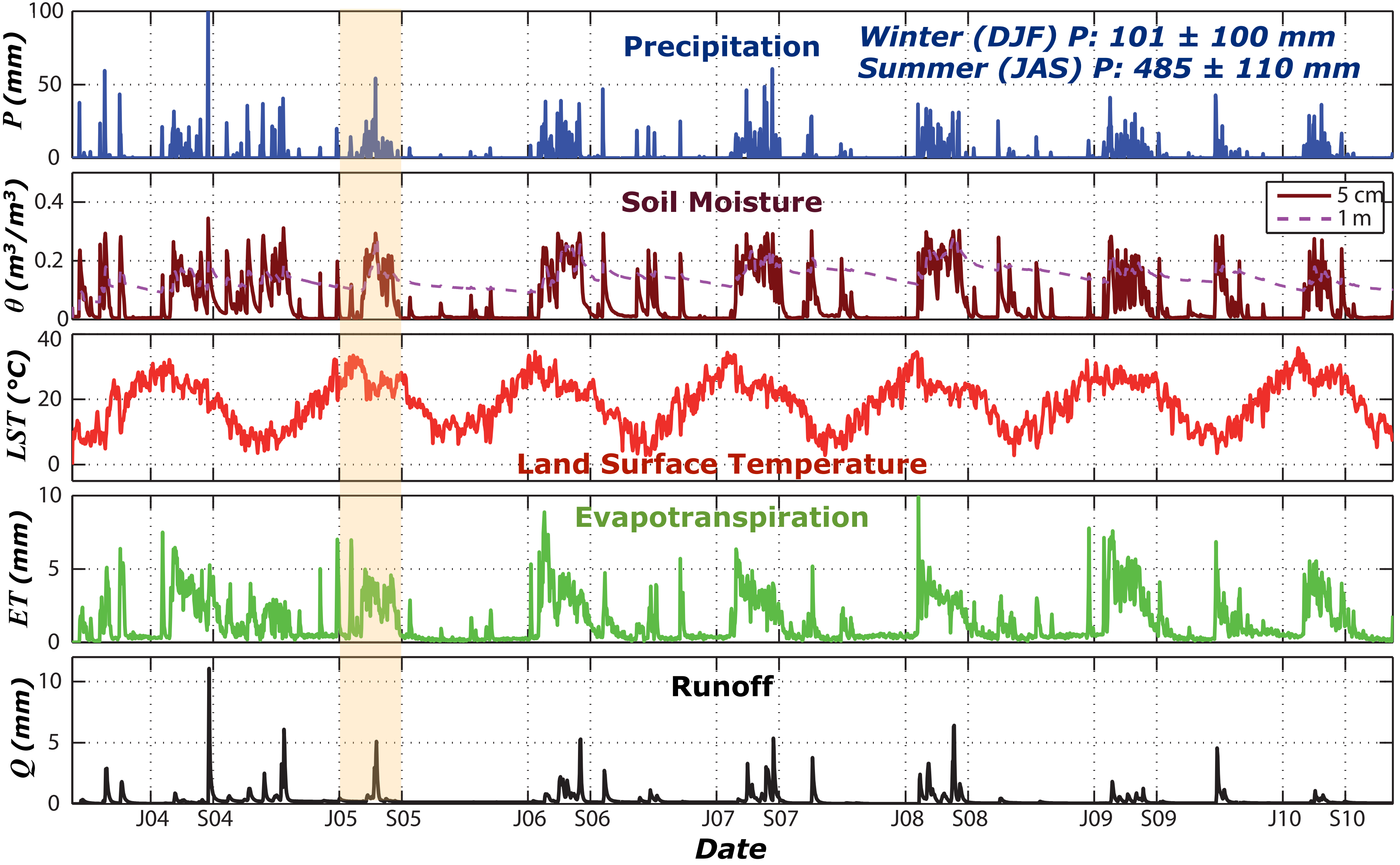

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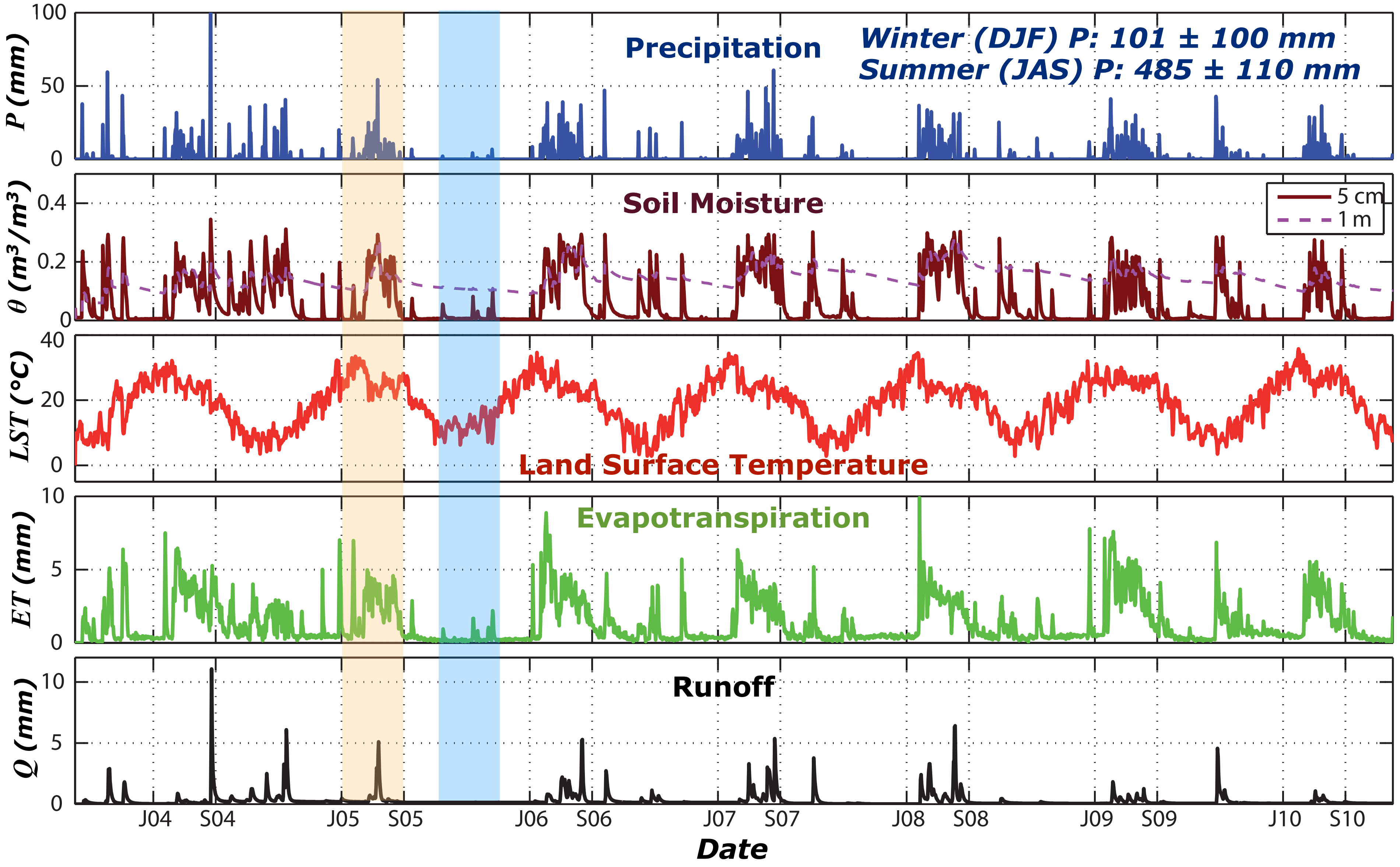
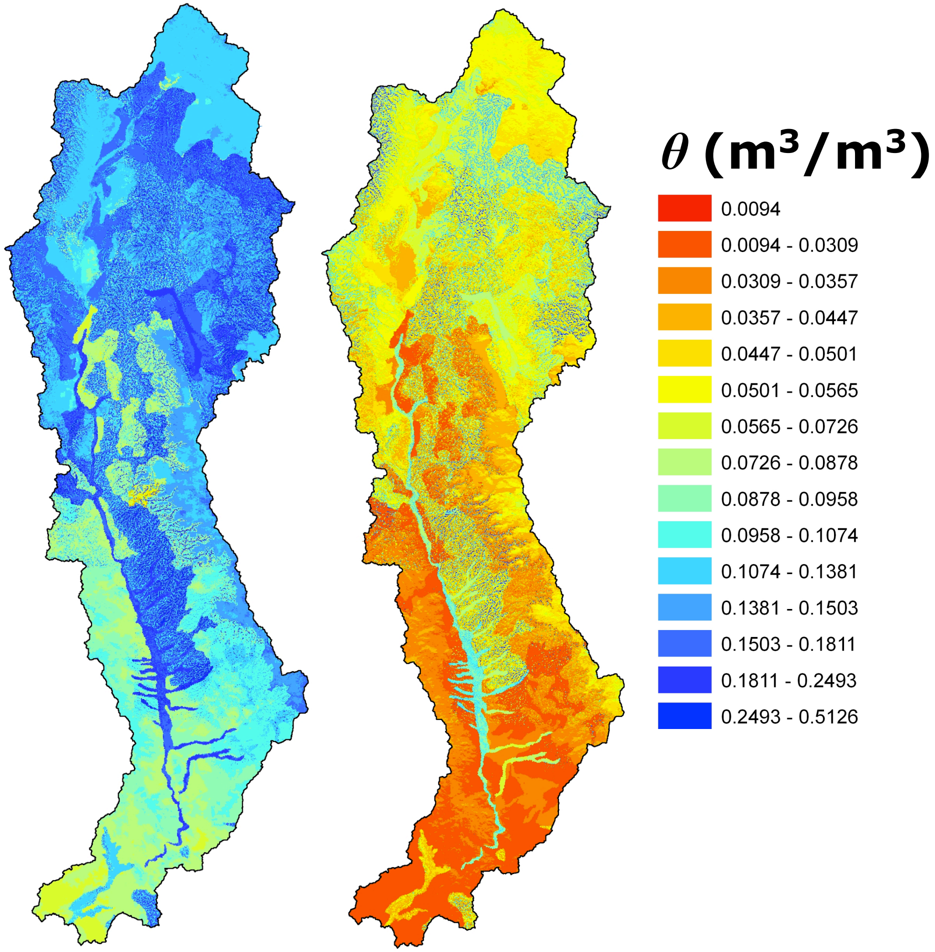


Ecohydrological study

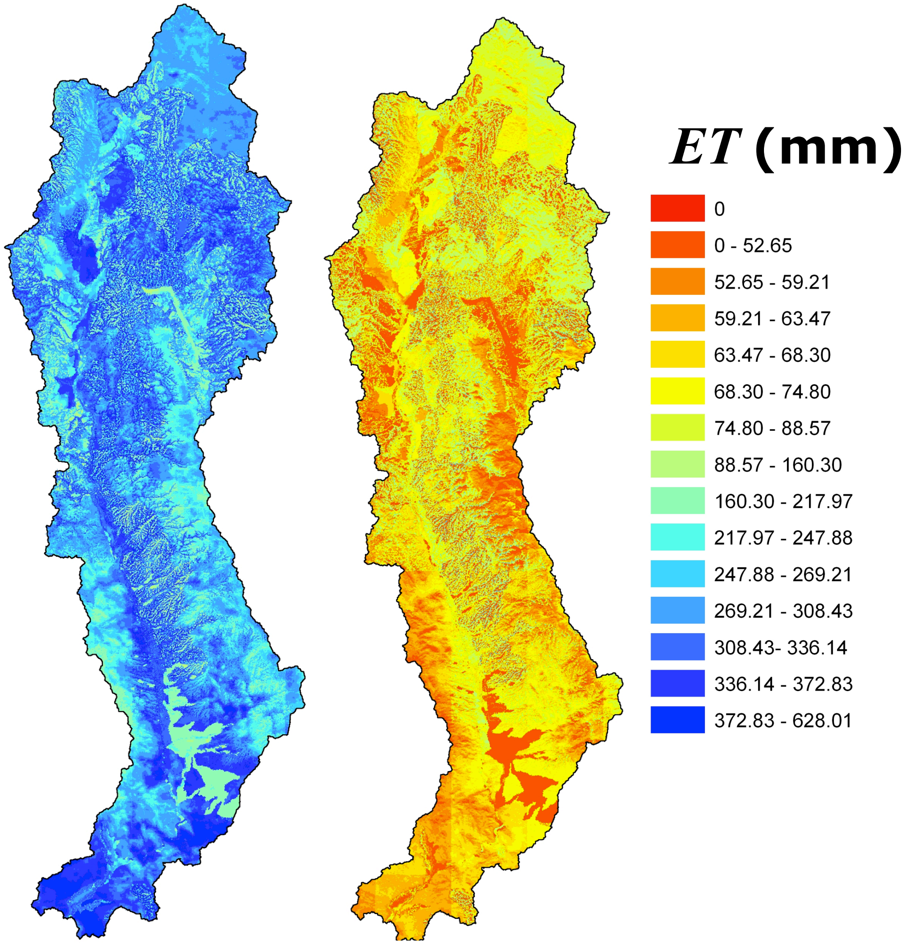
Mean θ



Summer (JAS)

Winter (DJF)

Mean *ET*

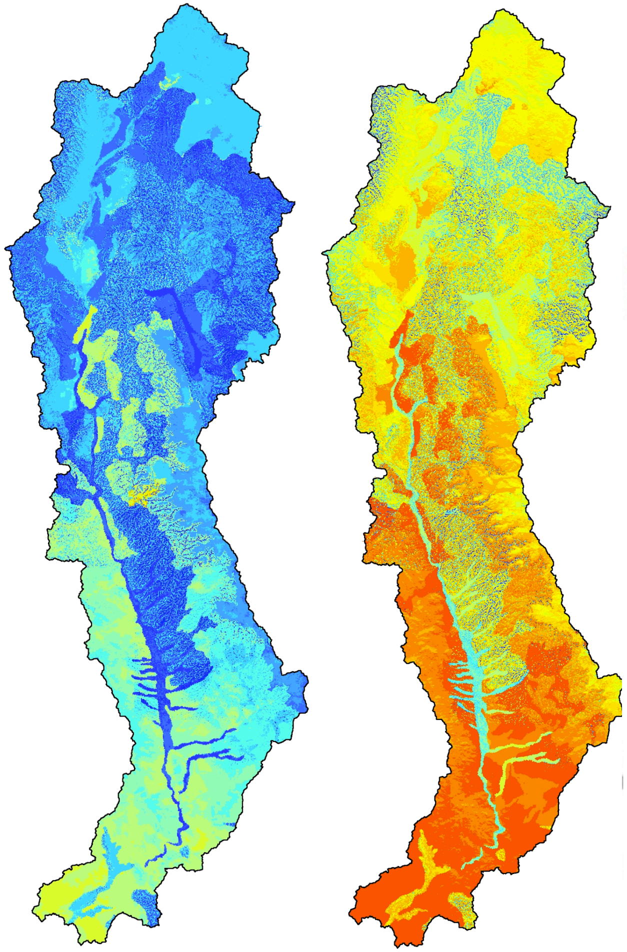


Summer (JAS)

Winter (DJF)

Ecohydrological study

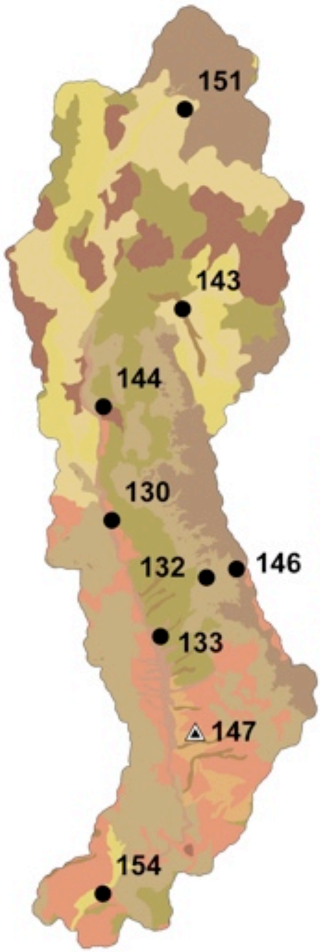
Mean θ



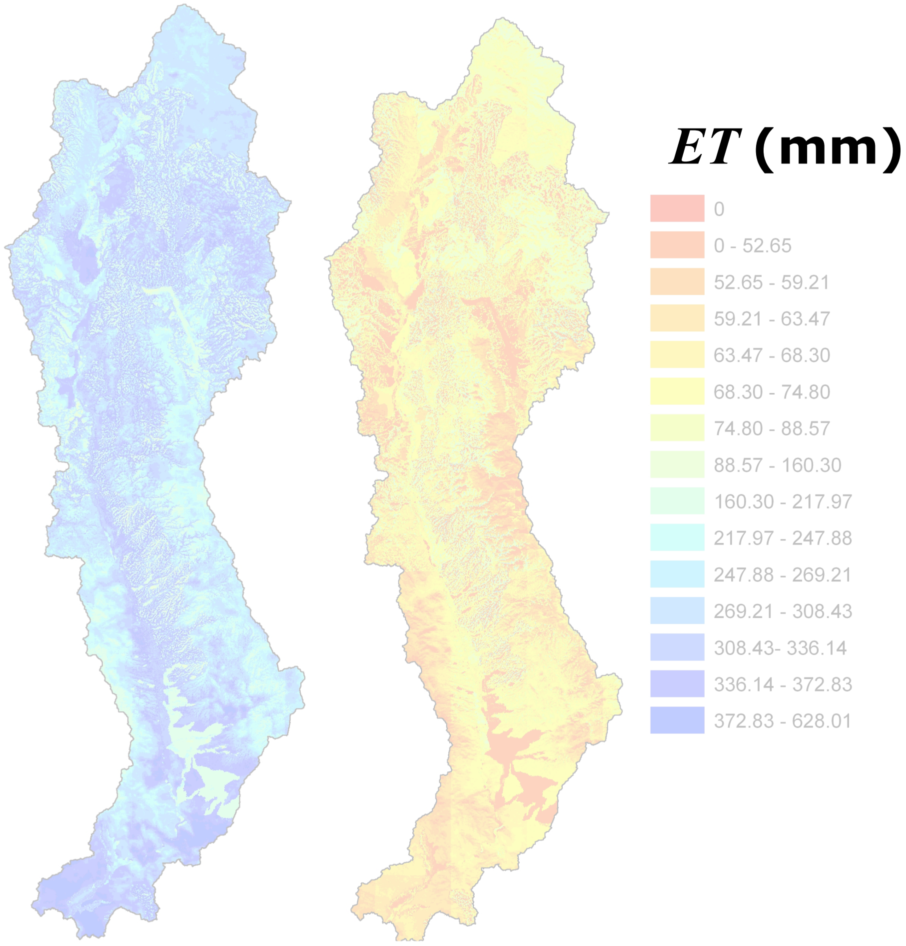
Summer (JAS)

Winter (DJF)

Soil Texture



Mean ET

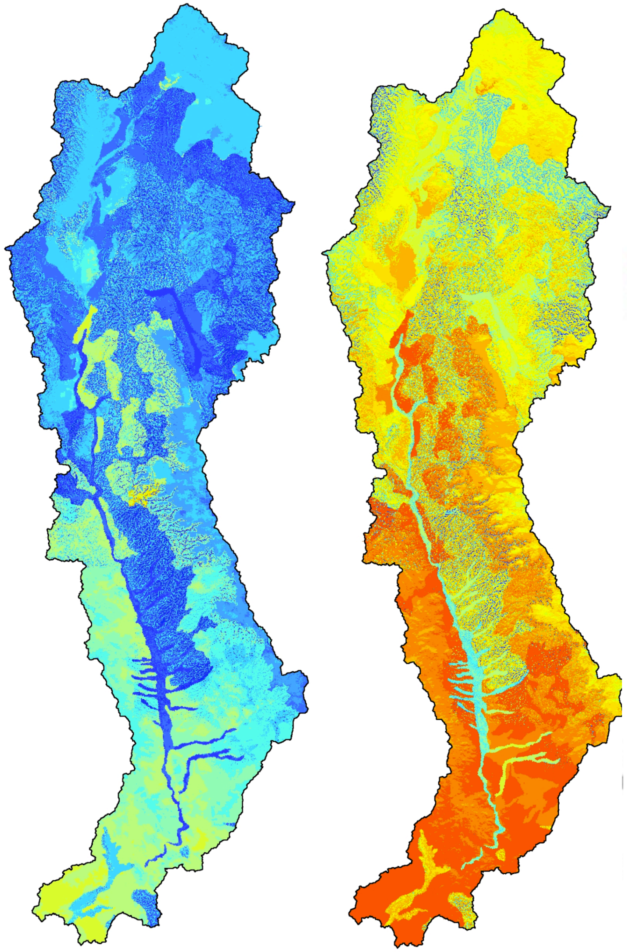


Summer (JAS)

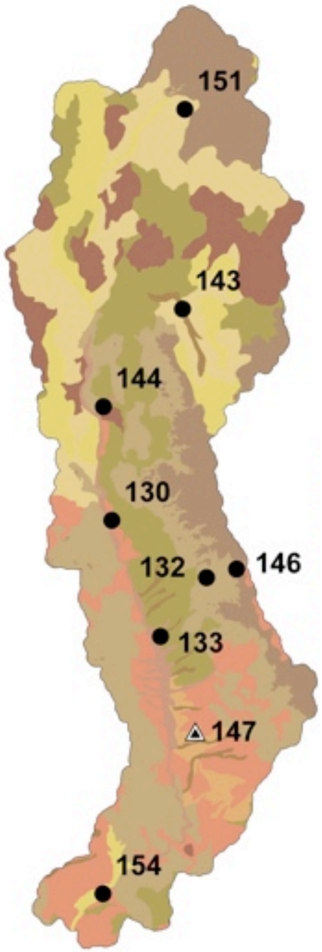
Winter (DJF)

Ecohydrological study

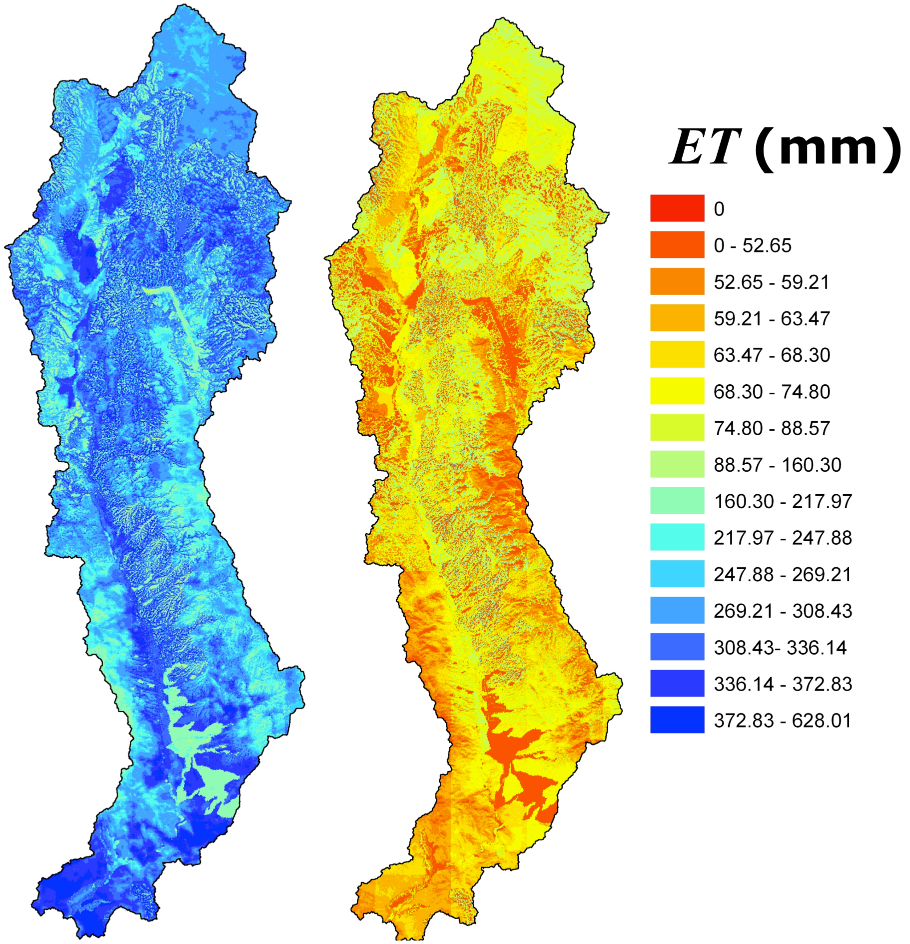
Mean θ



Soil Texture



Mean ET



Summer (JAS) **Winter (DJF)**

Summer (JAS) **Winter (DJF)**

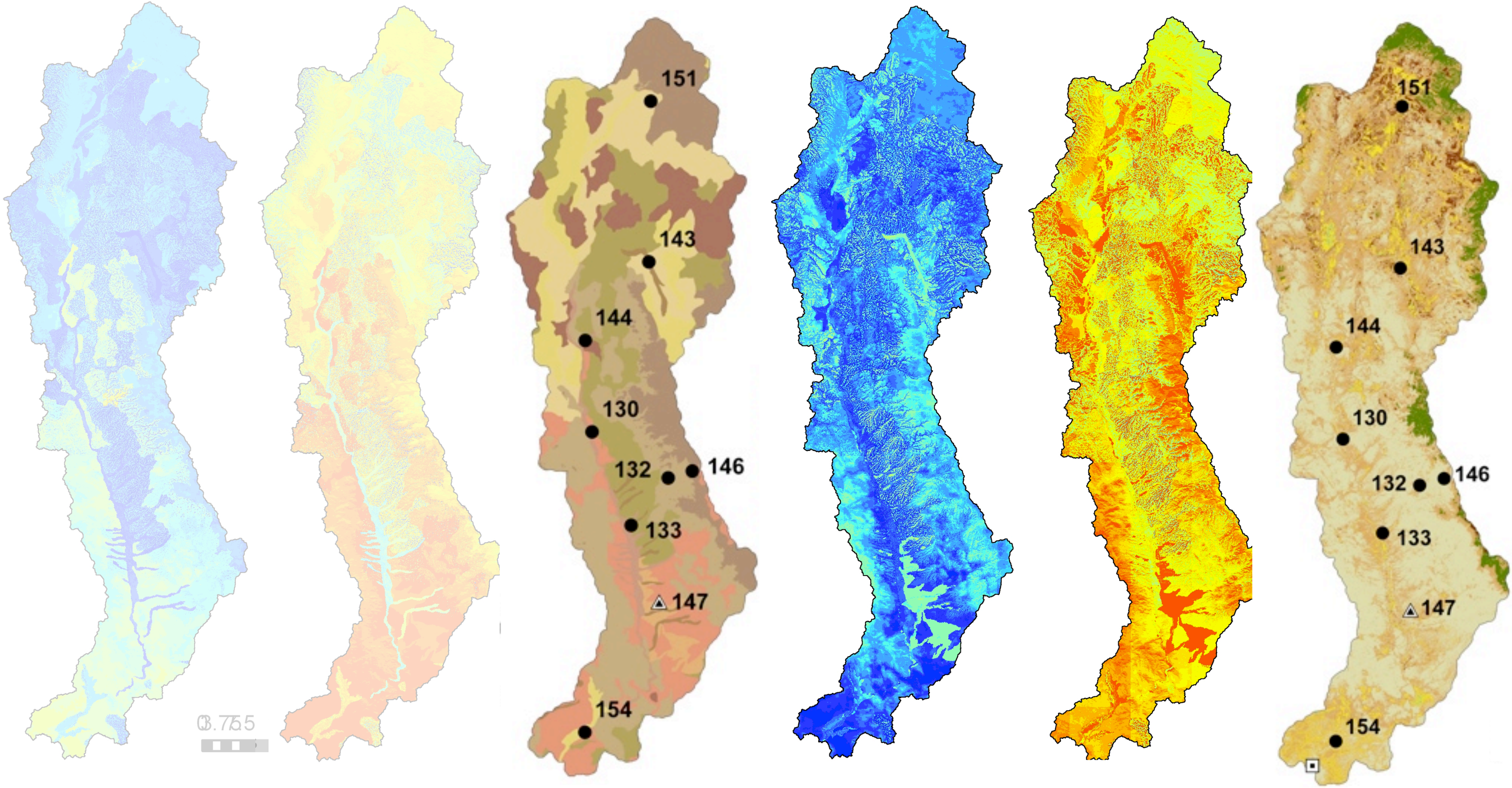
Ecohydrological study

Mean θ

Mean ET

Soil Texture

Land Cover



Summer (JAS)

Winter (DJF)

Summer (JAS)

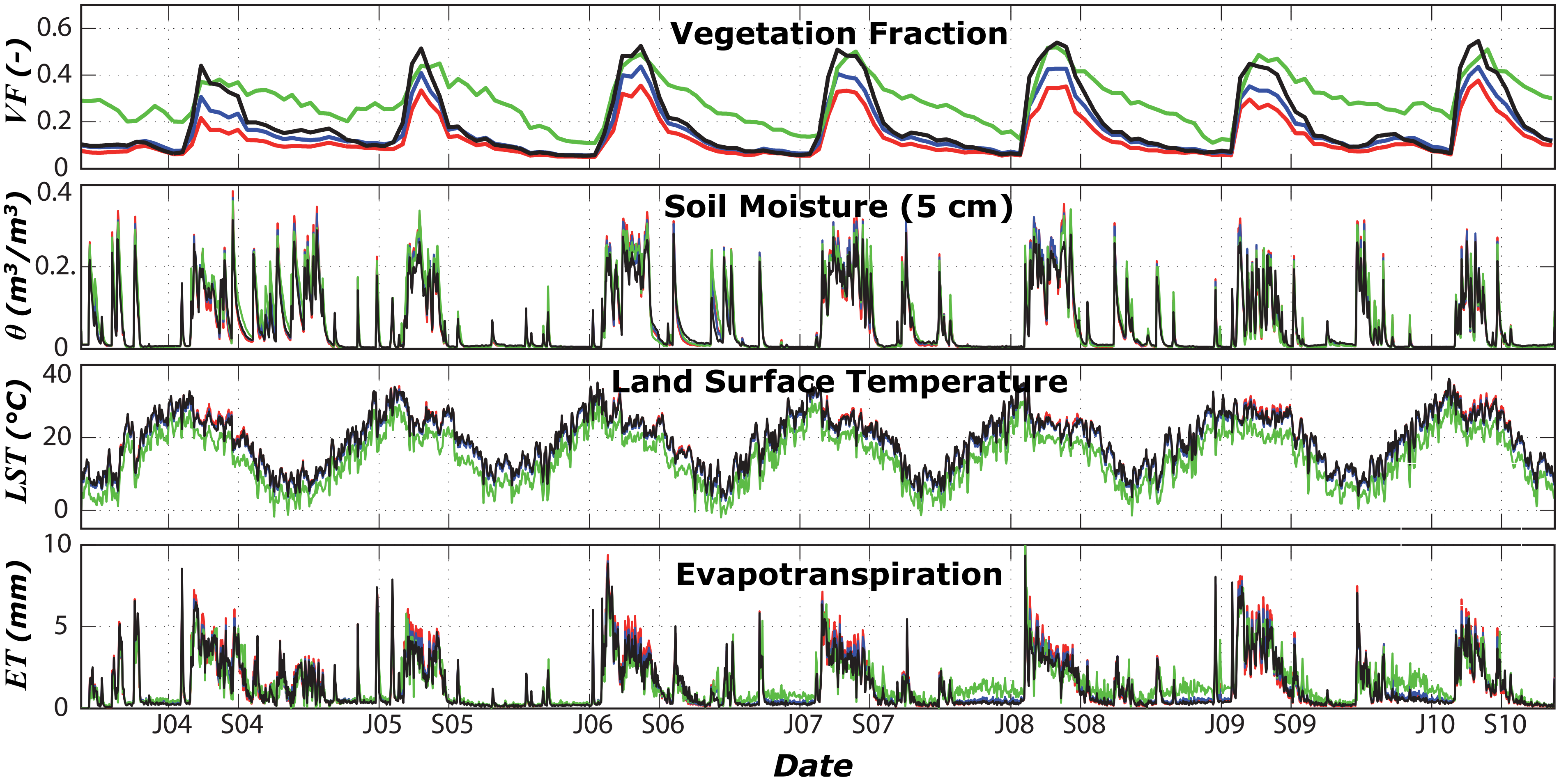
Winter (DJF)

Ecohydrological study

Model outputs averaged on ecosystems:

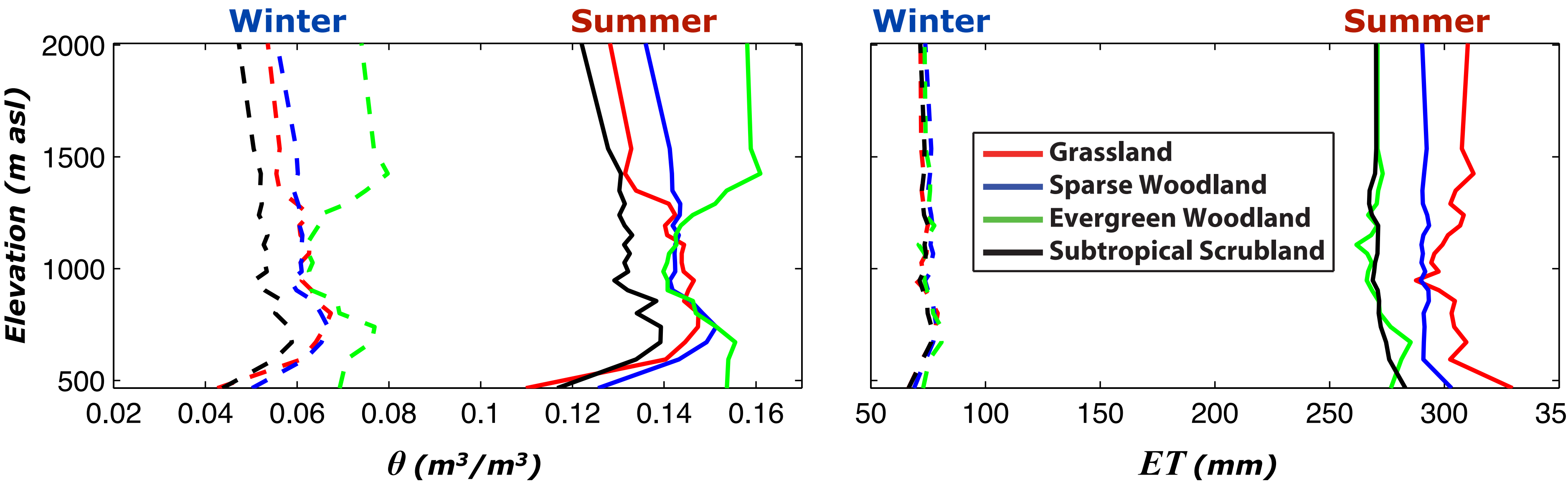
	Summer		*Winter*	
Ecosystem	$<\theta>$	$<ET>$	$<\theta>$	$<ET>$
G (6%)	0.14	306	0.06	74
SW (37%)	0.14	294	0.06	76
EW (4%)	0.15	269	0.05	75
SS (49%)	0.13	271	0.05	73

🟥 **Grassland**
🟦 **Sparse Woodland**
🟩 **Evergreen Woodland**
⬛ **Subtropical Scrubland**



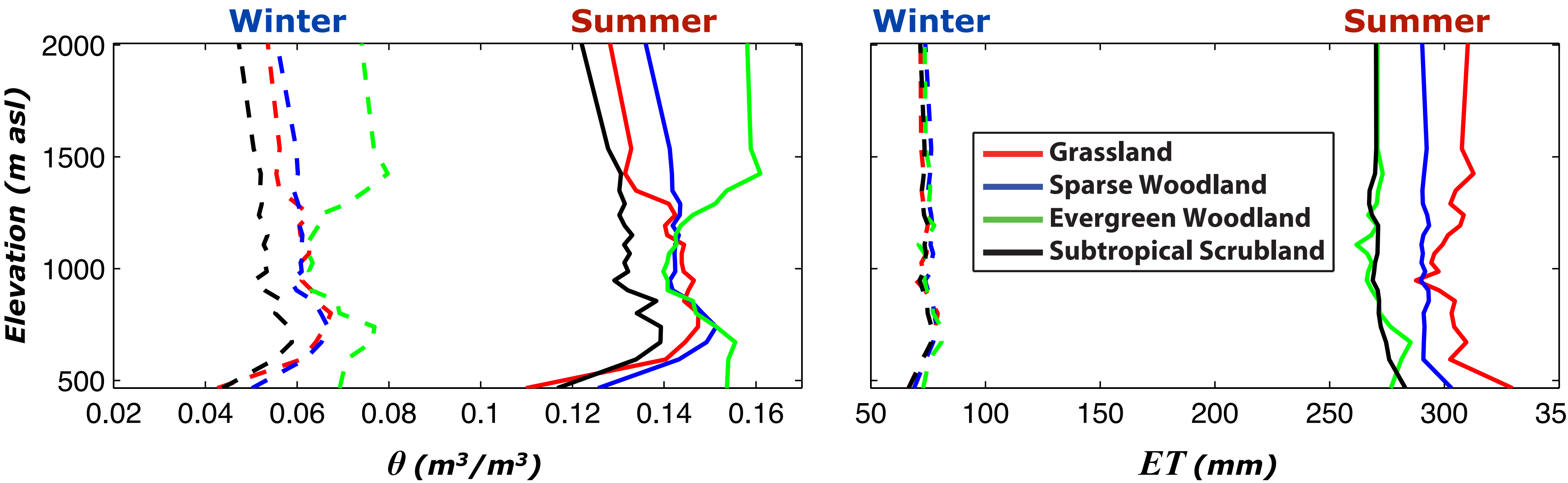
Ecohydrological study

Effect of **elevation** on θ and ET in the main ecosystems:



Ecohydrological study

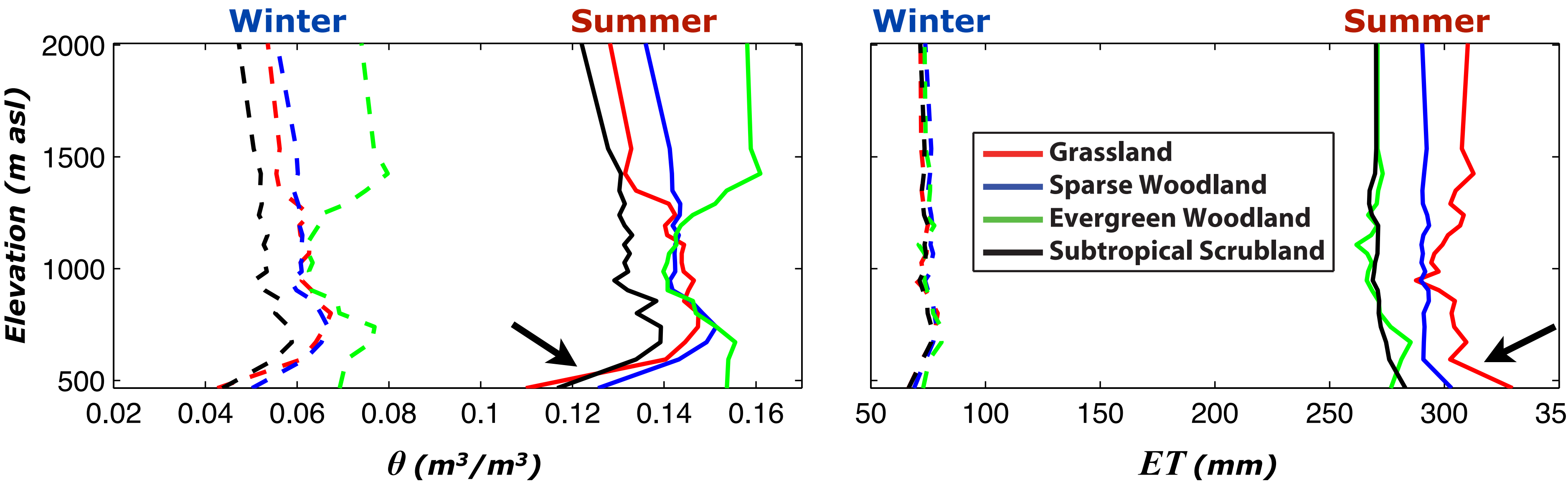
Effect of **elevation** on θ and ET in the main ecosystems:



★Clear differences between summer and winter.

Ecohydrological study

Effect of **elevation** on θ and ET in the main ecosystems:



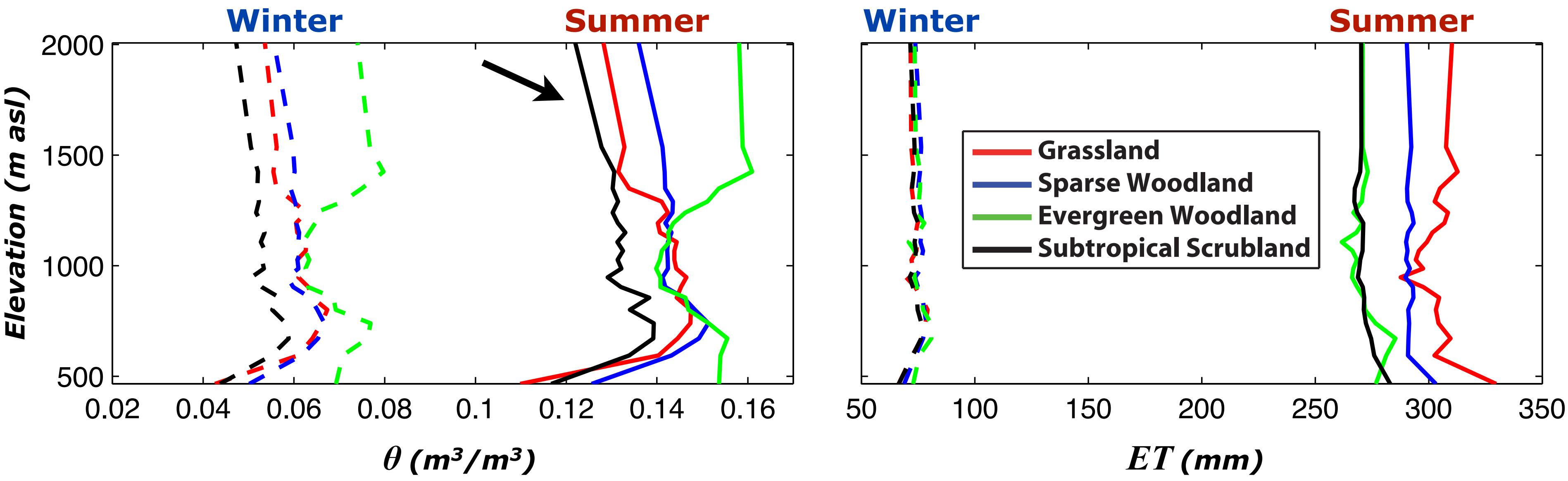
★Clear differences between summer and winter.

Grassland, Sparse Woodland, Subtropical Scrubland:

➡Lower θ at low elevation due to larger ET, in turn due to higher T.

Ecohydrological study

Effect of **elevation** on θ and ET in the main ecosystems:



★Clear differences between summer and winter.

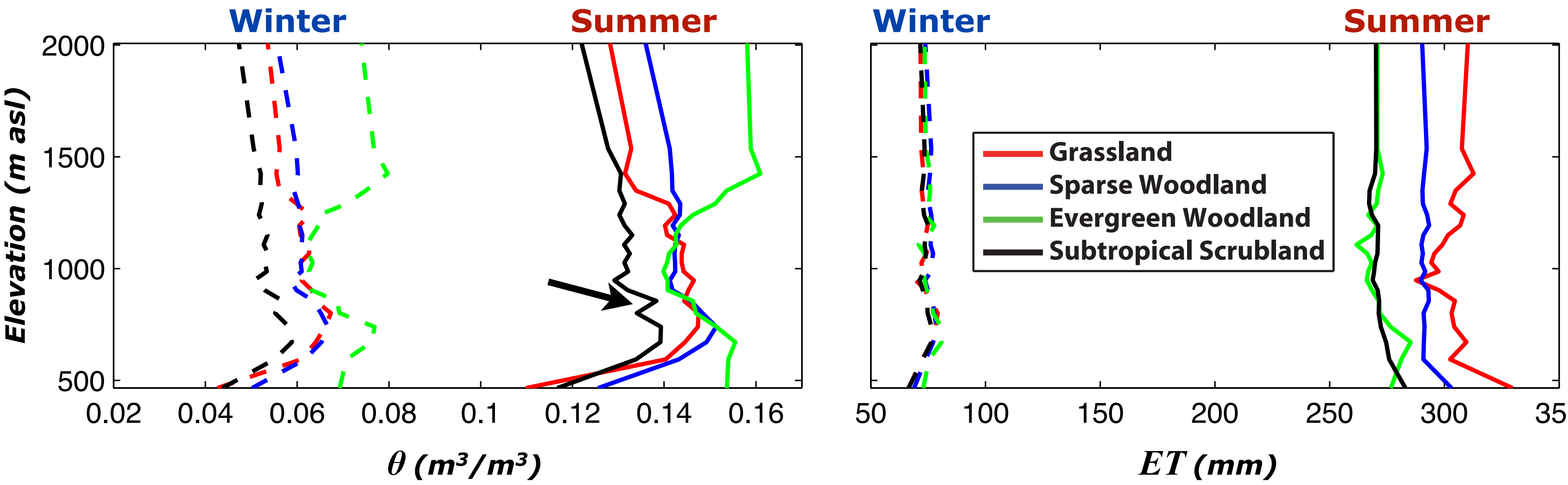
Grassland, Sparse Woodland, Subtropical Scrubland:

➡Lower θ at low elevation due to larger ET, in turn due to higher T.

➡Lower θ at high elevation, likely due to lateral water transfer.

Ecohydrological study

Effect of **elevation** on θ and ET in the main ecosystems:



★Clear differences between summer and winter.

Grassland, Sparse Woodland, Subtropical Scrubland:

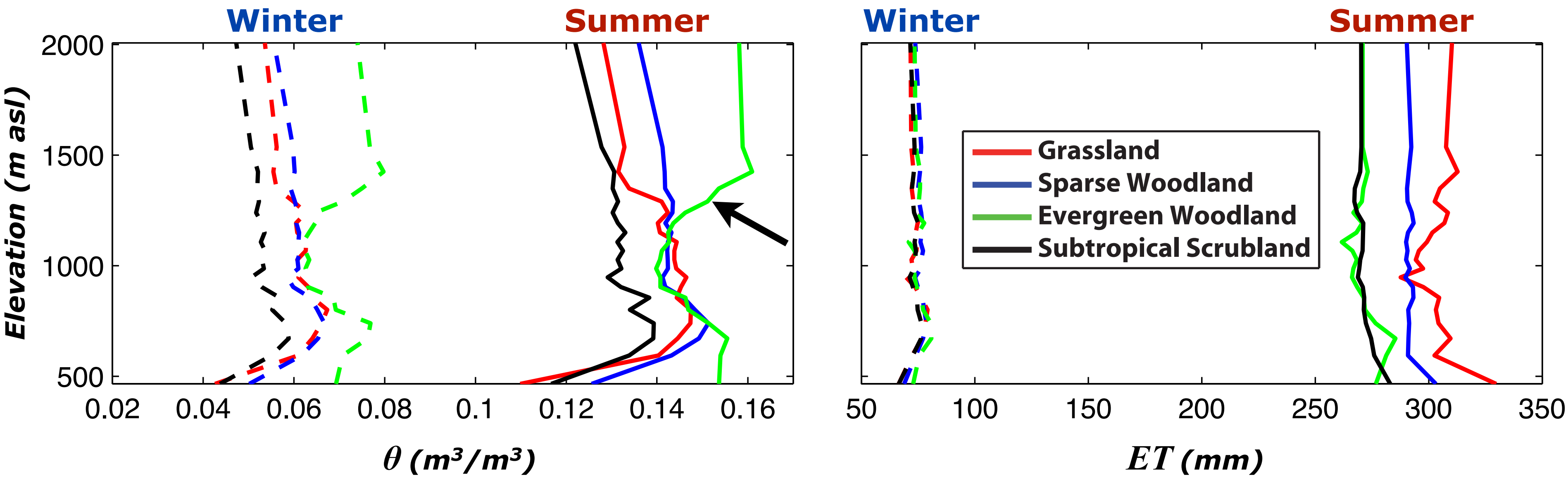
➡Lower θ at low elevation due to larger ET, in turn due to higher T.

➡Lower θ at high elevation, likely due to lateral water transfer.

➡Higher θ at mid-elevation, likely due to lower ET (lower T) and transfer from areas at higher elevation.

Ecohydrological study

Effect of **elevation** on θ and ET in the main ecosystems:



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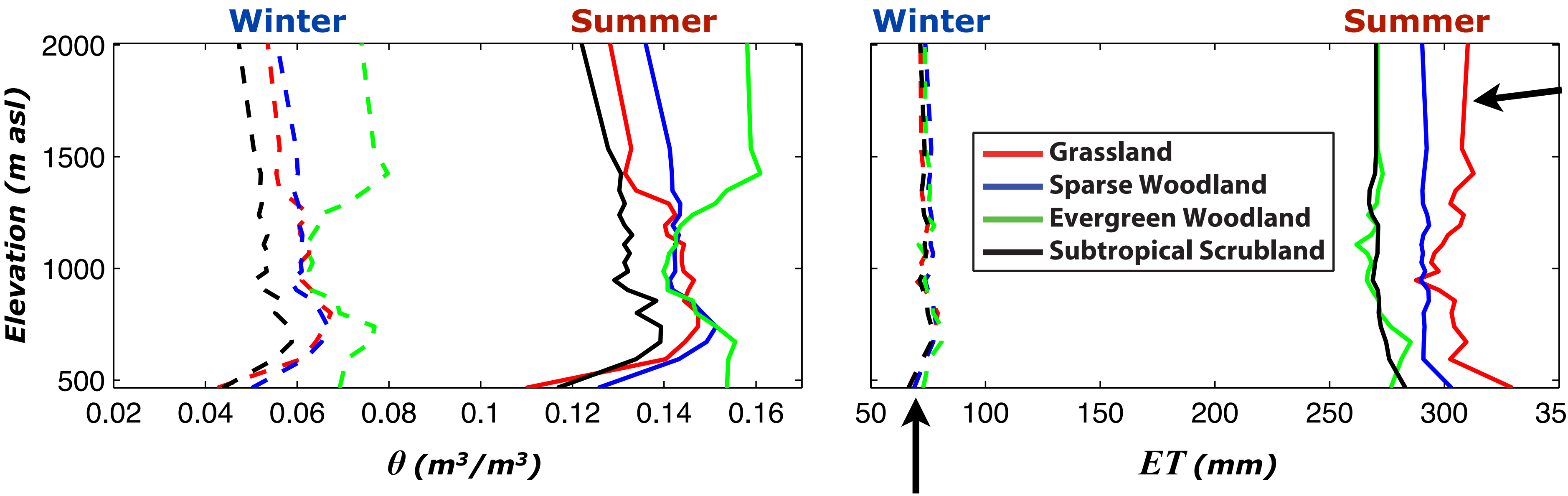
Evergreen Woodland:

➡θ has an opposite behavior due to larger presence of this class at higher elevation.

Ecohydrological study

Effect of **elevation** on θ and ET in the main ecosystems:



★Clear differences between summer and winter.

Grassland, Sparse Woodland, Subtropical Scrubland:

➡Lower θ at low elevation due to larger ET, in turn due to higher T.

➡Lower θ at high elevation, likely due to lateral water transfer.

➡Higher θ at mid-elevation, likely due to lower ET (lower T) and transfer from areas at higher elevation.

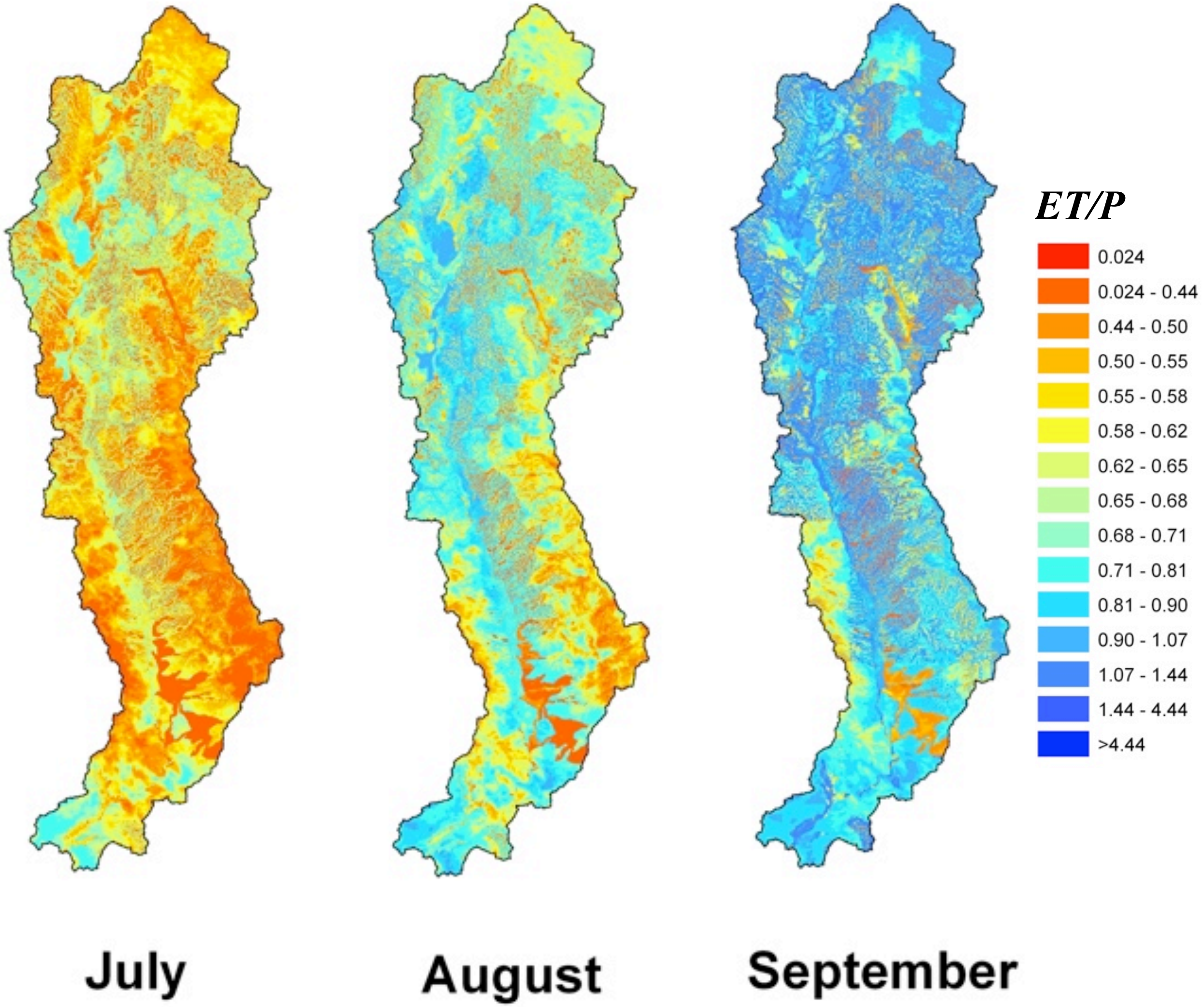
Evergreen Woodland:

➡θ has an opposite behavior due to larger presence of this class at higher elevation.

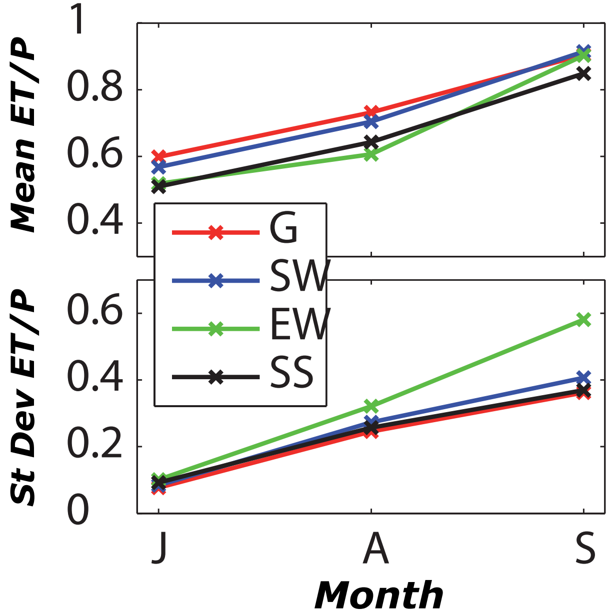
★No differences in ET among ecosystems in winter. Limited control of elevation.

Ecohydrological study

Investigation of **rainfall recycling** through the **spatiotemporal evolution of ET/P** in summer:

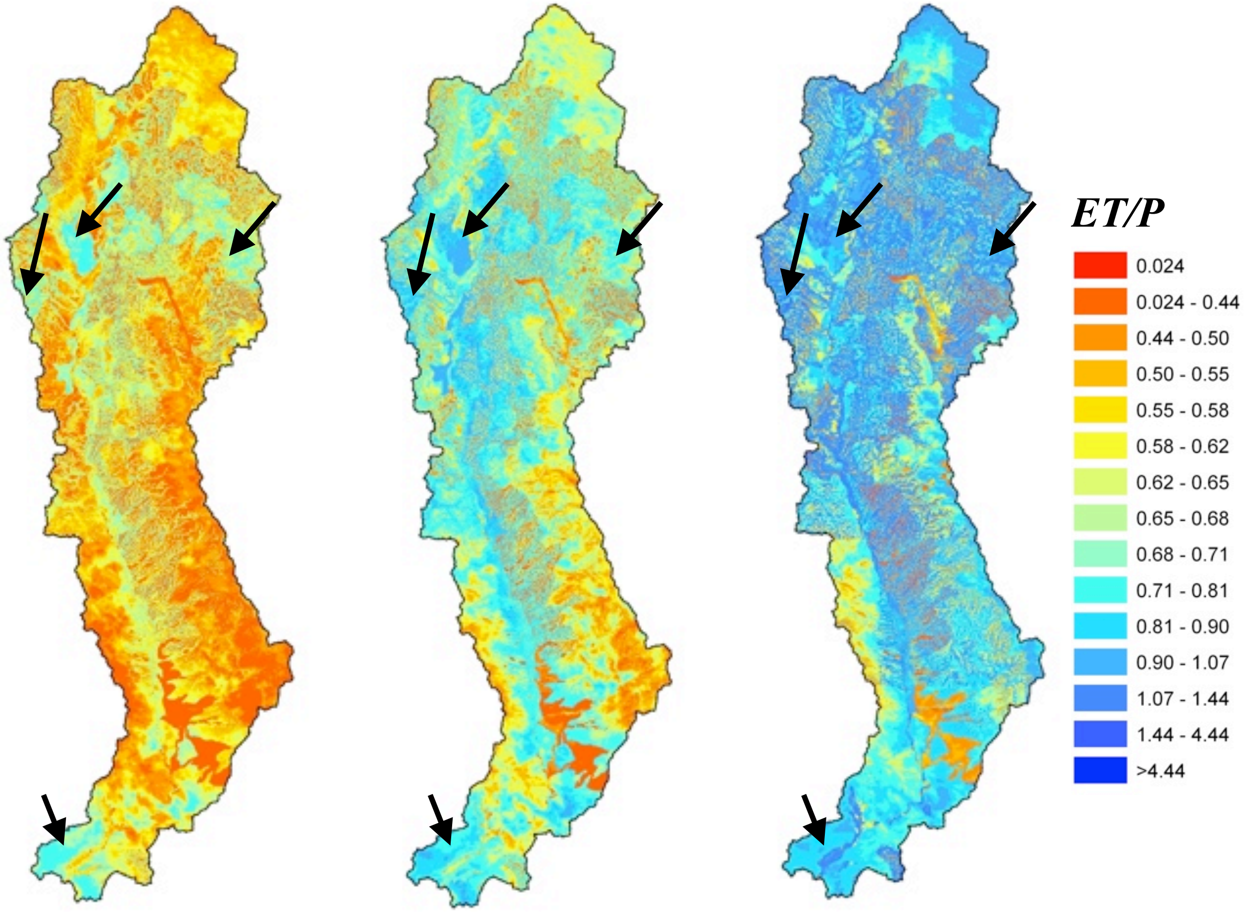


Evolution of spatial mean and standard deviation of ET/P in dominant ecosystems:



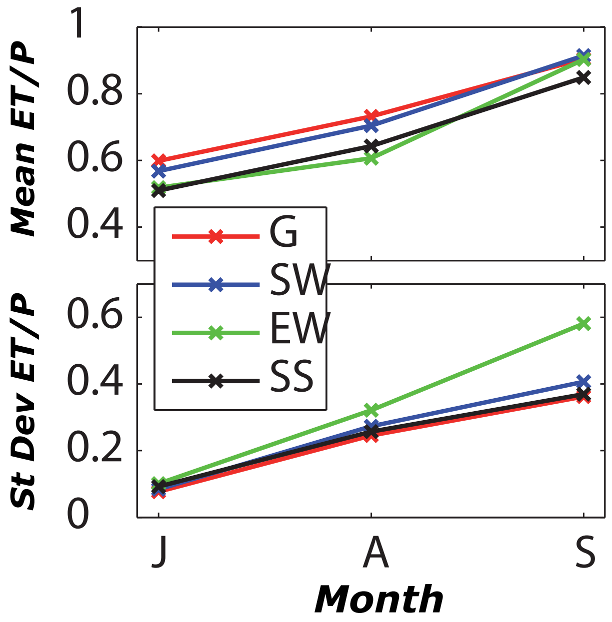
Ecohydrological study

Investigation of **rainfall recycling** through the **spatiotemporal evolution of ET/P** in summer:



July **August** **September**

Evolution of spatial mean and standard deviation of ET/P in dominant ecosystems:



Ecohydrological study

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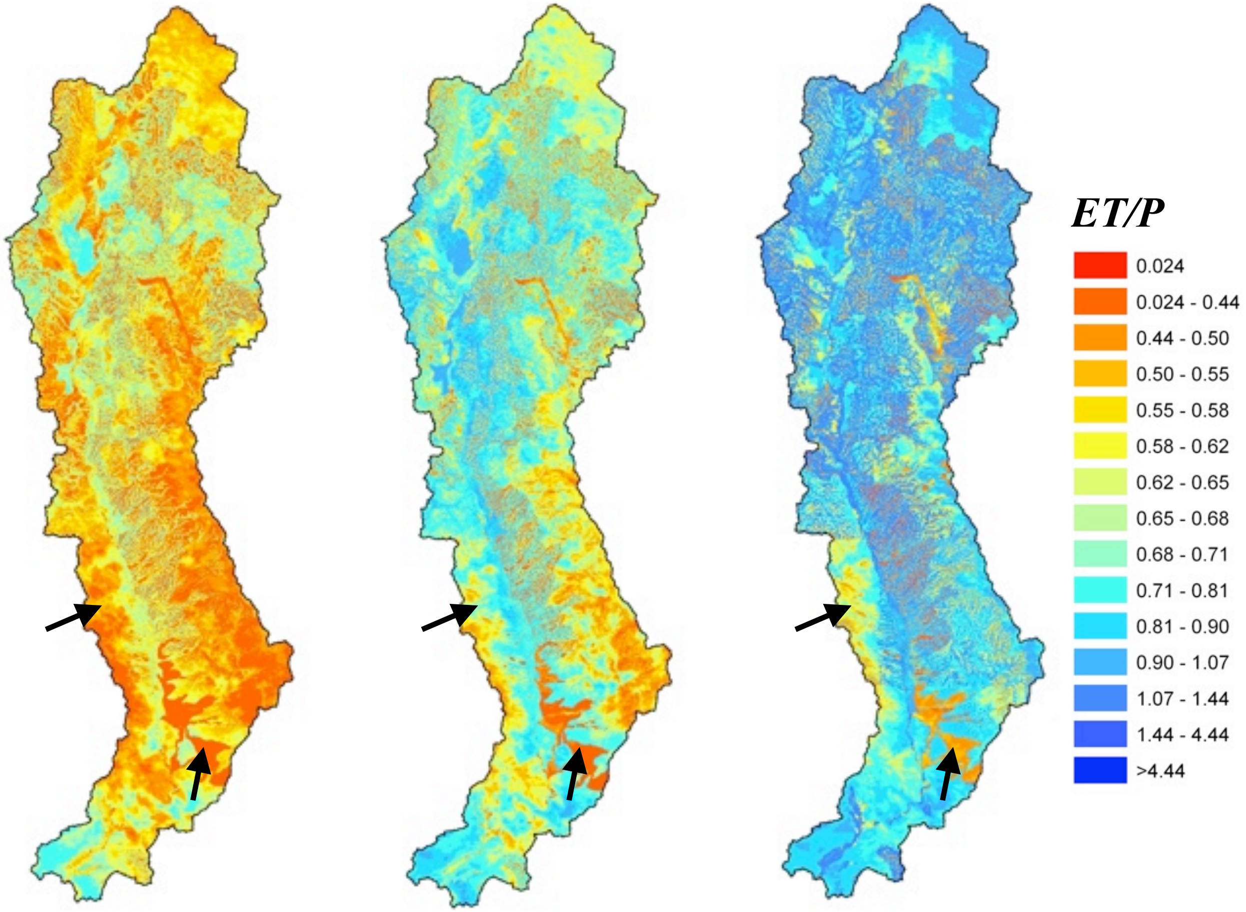

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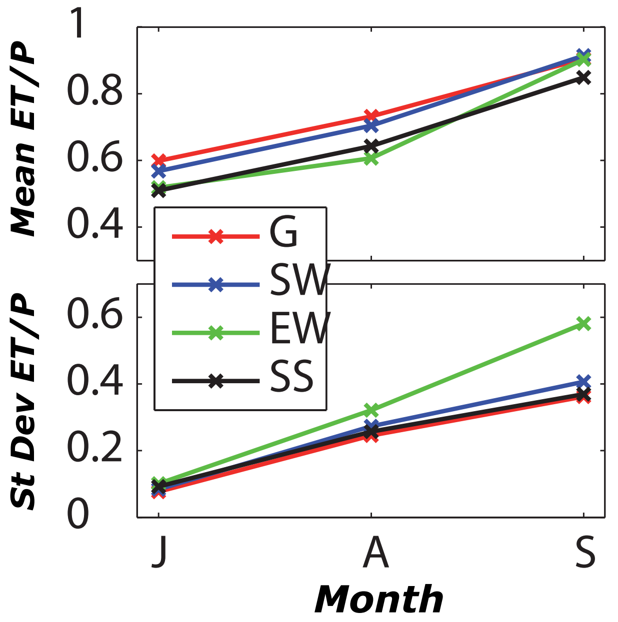

Ecohydrological study

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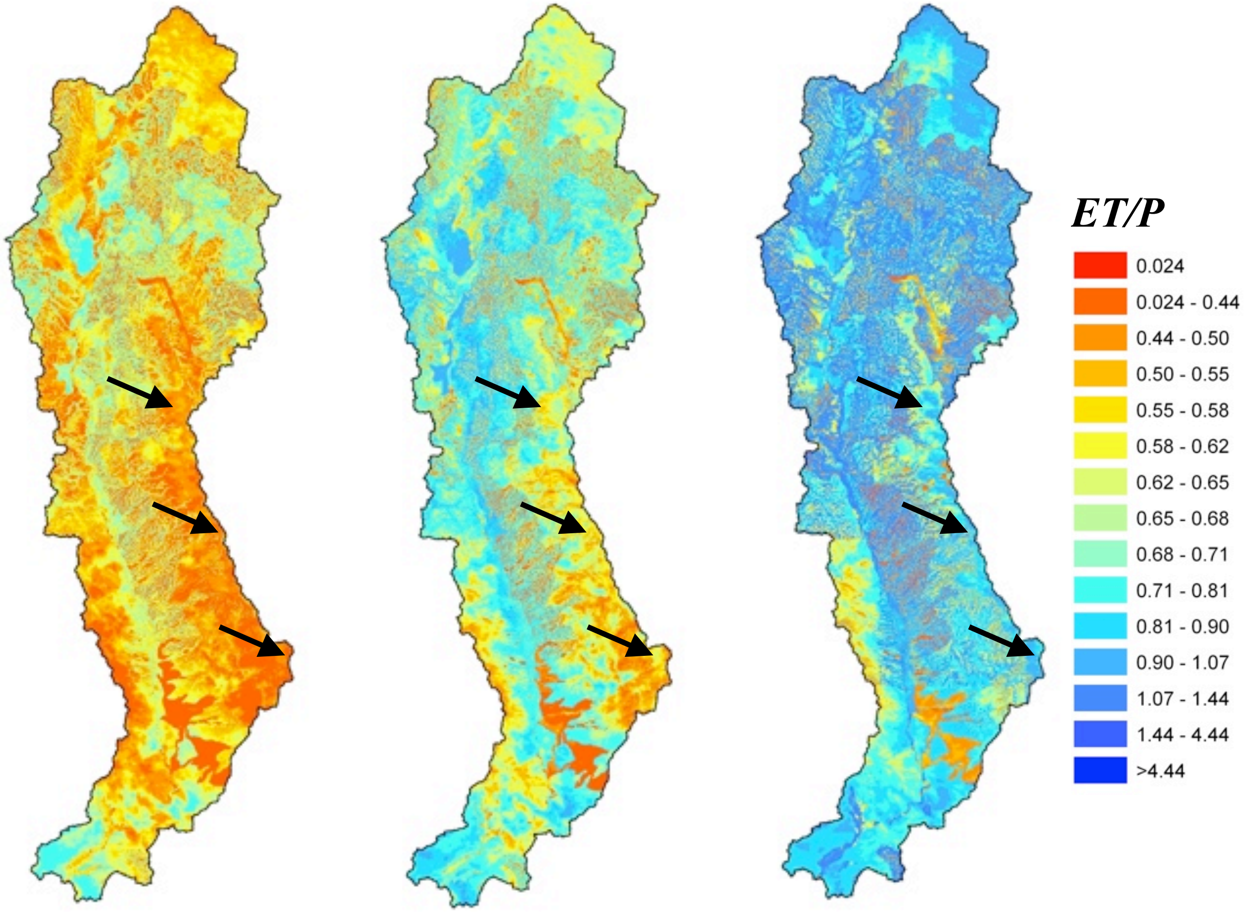

July **August** **September**

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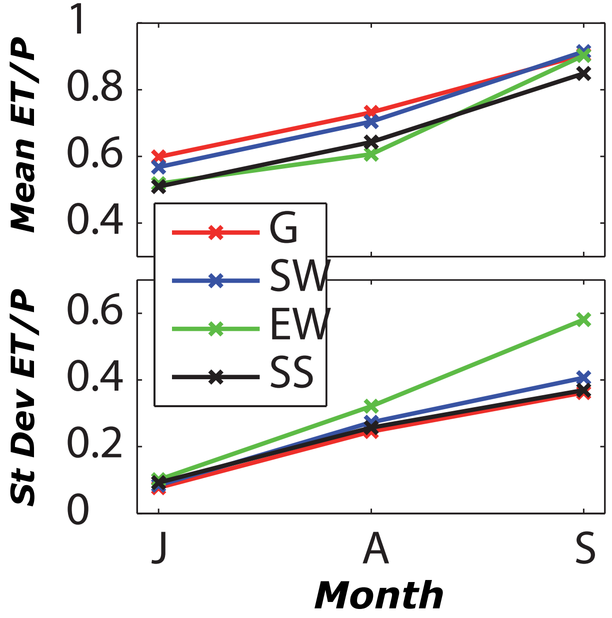
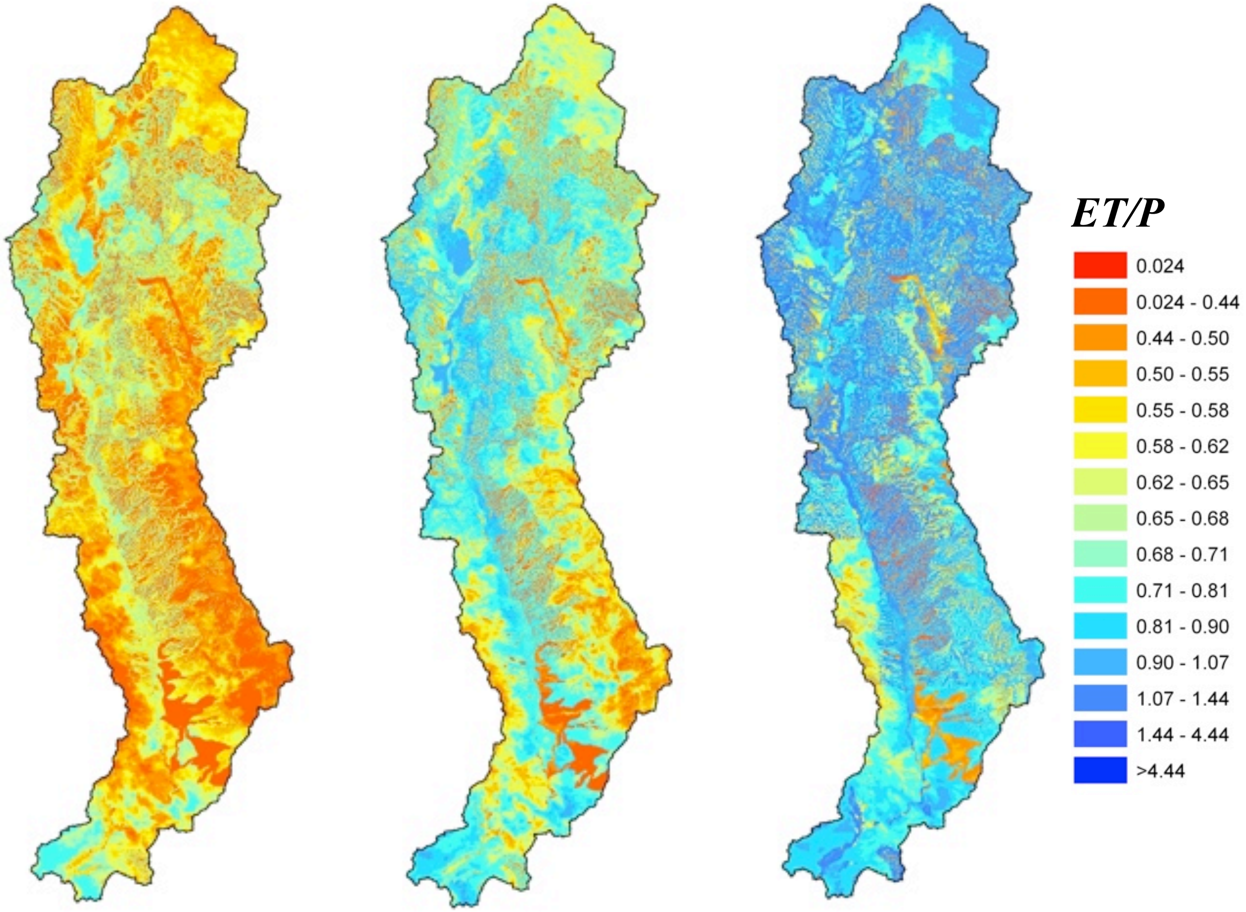


Ecohydrological study

Investigation of **rainfall recycling** through the **spatiotemporal evolution of ET/P** in summer:



July **August** **September**

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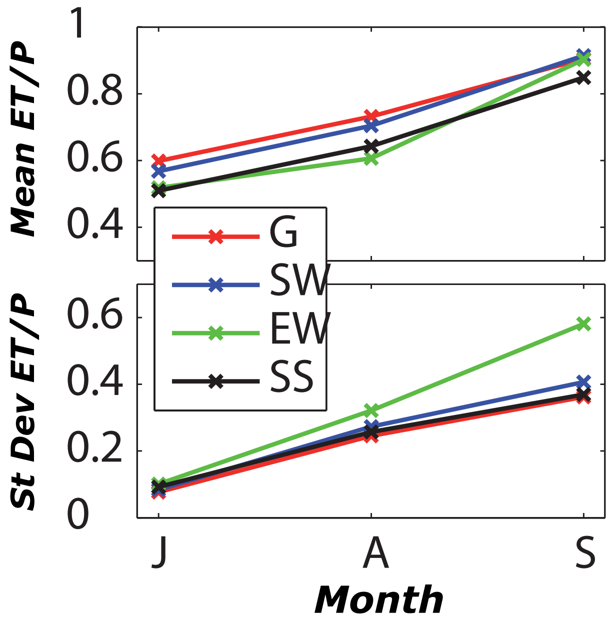

Ecohydrological study

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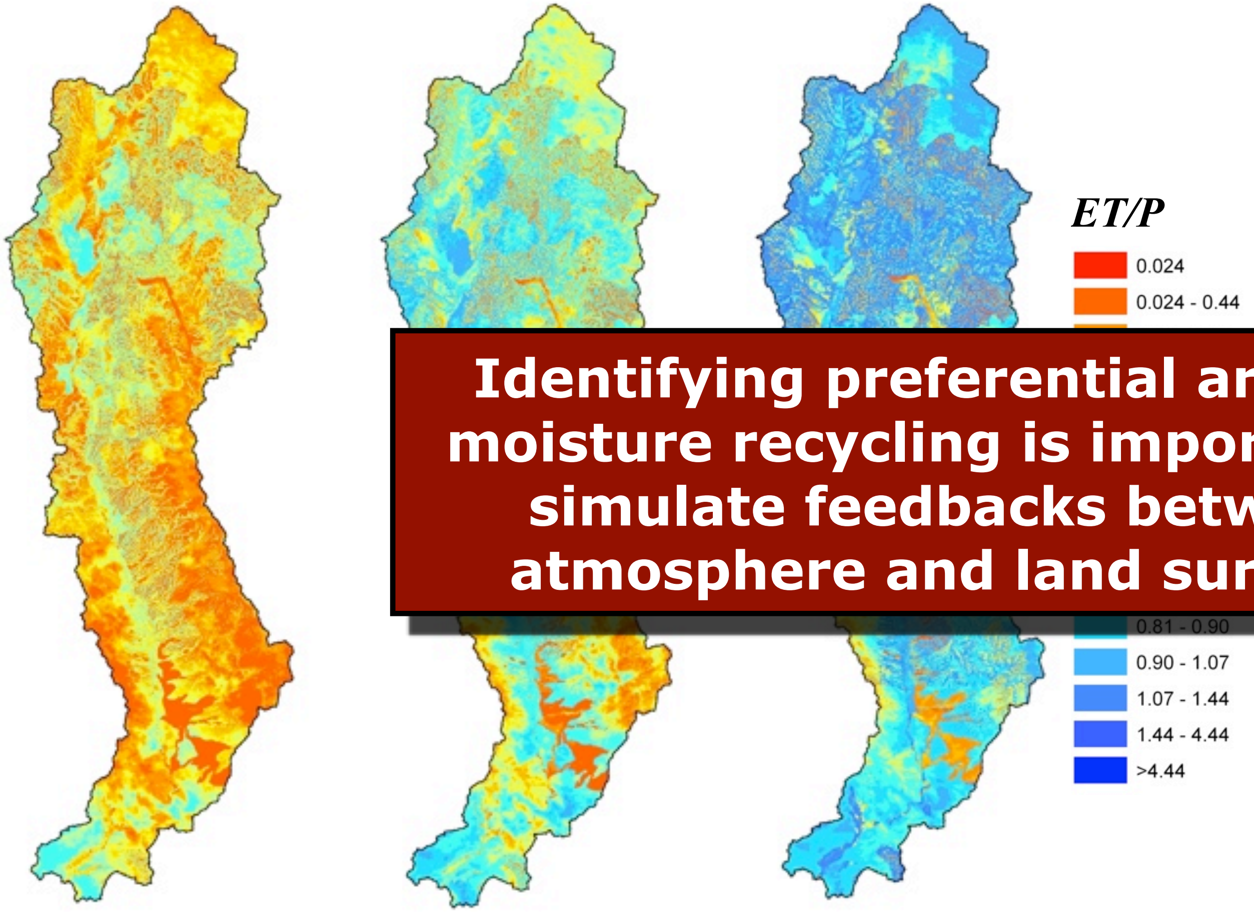

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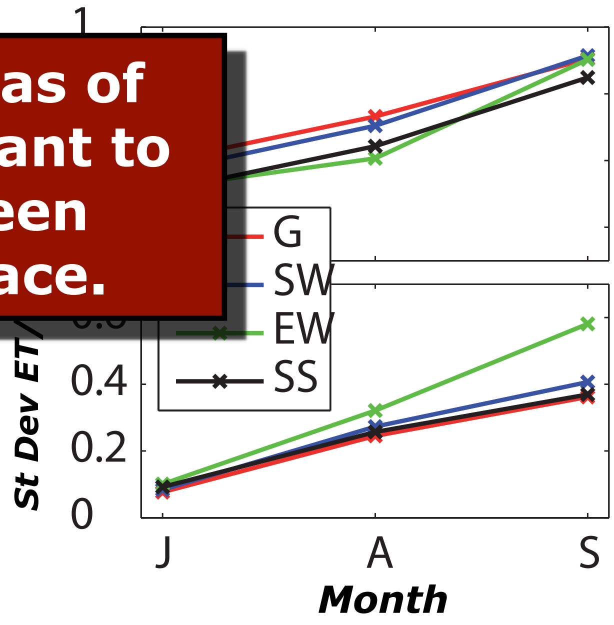

Identifying preferential areas of moisture recycling is important to simulate feedbacks between atmosphere and land surface.

Thank you!