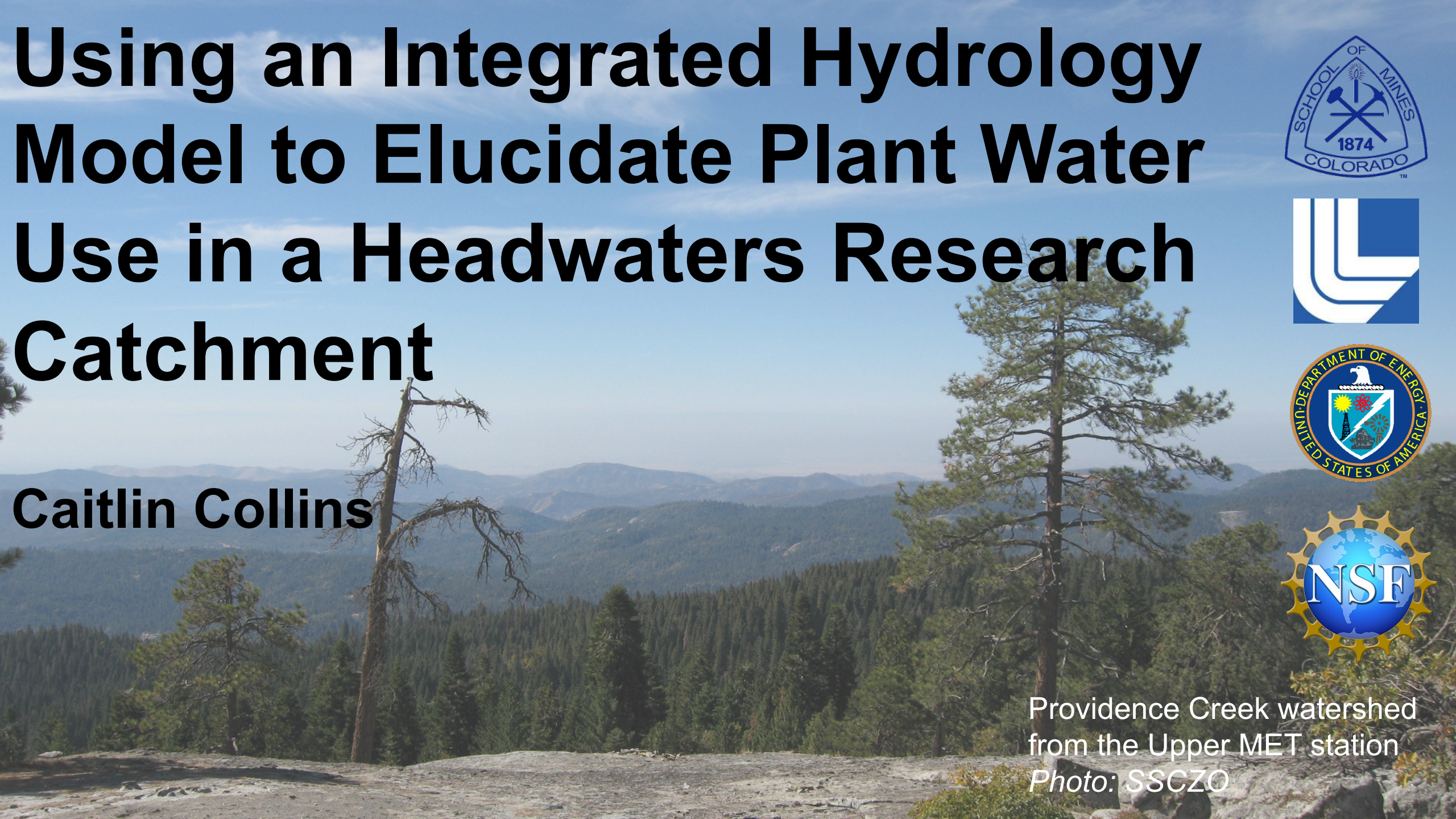
Using an Integrated Hydrology Model to Elucidate Plant Water Use in a Headwaters Research Catchment

Caitlin Collins



Providence Creek watershed from the Upper MET station
Photo: SSCZO

Mountain headwaters are vulnerable to change



- Mountains support half of the world's population
- One third of Earth's land surface is seasonally covered with snow
- Snowmelt strongly influences soil water availability during the summer
- IPCC predicts an increase in global temperature of 4°C by 2100
- Translates to reduced snow and icepack, earlier snowmelt and peak flows, longer growing seasons, and increasing frequency and severity of extreme events, such as drought

These impacts are predicted to be most prominent in mountain regions

“We have to proactively plan for a drought. We cannot keep lurching from crisis to crisis. We have to better manage our groundwater to prevent avoidable emergencies like this.”

-- *Jonathan Nelson, Community Water Center*

- Parts of the Sierras saw a 70% decrease in precipitation from 2011 to 2012
- Sierras supply 60% of water used by CA agricultural and commercial industries, and residents
- By summer 2014, 60% of CA was experiencing “exceptional drought” conditions

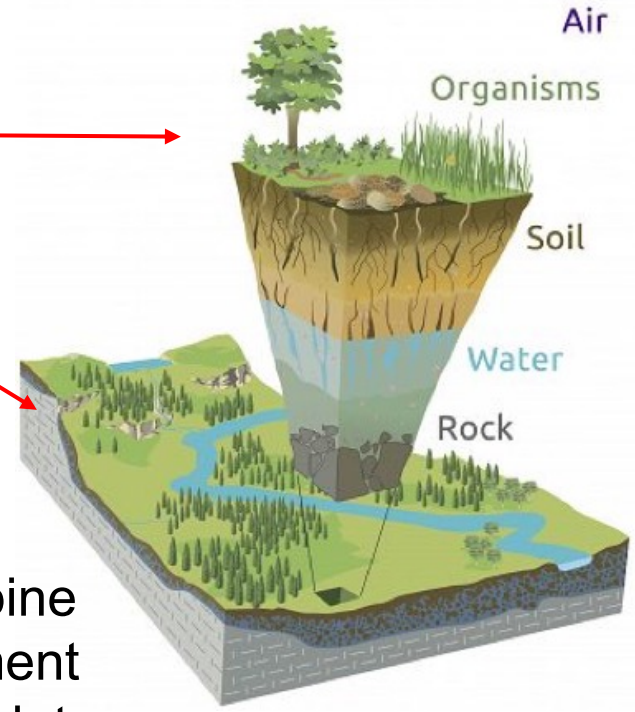




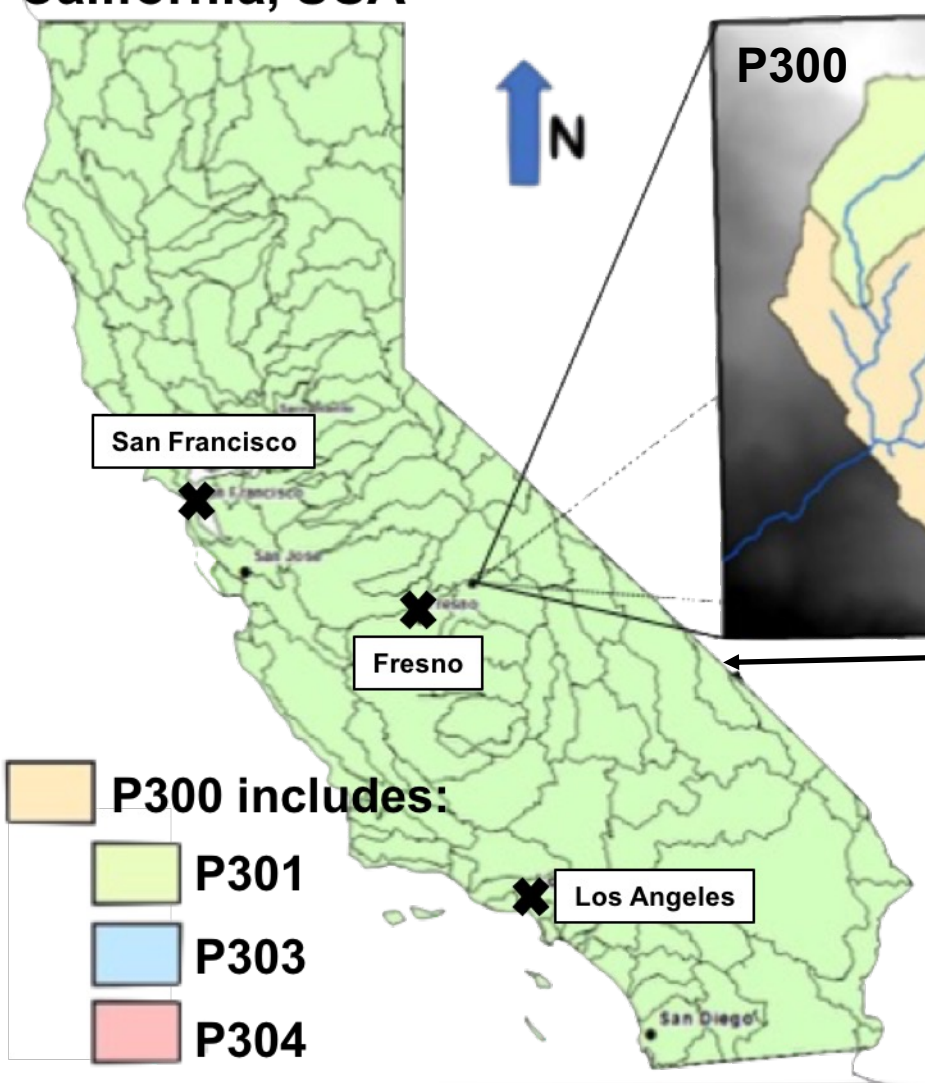
Justin Sullivan, Getty Images

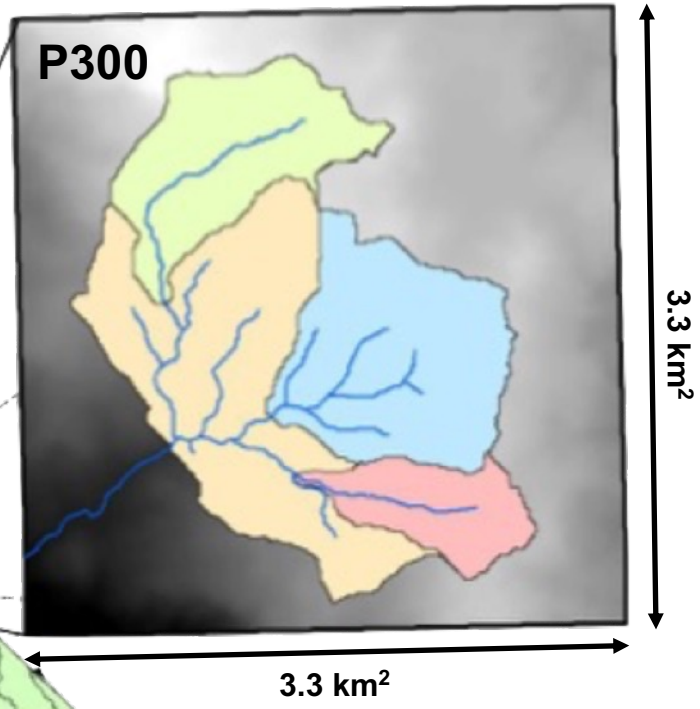
Providence Creek watershed

Critical Zone = region between the bedrock and canopy



California, USA



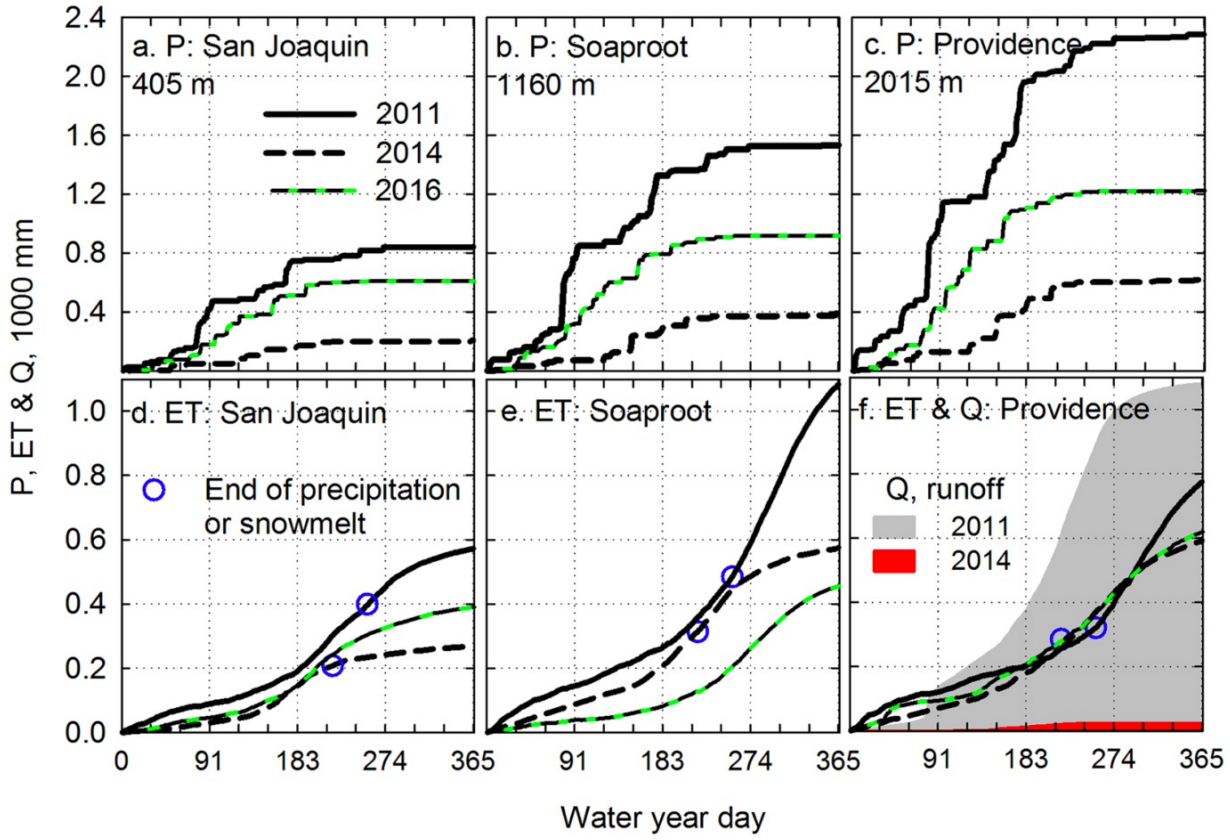


Heavily instrumented alpine research catchment with continuous data collection pre-, present-, and post-drought

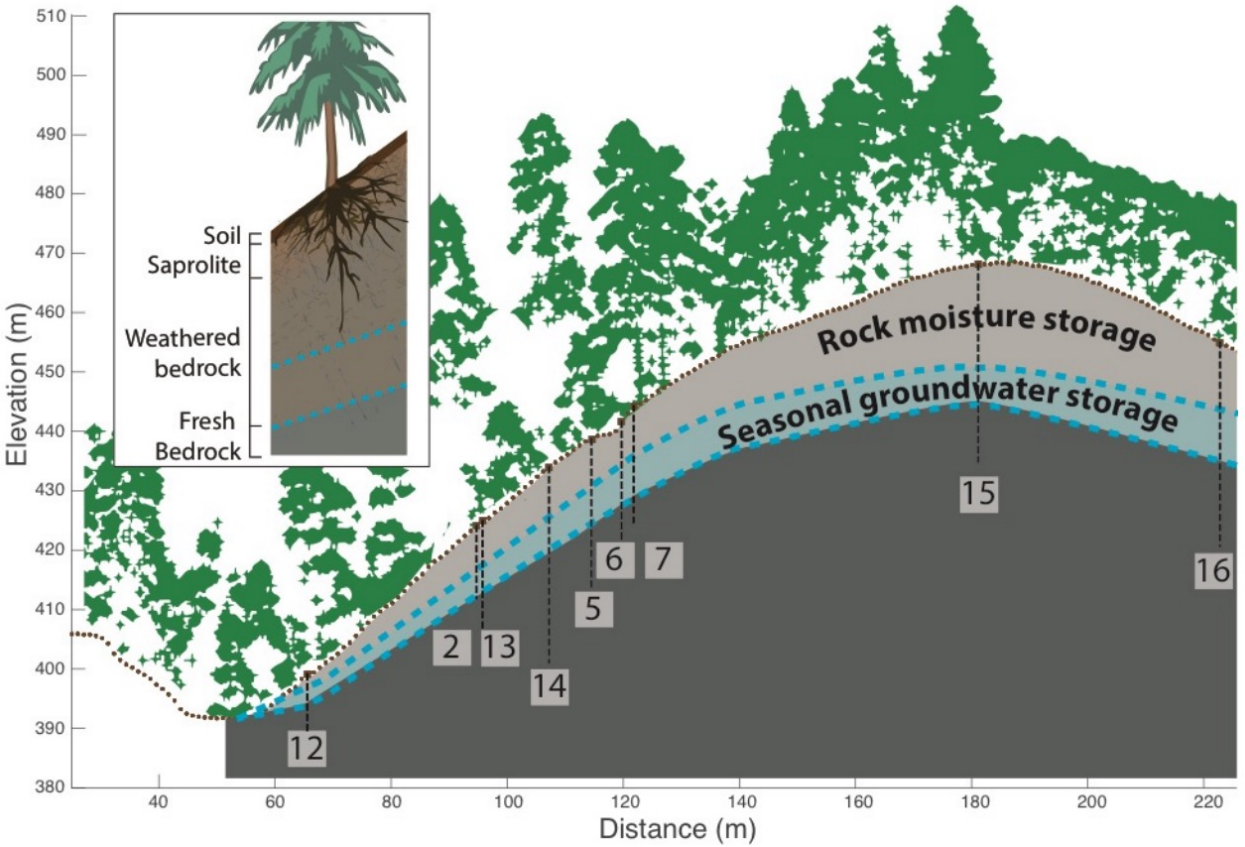
Reliable observations are challenging, limited by uncertainties, and difficult to scale.

Even though it was the worst drought in history, the trees didn't die!

Bales et al. (2018)

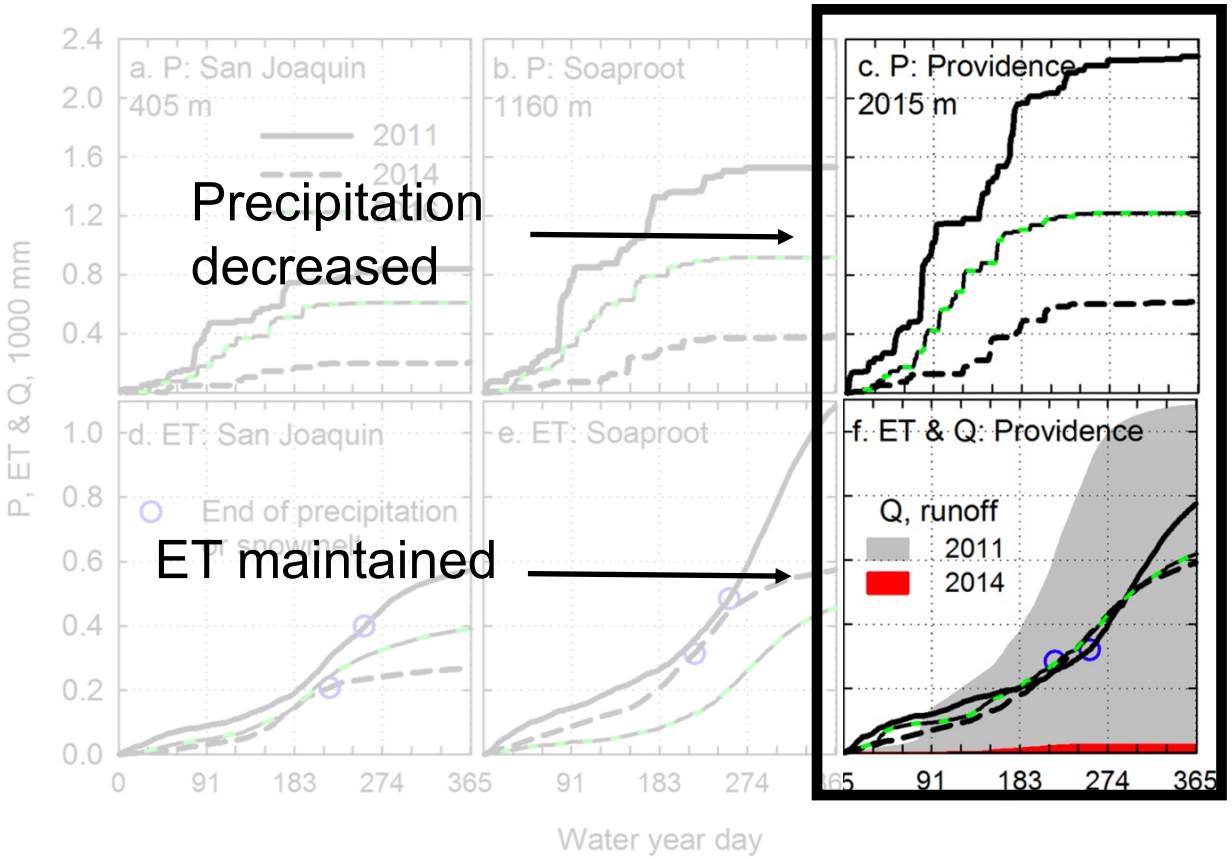


Rempe and Dietrich (2018)

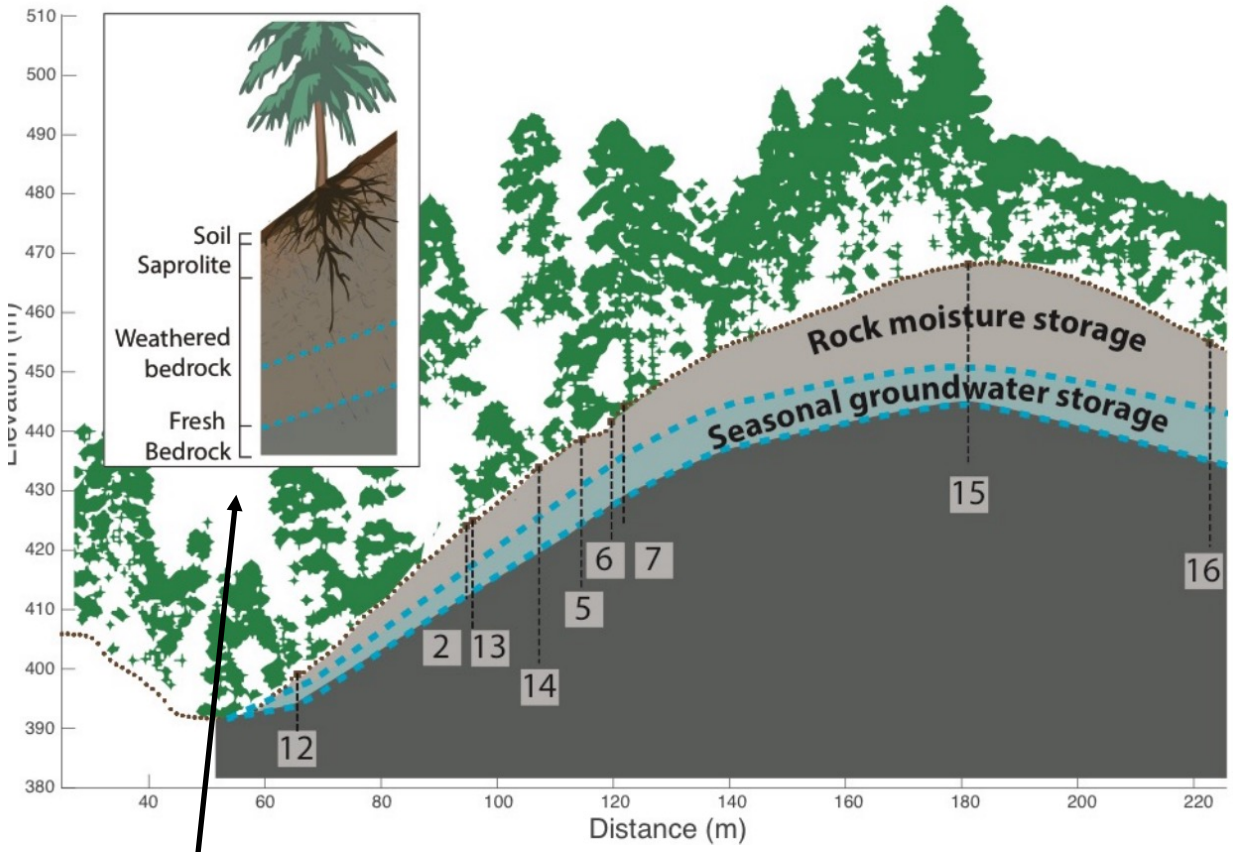


Even though it was the worst drought in history, the trees didn't die!

Bales et al. (2018)



Rempe and Dietrich (2018)



Tree roots extend past soil to access deeper water sources

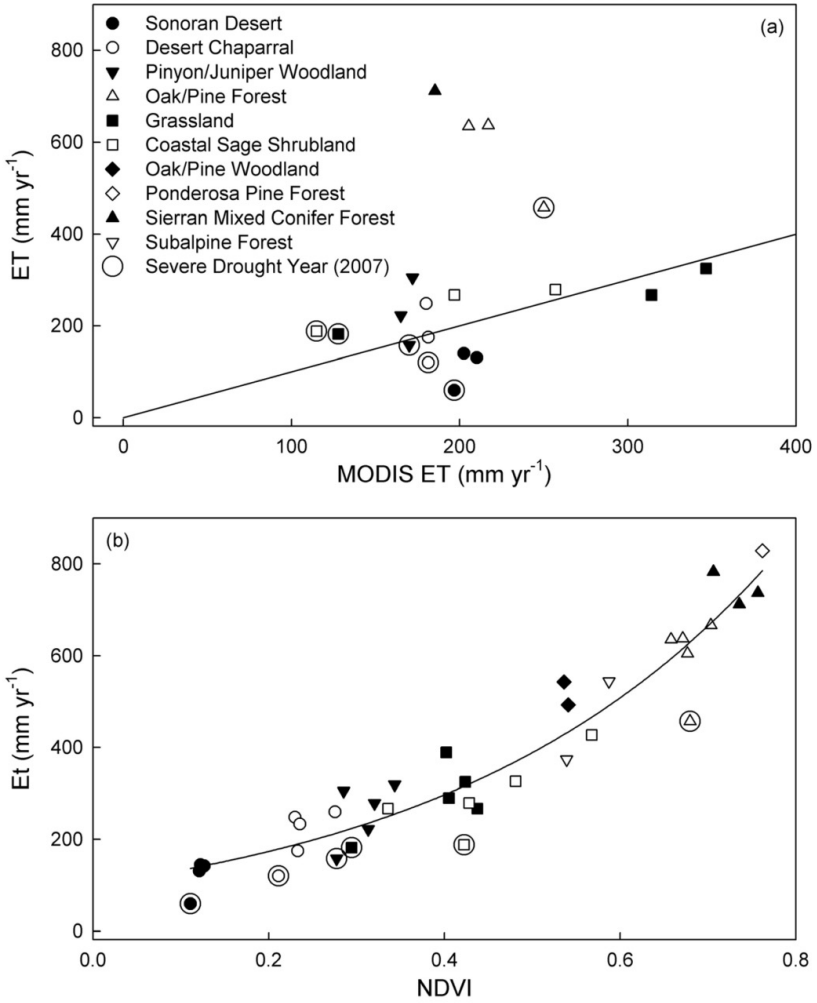
Evapotranspiration is hard

P301 Flux Tower, SSCZO



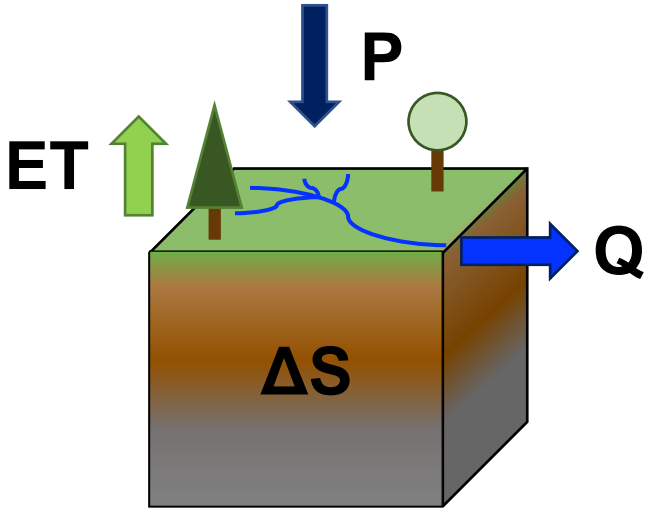
Field estimates are sourced from point observations at eddy covariance flux towers

Goulden et al. (2012)



Remote sensing approximations aren't much better

Integrated hydrologic models may help bridge scale and knowledge gaps between observations and theory

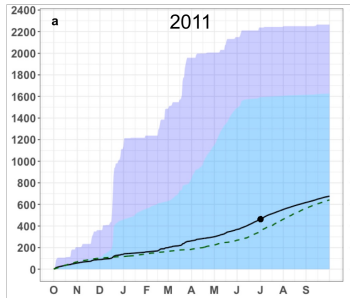


$$\Delta S = P - Q - ET$$

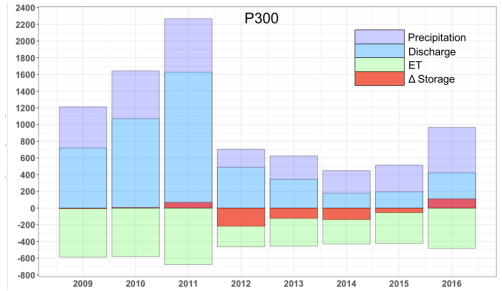
ΔS = change in storage
P = precipitation
Q = runoff
ET = evapotranspiration

- Even though sustained decreased P directly decreases Q, the role of ET and S is difficult to constrain, especially in highly heterogeneous mountain regions
- Nonlinear feedbacks between components make it difficult to isolate mechanisms under changing climate regimes
- Integrated models will help to bridge these gaps

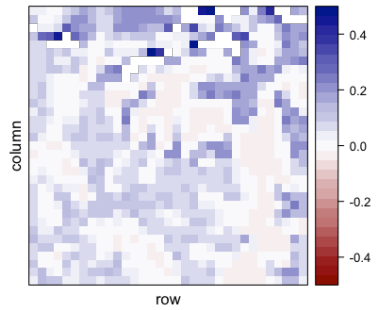
I will use an integrated hydrology model of P300 to study plant water use during the drought, addressing three main research questions:



Can we use integrated physically-based models to accurately represent mountain hydrology?



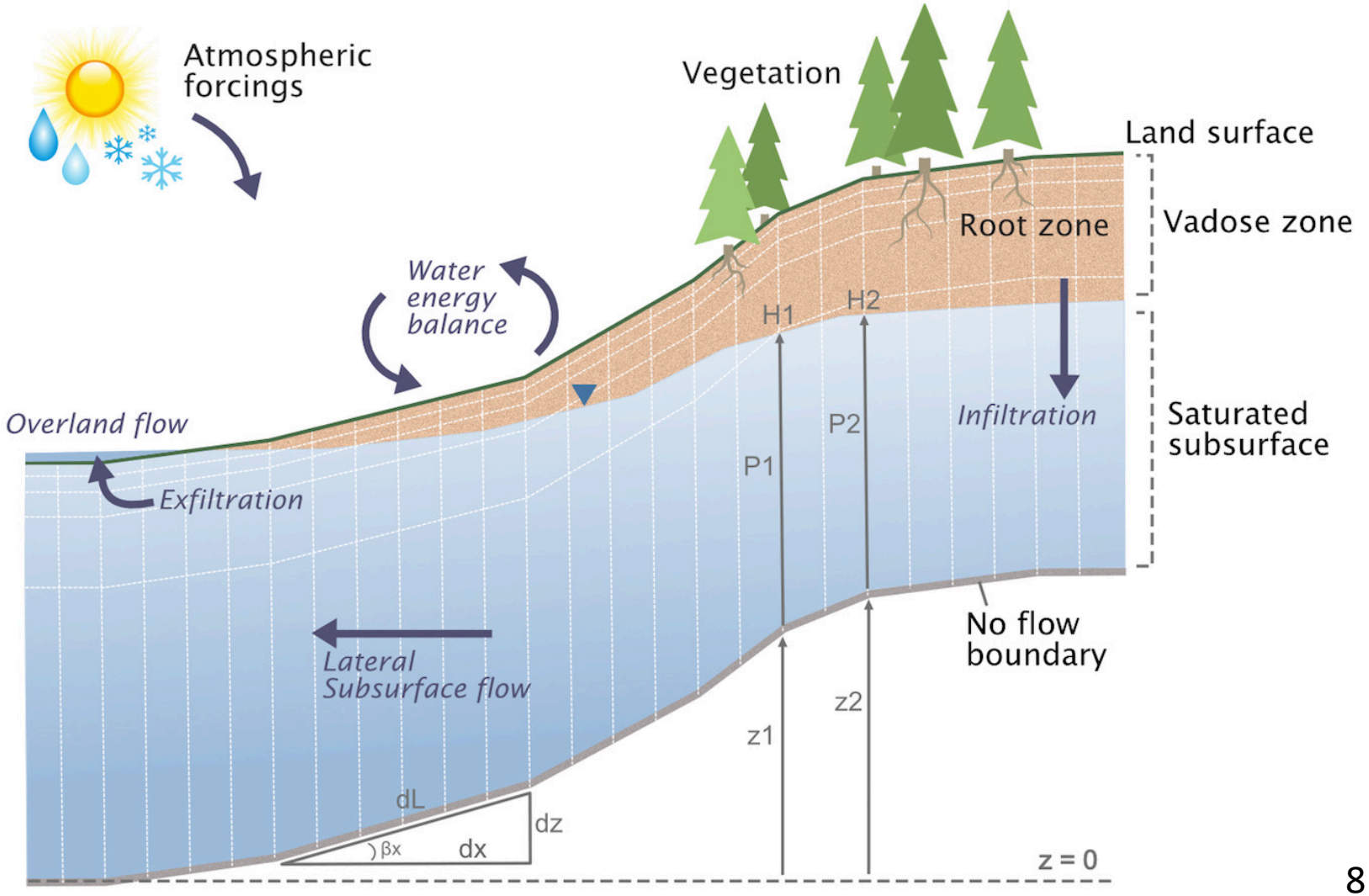
Is groundwater the missing link in understanding plant water use?



What is the effect of lateral groundwater flow on plant water use through drought?

ParFlow-CLM provides an opportunity to assess the effects of lateral groundwater flow on plant water stress with change at Providence Creek

- Physically-based integrated hydrologic model
- Groundwater utilizes 3D Richards equation
- Fully coupled to Common Land Model (CLM) to simulate land-energy balance and snow dynamics
- Parallel open source code provides efficiency for large-scale complex problems and collaborative improvements



Physically-based models have a combination of data needs and challenges

Atmospheric forcing

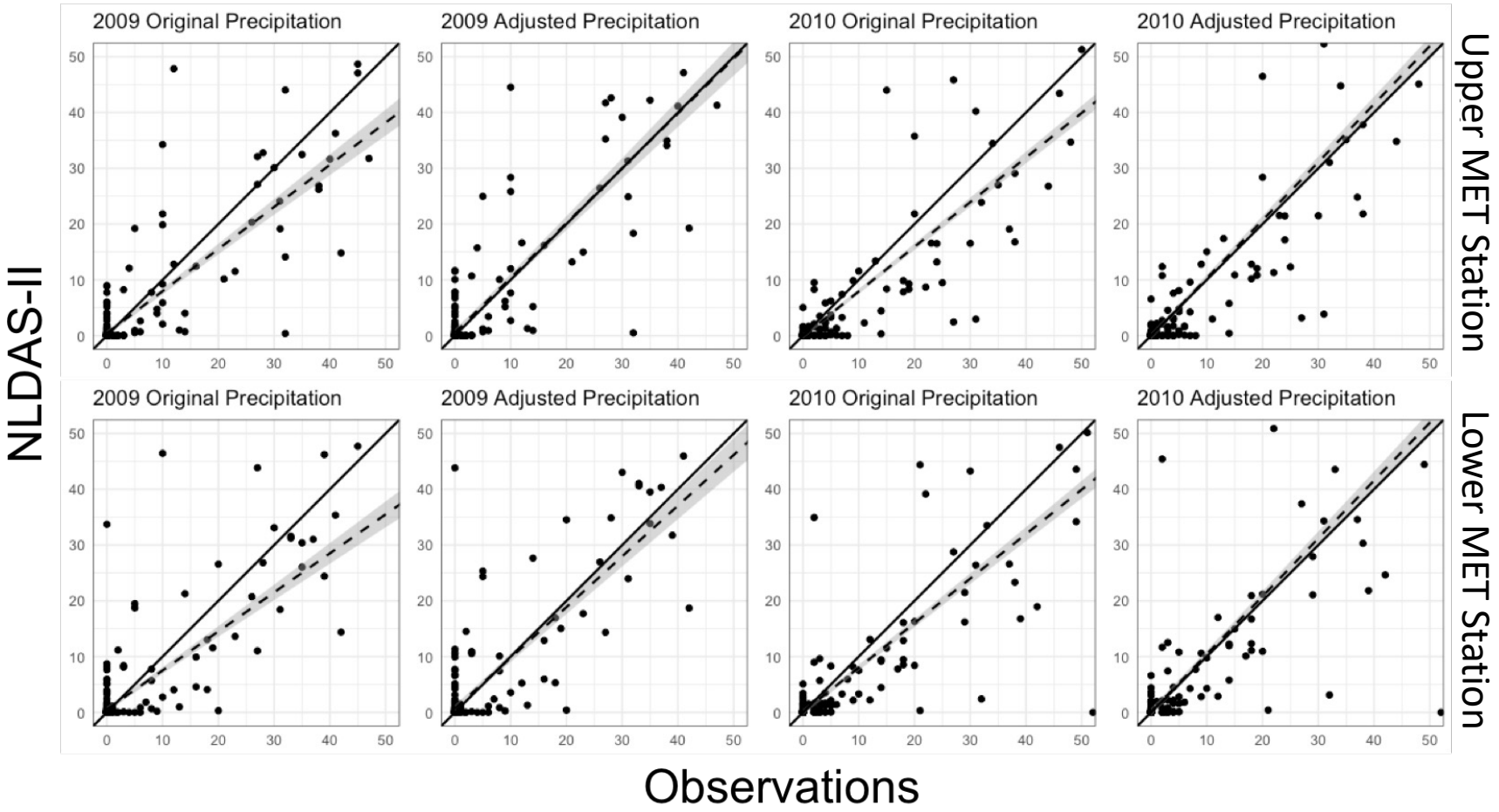


Subsurface characterization



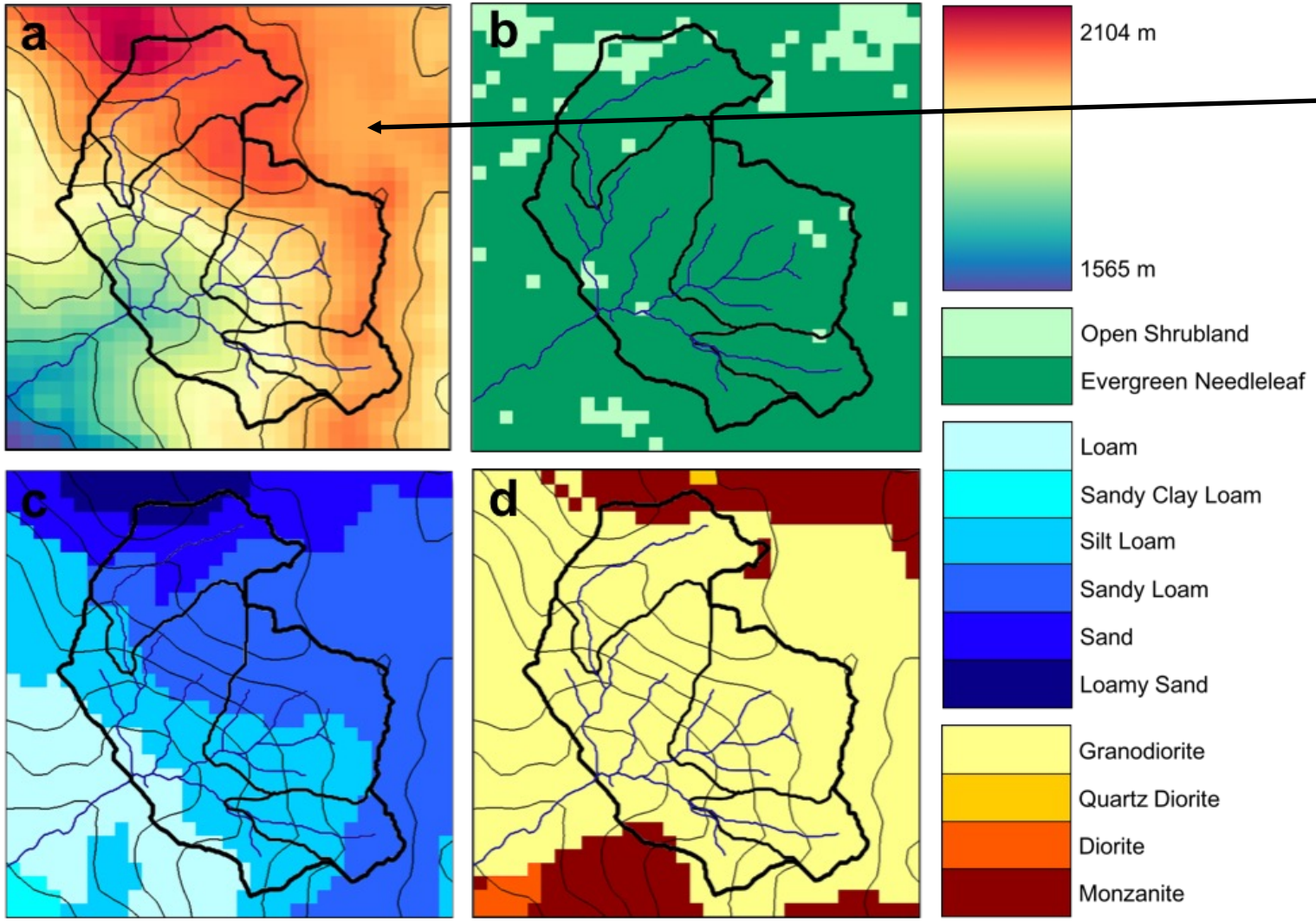
Making accurate meteorology is especially challenging in the mountains

- NLDAS-II is a validated 32 km^2 climate data product which utilizes four observationally informed LSMs to create real-time and retrospective land surface states over the CONUS

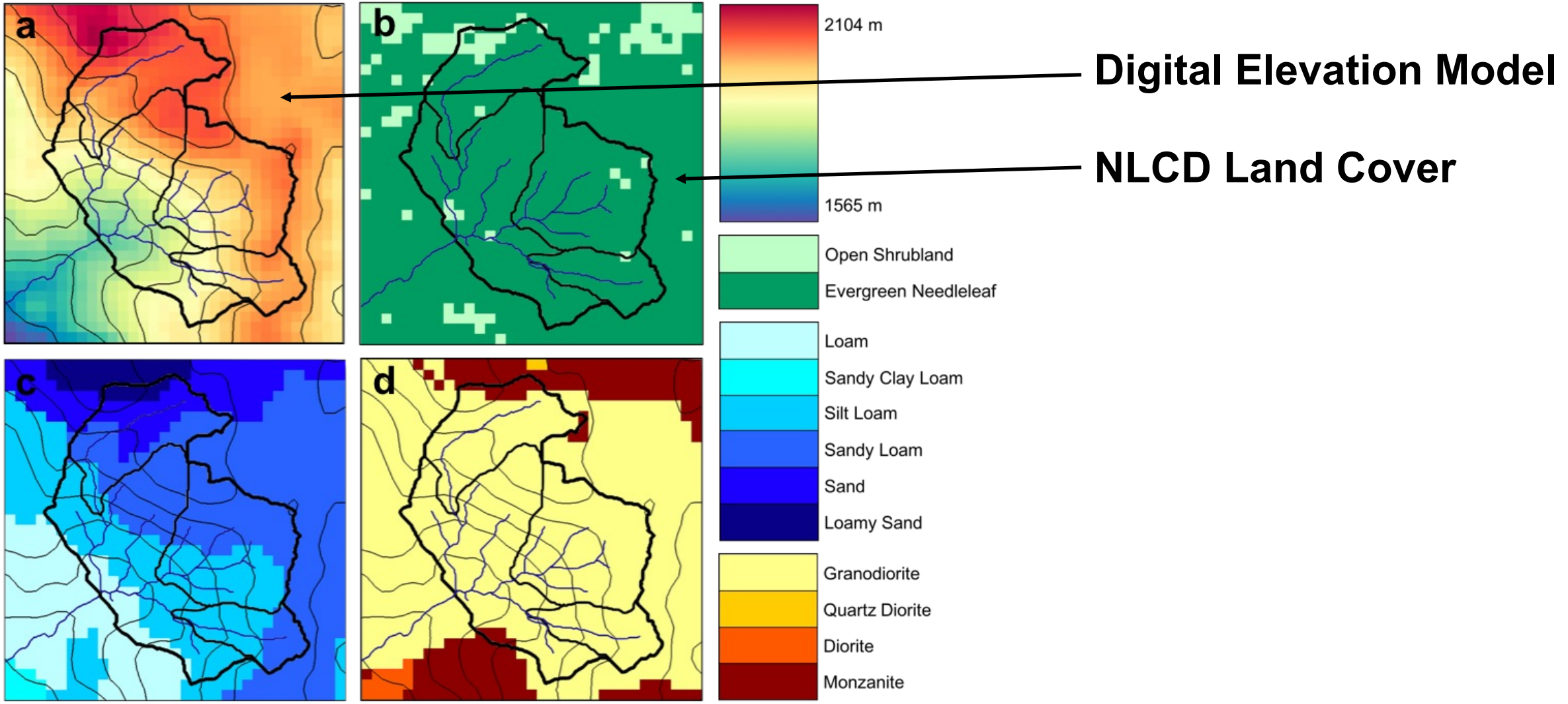


- Climate variables often do not behave uniformly
- Low-resolution climate products often usurp mountain systems all together
- Low frequency observations of precipitation in P300 were used to bias correct NLDAS-II, a low spatial resolution but high frequency reconstruction of meteorology

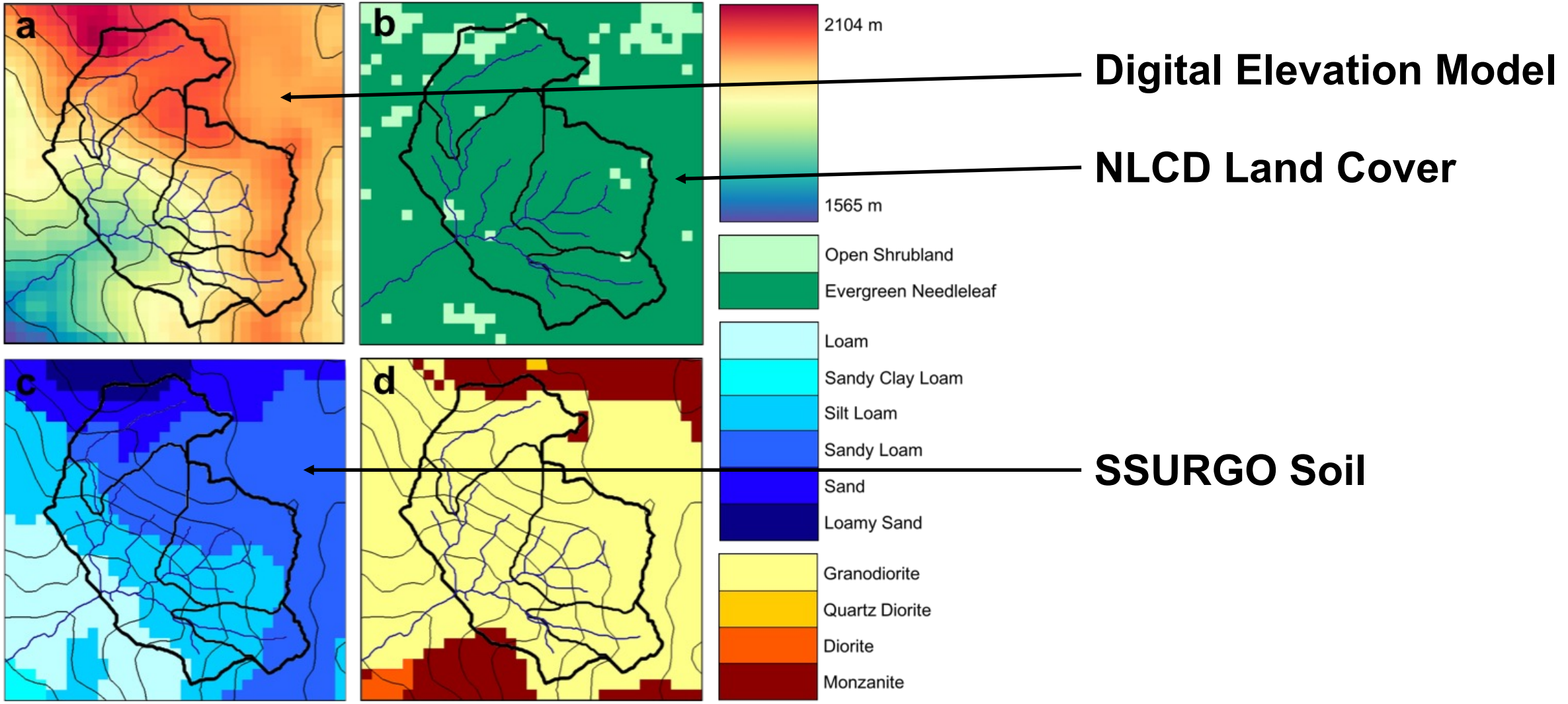
Site characterization is developed from complex datasets and implemented onto a computational grid



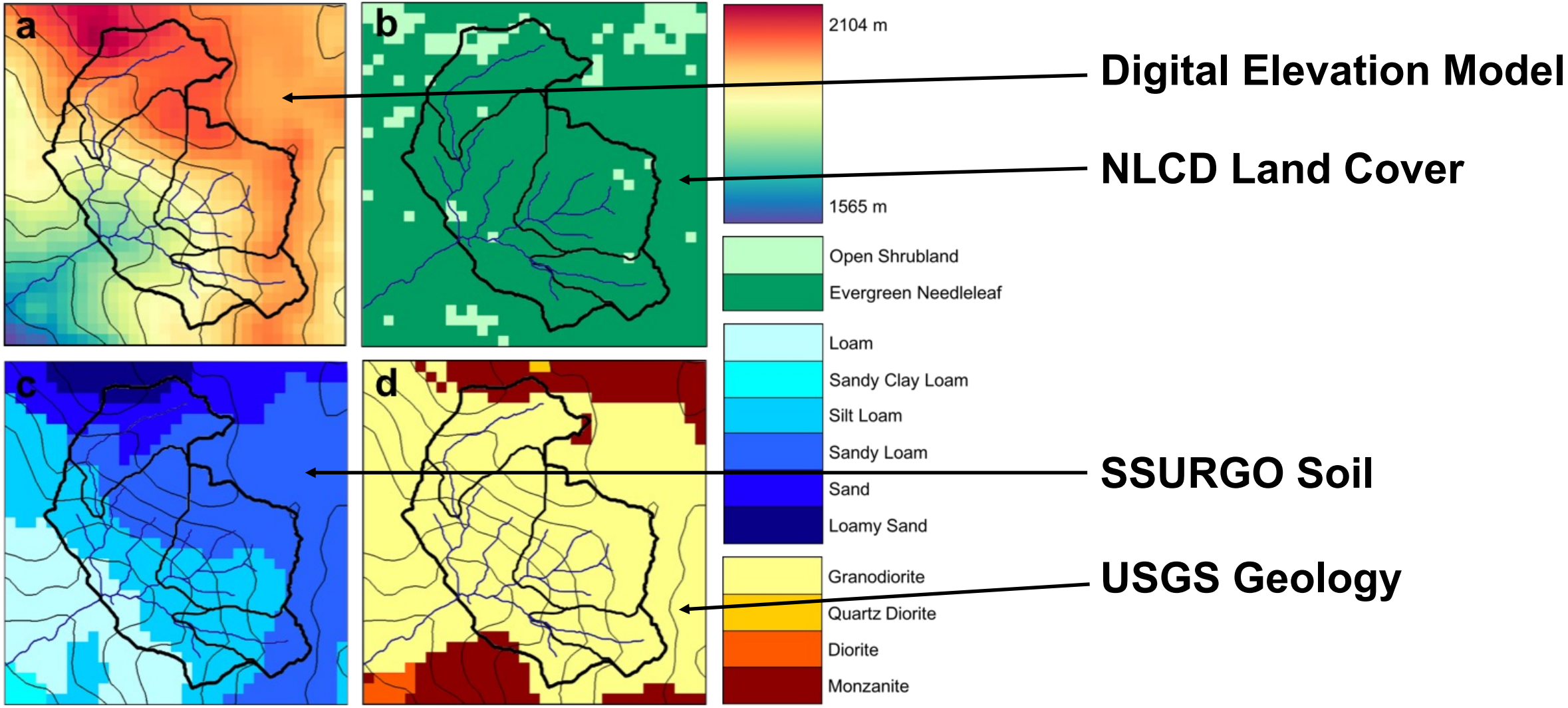
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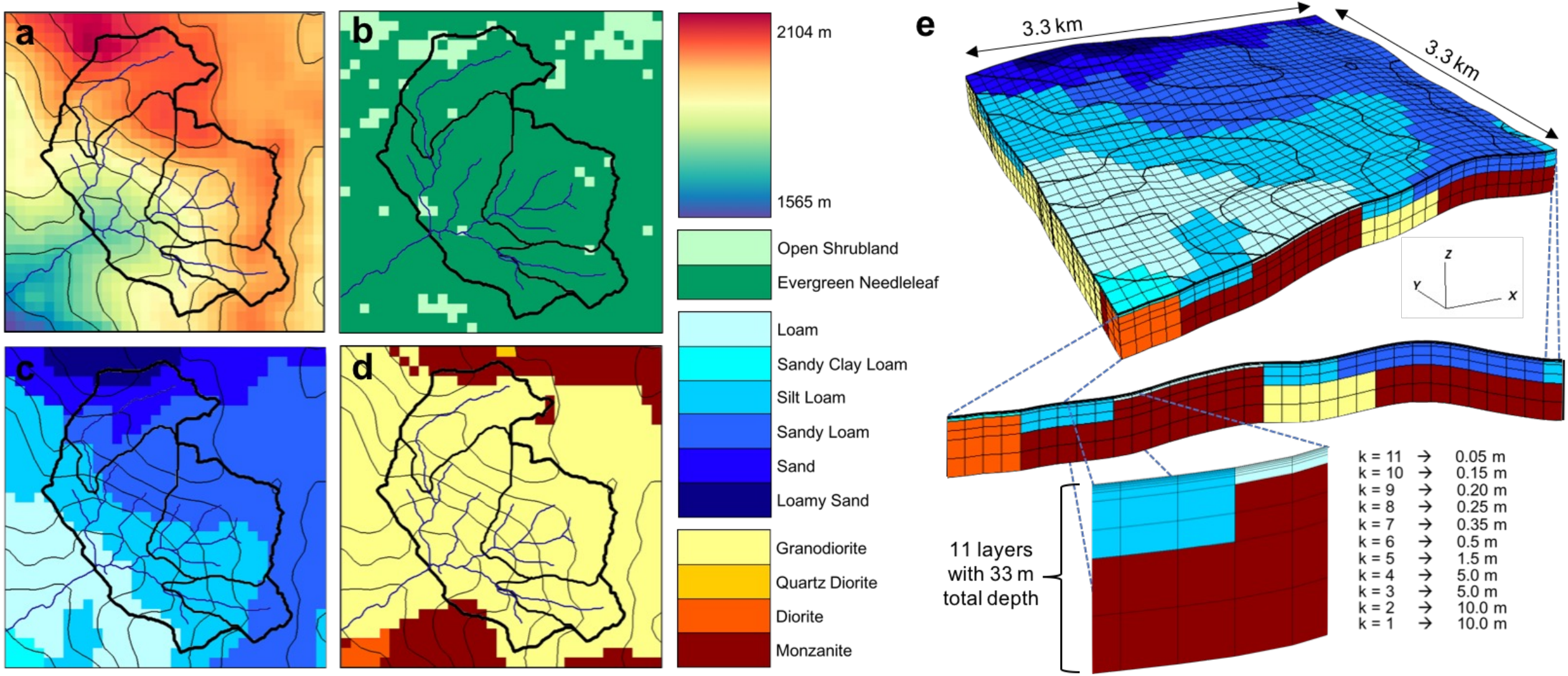
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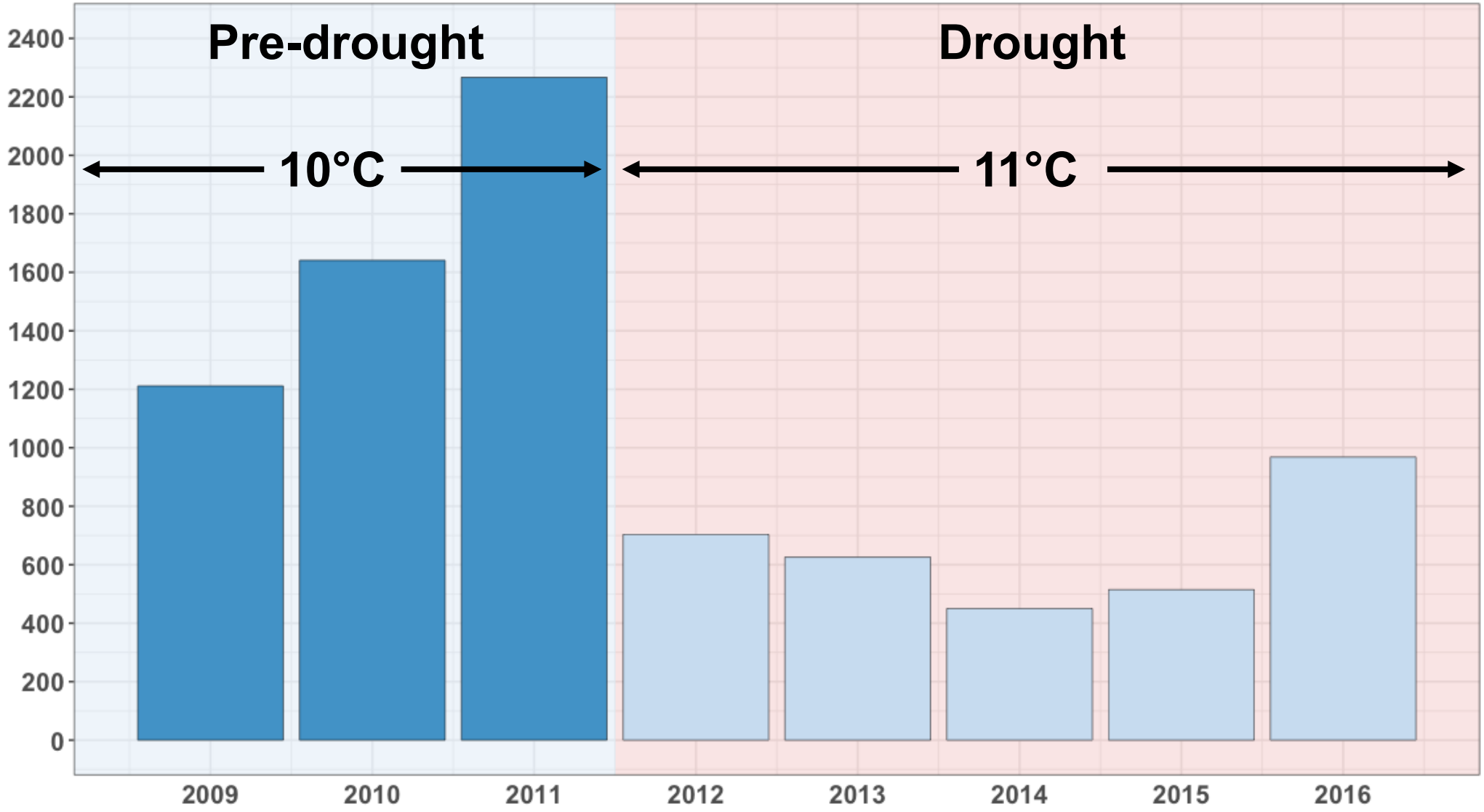
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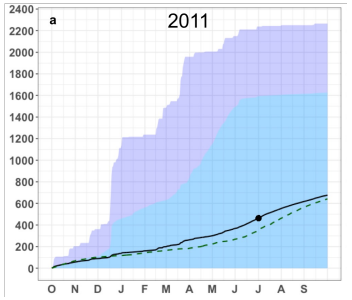


Site characterization is developed from complex datasets and implemented onto a computational grid



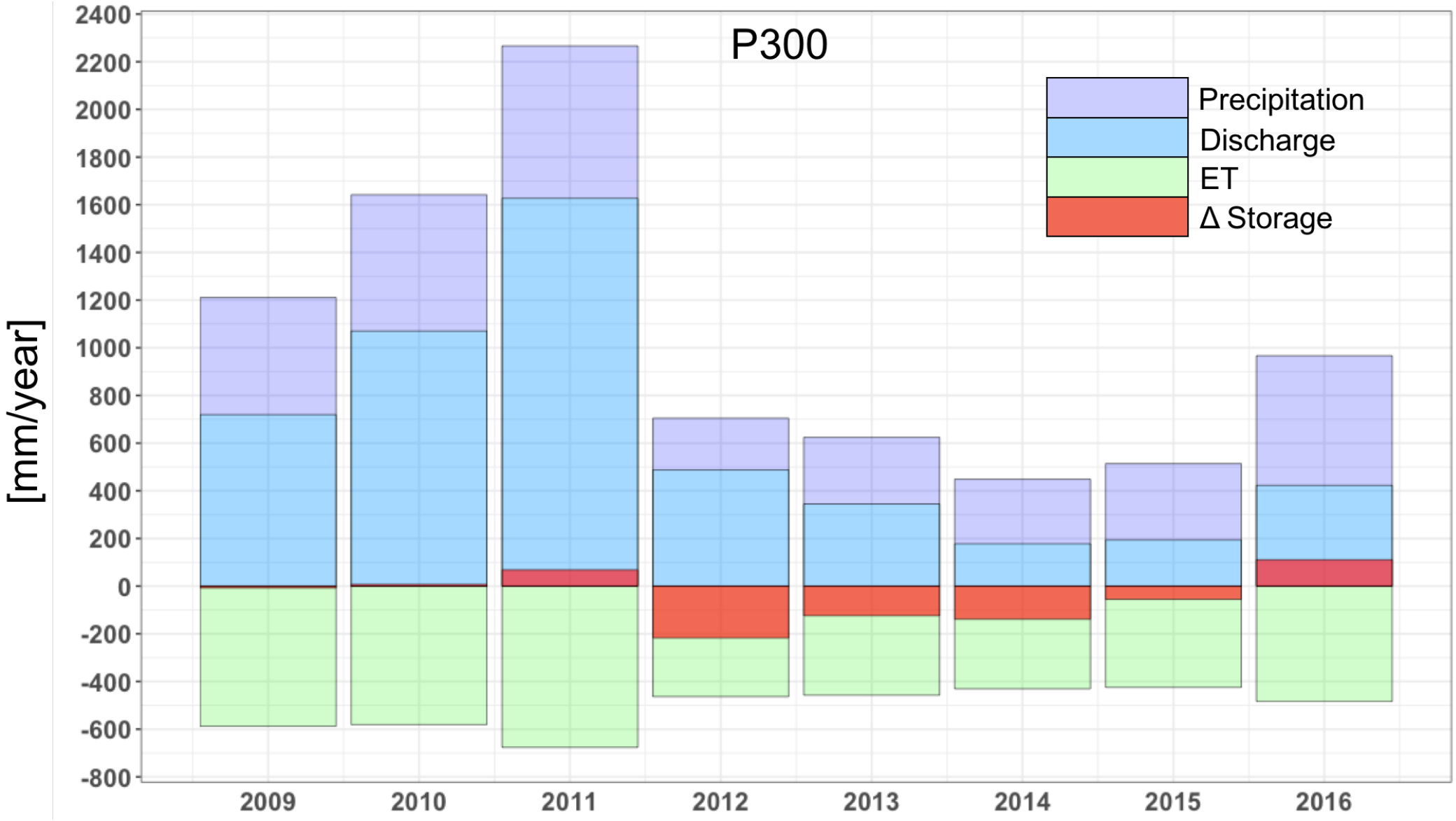
Capturing the drought: P300 experienced 62% ↓ in precipitation



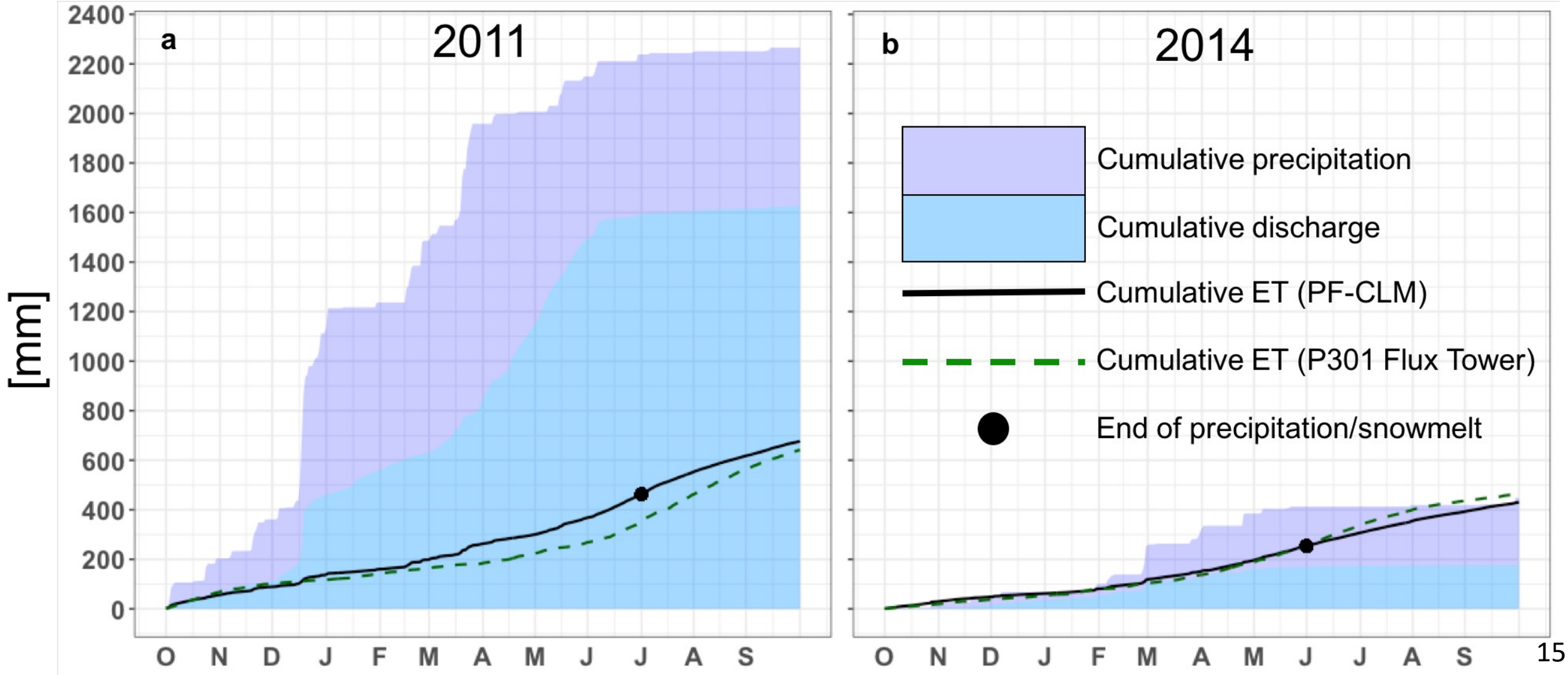


Can we use integrated physically-based models to accurately represent mountain hydrology?

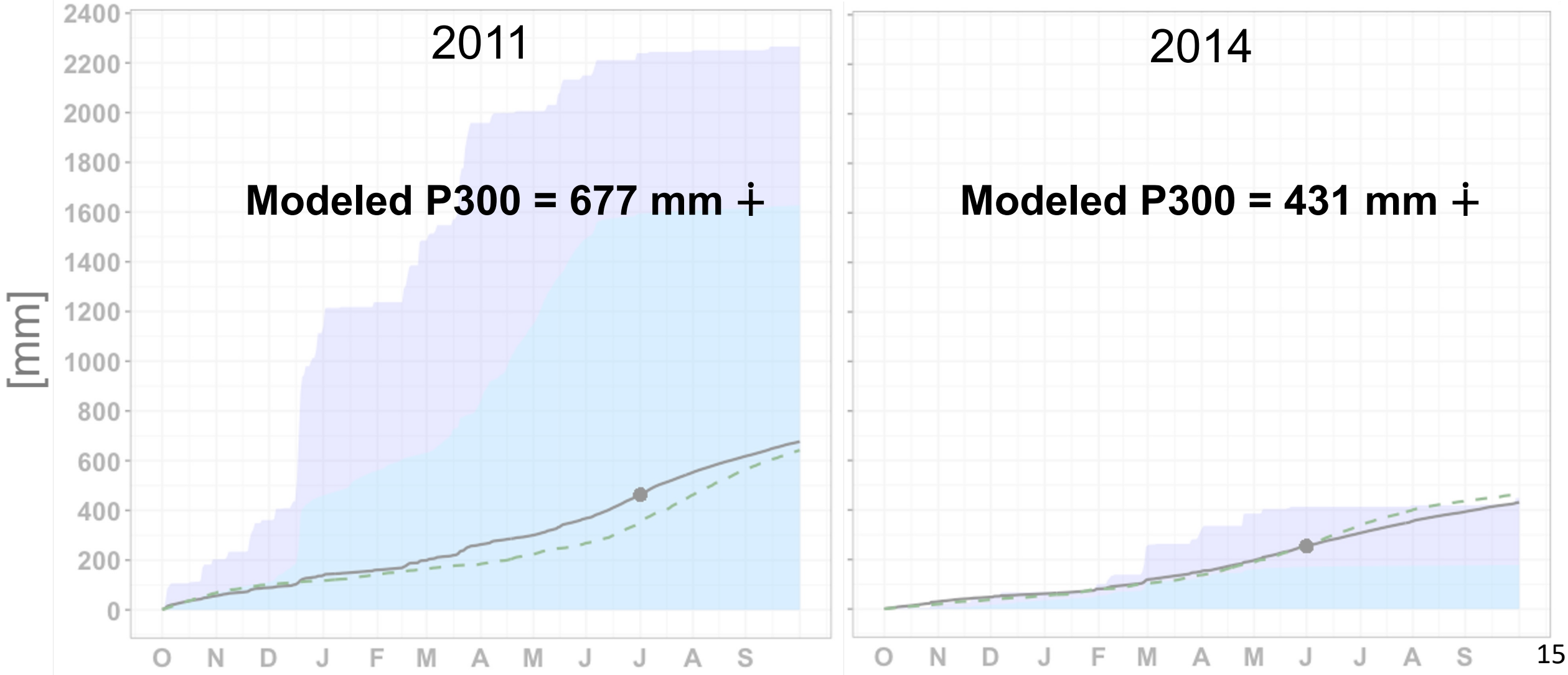
Despite a significant decrease in precipitation, ET is maintained



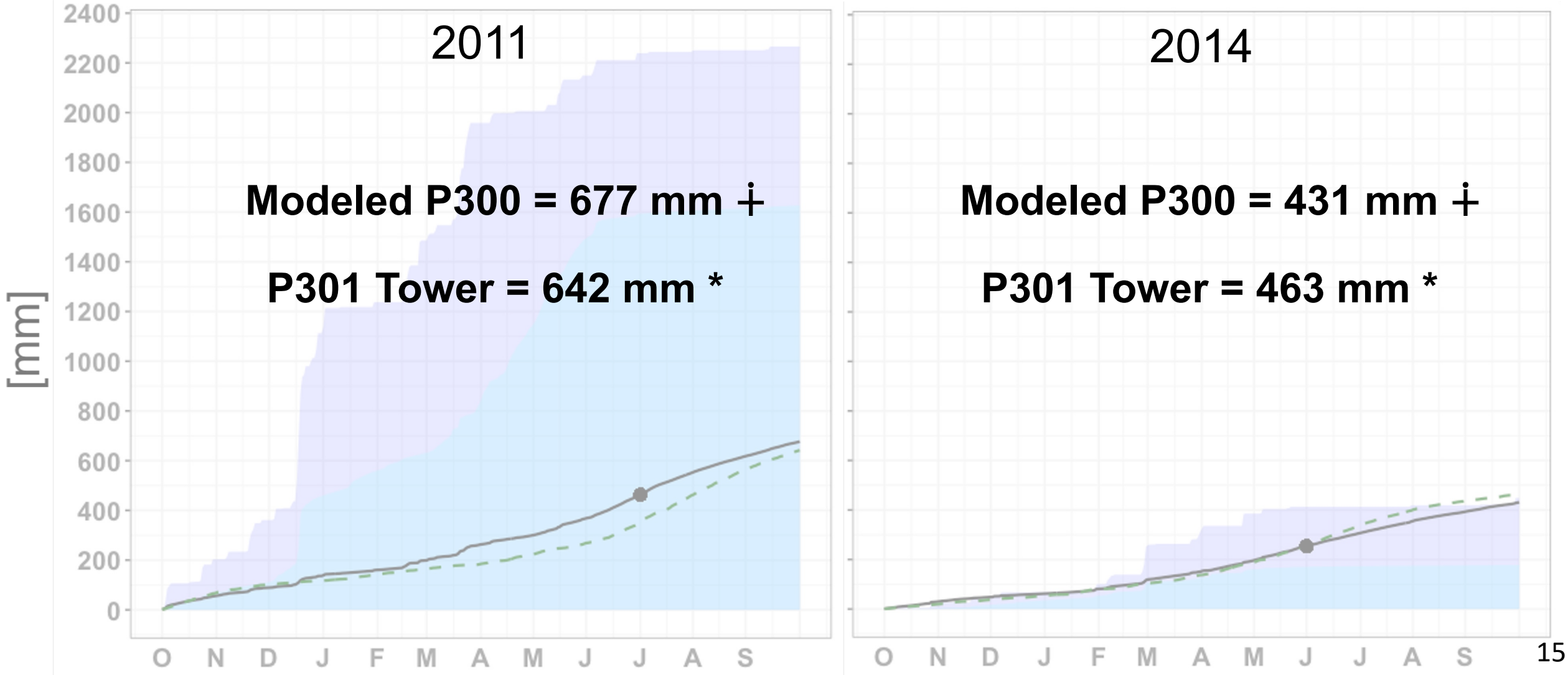
Total ET exceeds total precipitation suggesting vegetation is sustained by plant-accessible GW storage



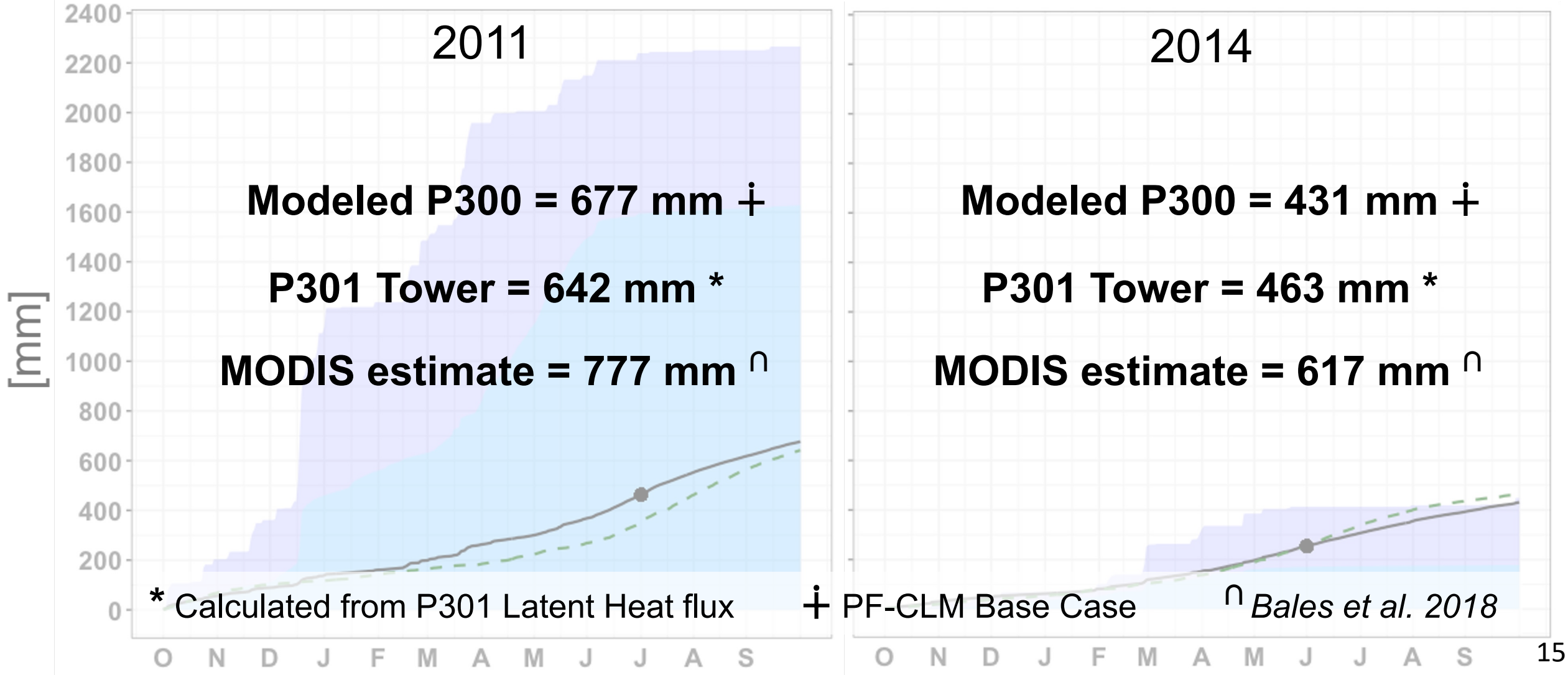
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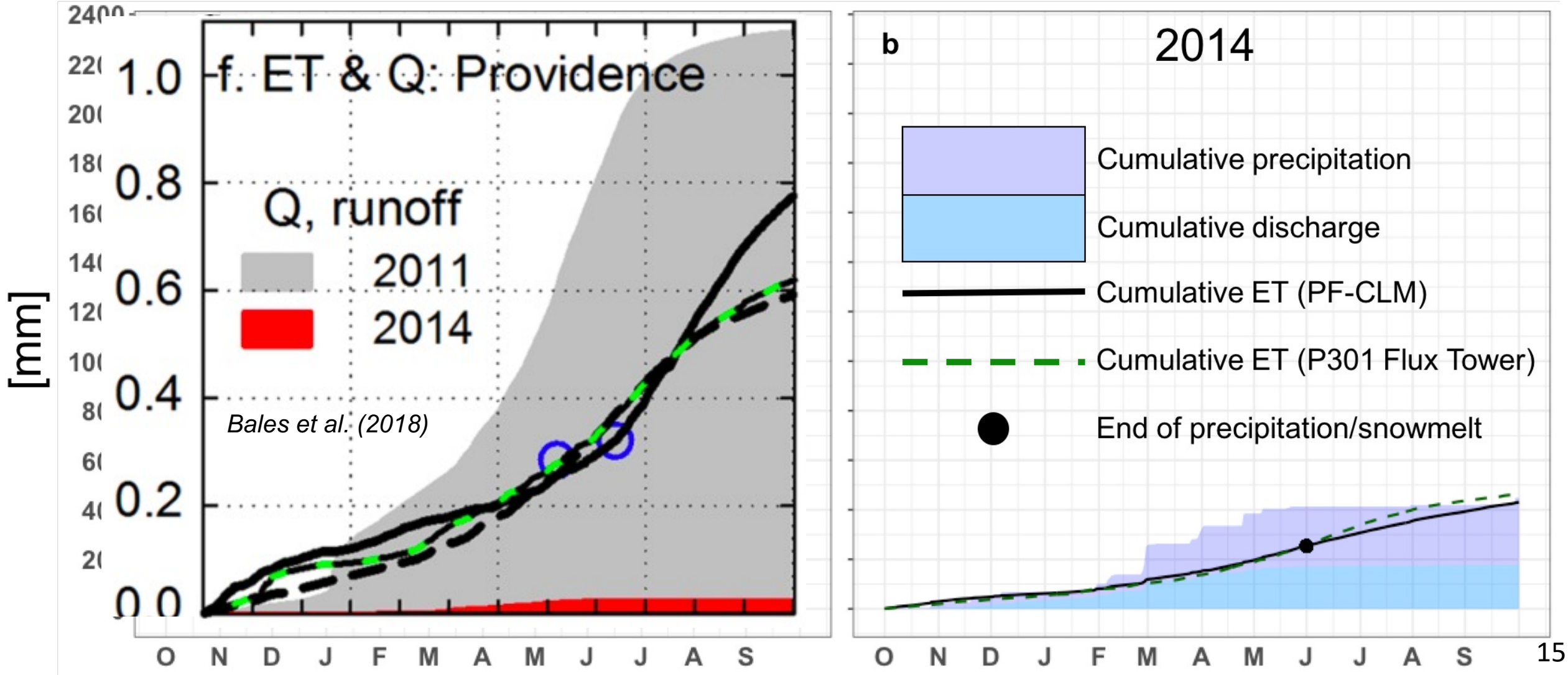
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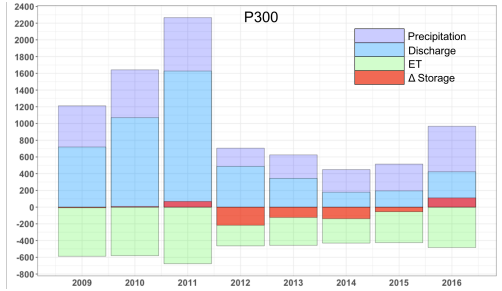


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Total ET exceeds total precipitation suggesting vegetation is sustained by plant-accessible GW storage

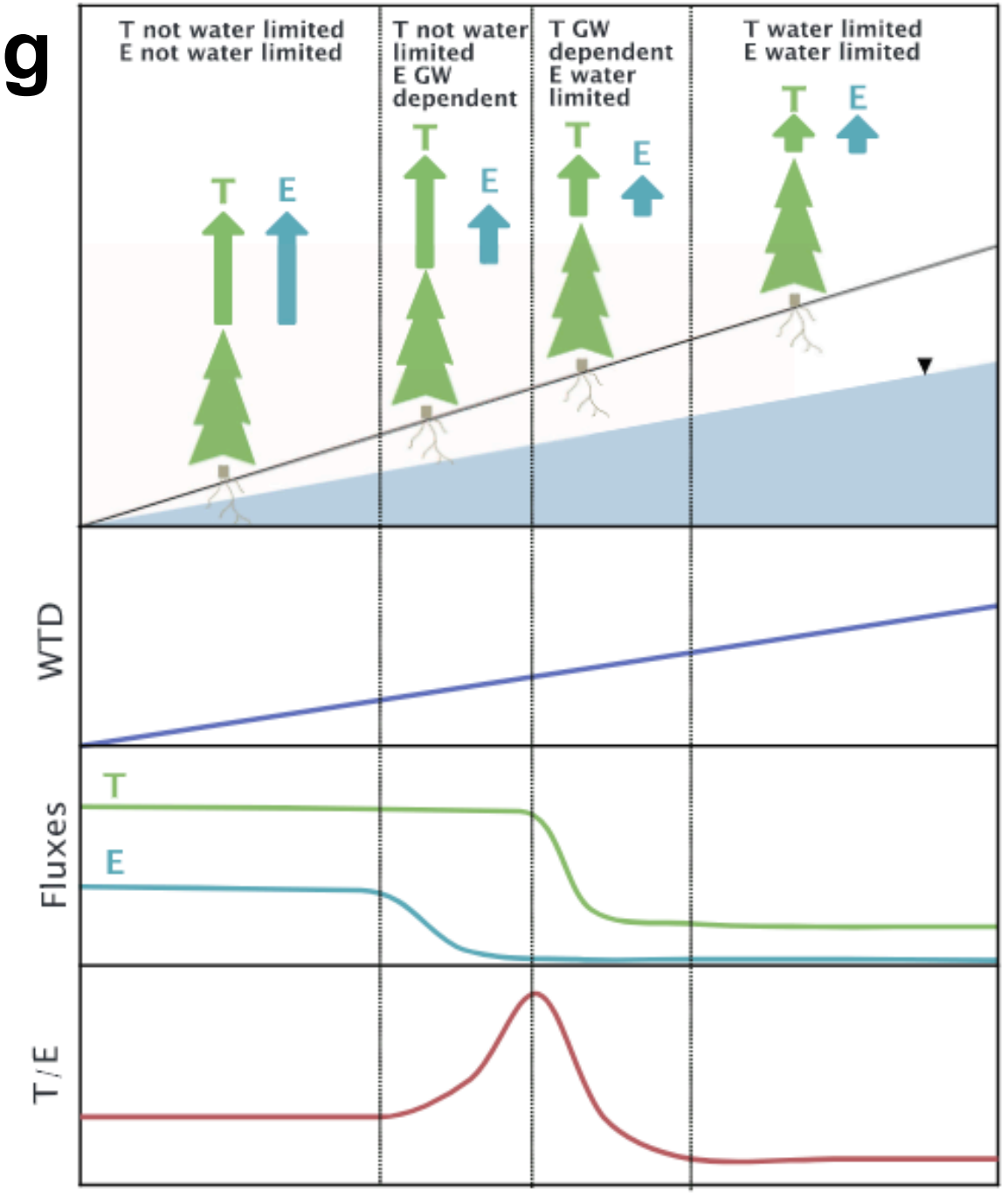




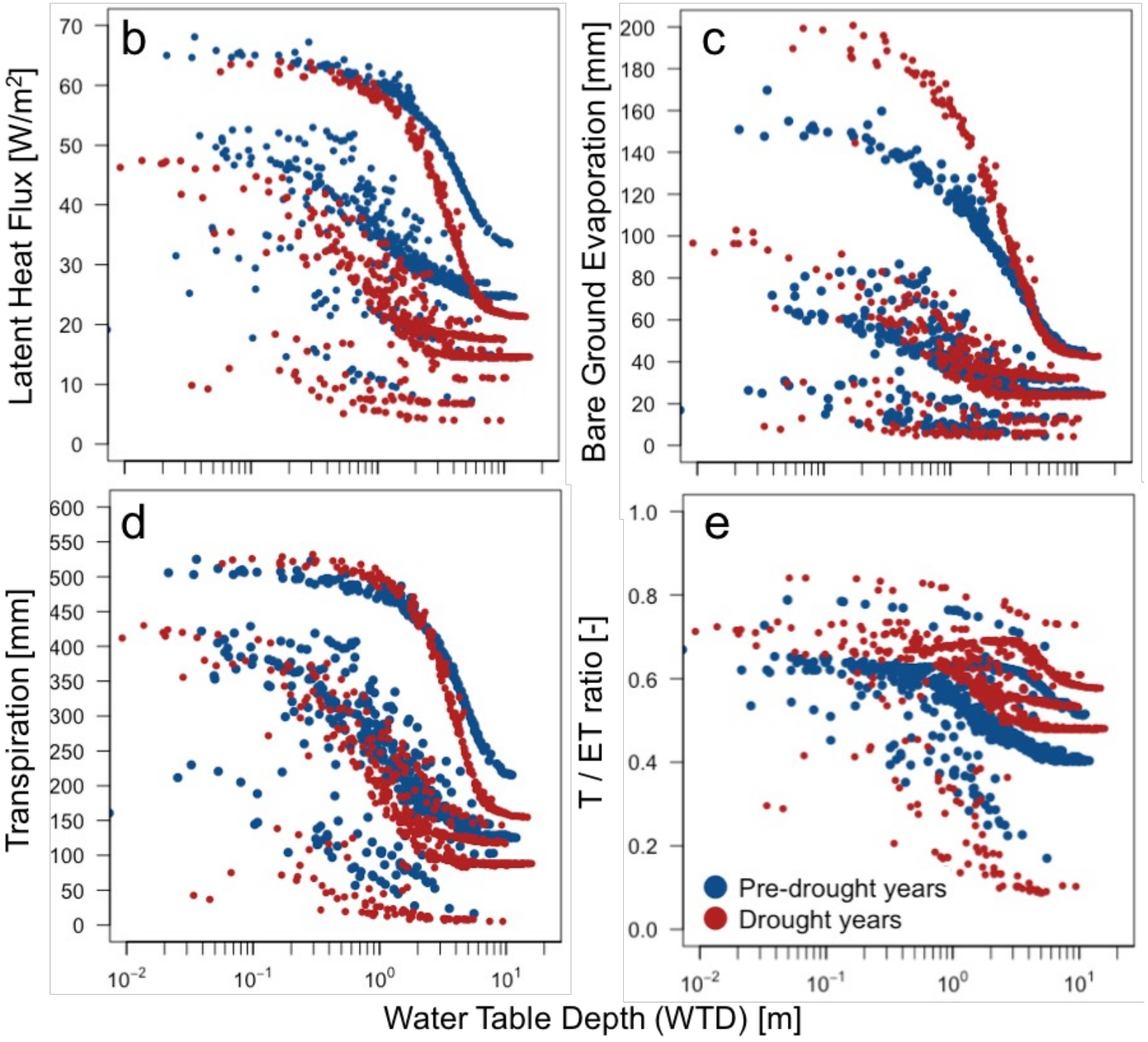
Is groundwater the missing link in understanding plant water use?

Evapotranspiration partitioning is sensitive to groundwater depth

- Evapotranspiration is the largest terrestrial flux in the water budget
- ET is difficult to estimate in the field
- Integrated models help us bracket the magnitude of this flux
- ET components are not water limited in the shallow subsurface due to lateral groundwater flow
- Evaporation cuts off in the shallow subsurface before transpiration

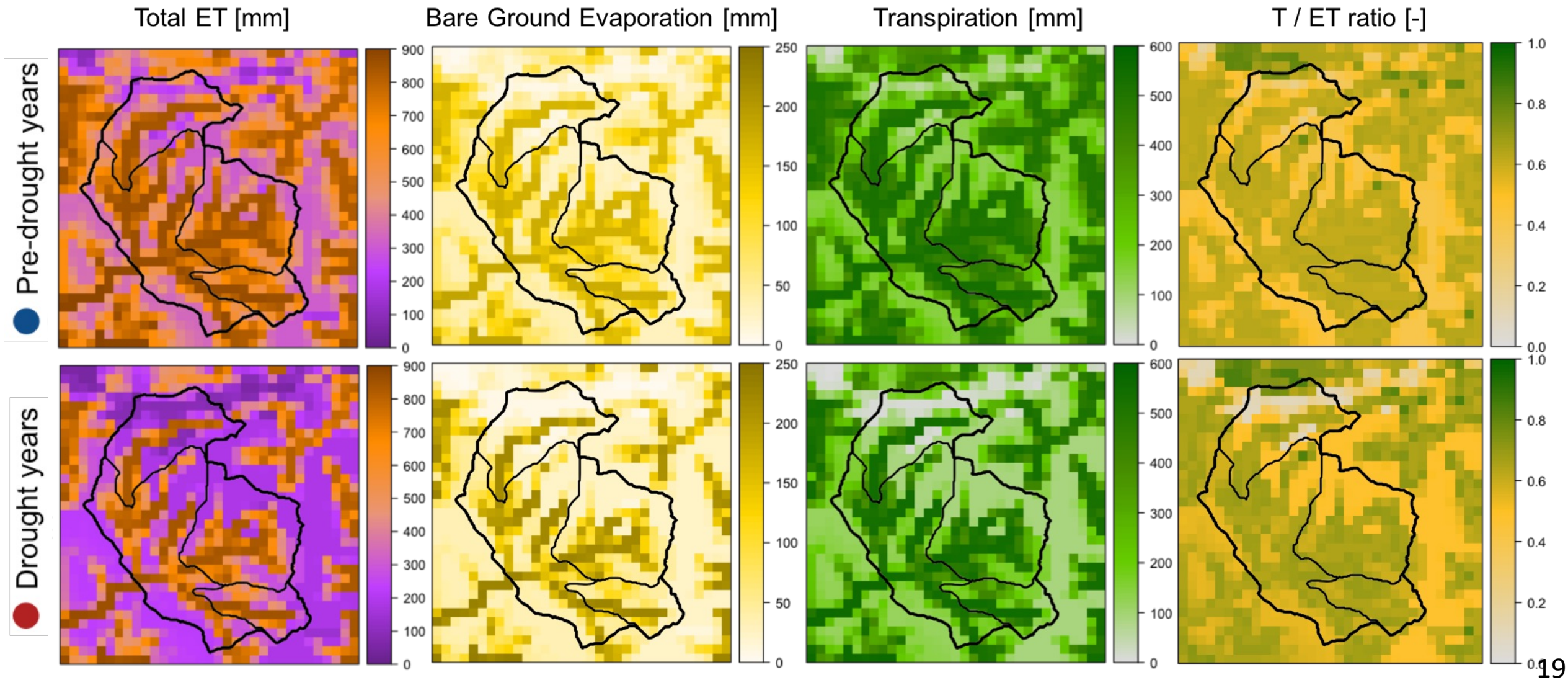


Maxwell and Condon (2016)

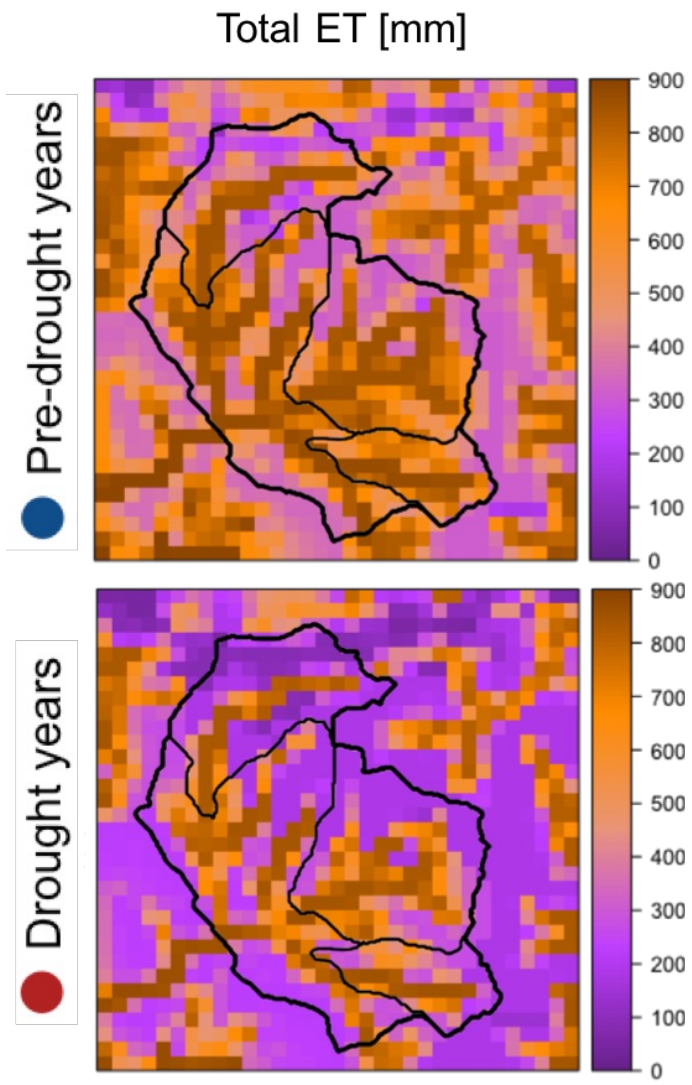


Shallow groundwater maintains ET, T and E fluxes through the drought

Evapotranspiration components can be explored spatially

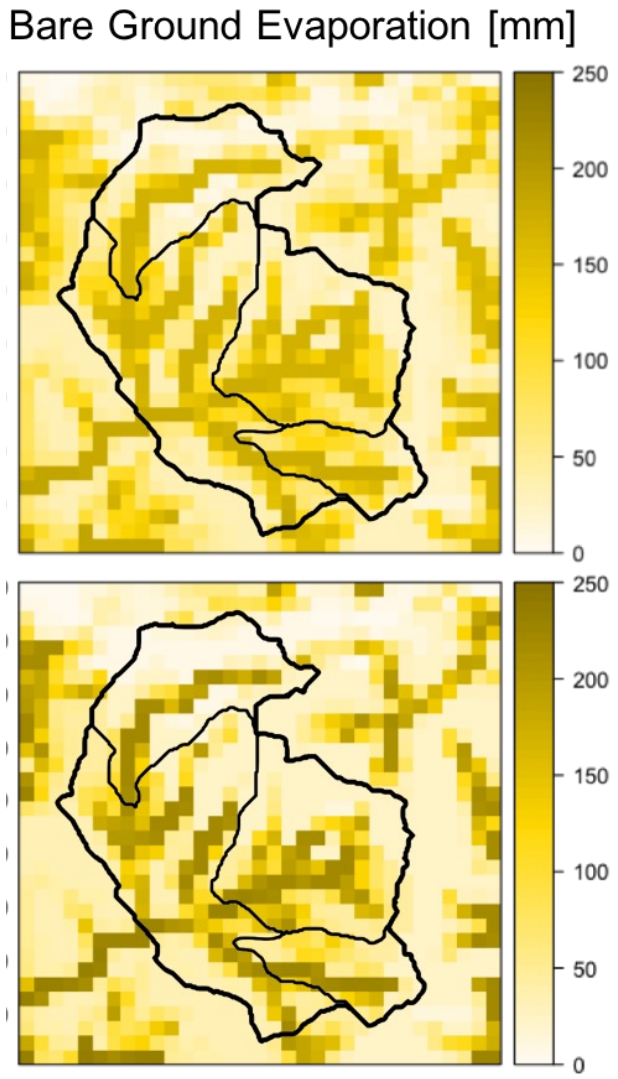


Evapotranspiration components can be explored spatially



P300 ET decreased by 26.5%

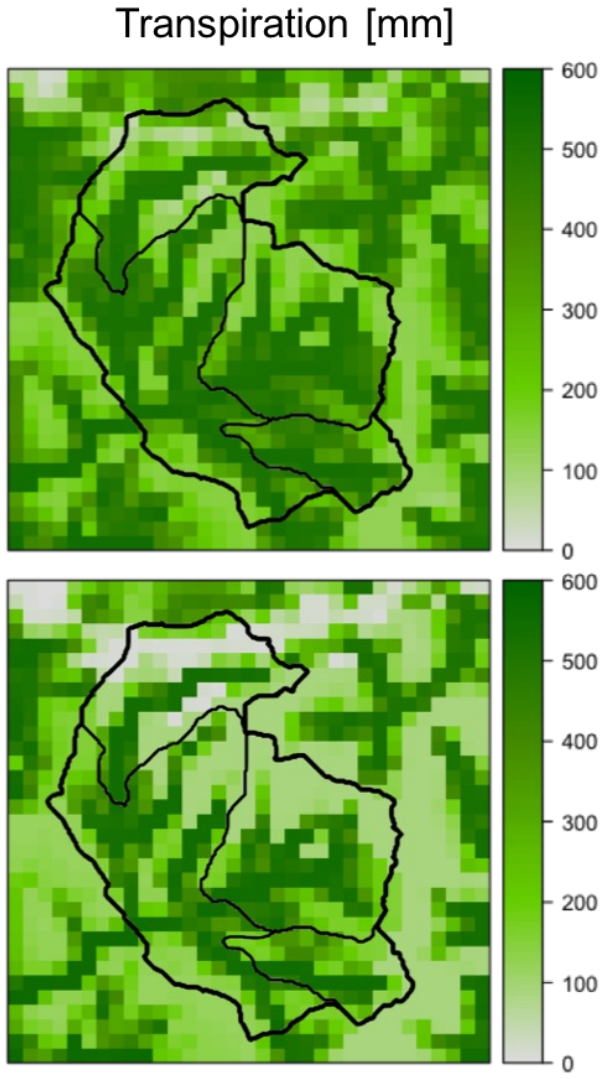
Evapotranspiration components can be explored spatially



P300 E decreased by 1.1%

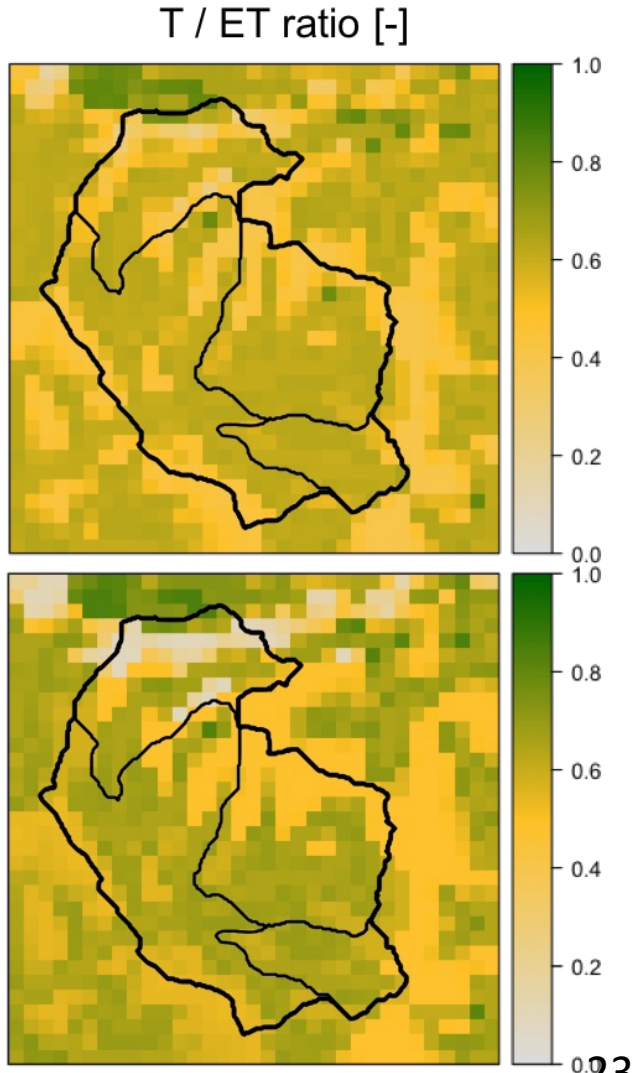
Evapotranspiration components can be explored spatially

P300 T decreased by 20.9%

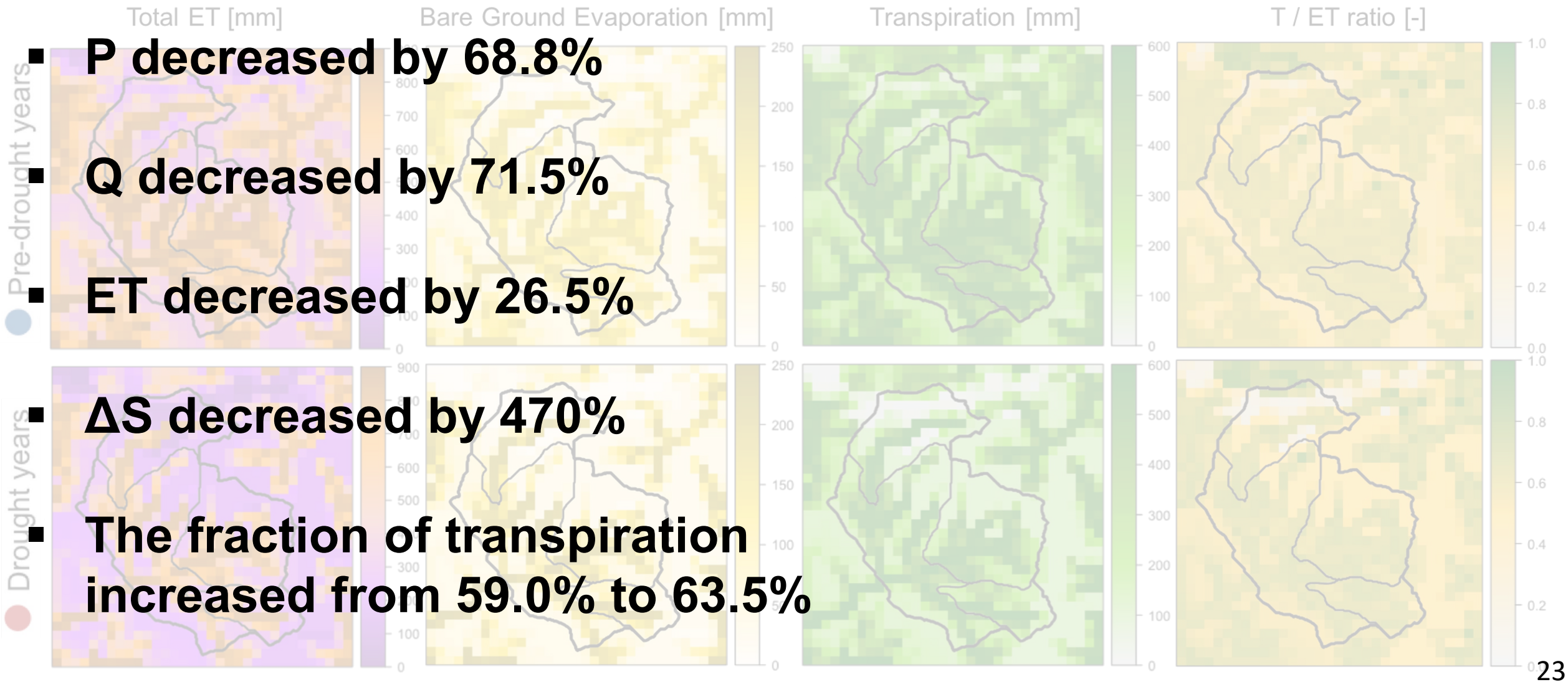


Evapotranspiration components can be explored spatially

P300 T/ET increased from an annual average of 59.0% during the pre-drought period to 63.5% annual average during the drought period.

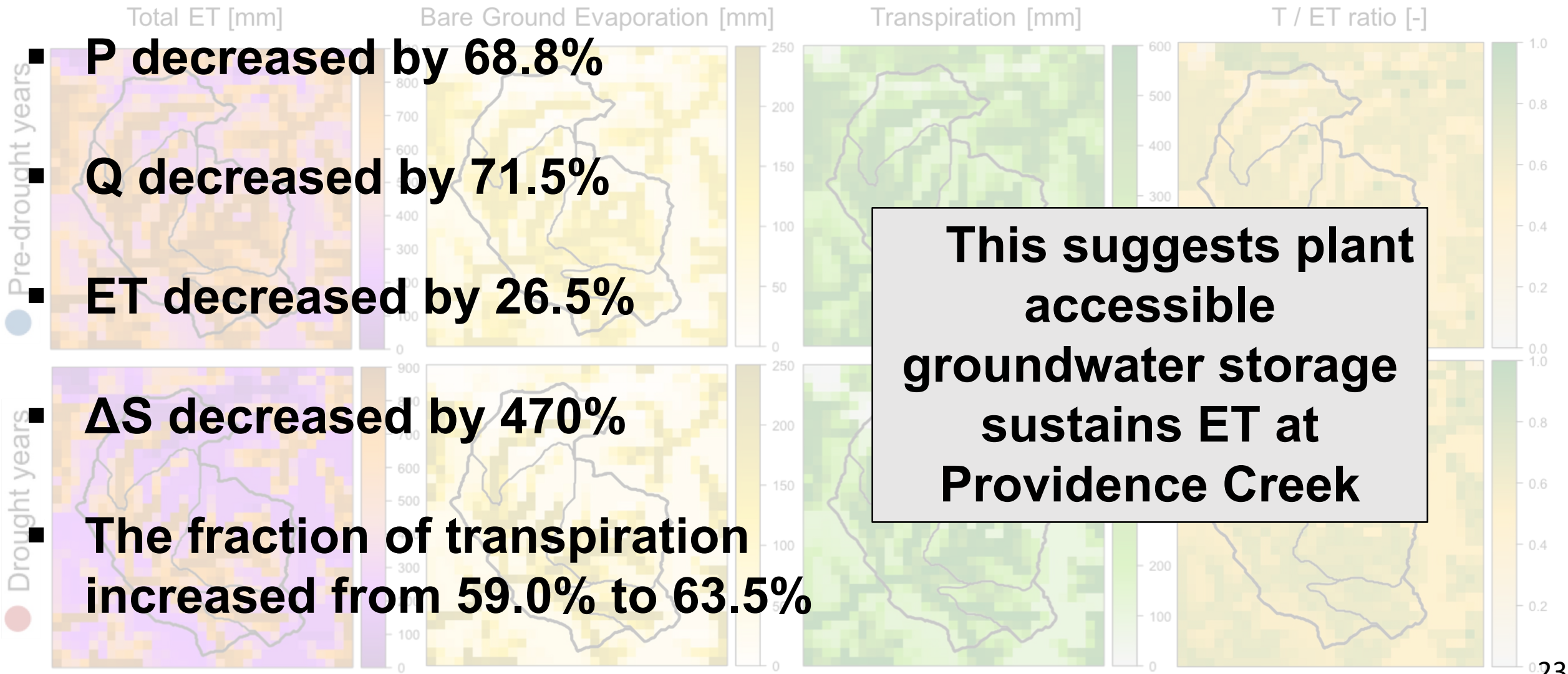


Evapotranspiration components can be explored spatially



- P decreased by 68.8%
- Q decreased by 71.5%
- ET decreased by 26.5%
- ΔS decreased by 470%
- The fraction of transpiration increased from 59.0% to 63.5%

Evapotranspiration components can be explored spatially



- P decreased by 68.8%
- Q decreased by 71.5%
- ET decreased by 26.5%
- ΔS decreased by 470%
- The fraction of transpiration increased from 59.0% to 63.5%

This suggests plant accessible groundwater storage sustains ET at Providence Creek

Heterogeneity is reality



Rocky outcrops

Meadows

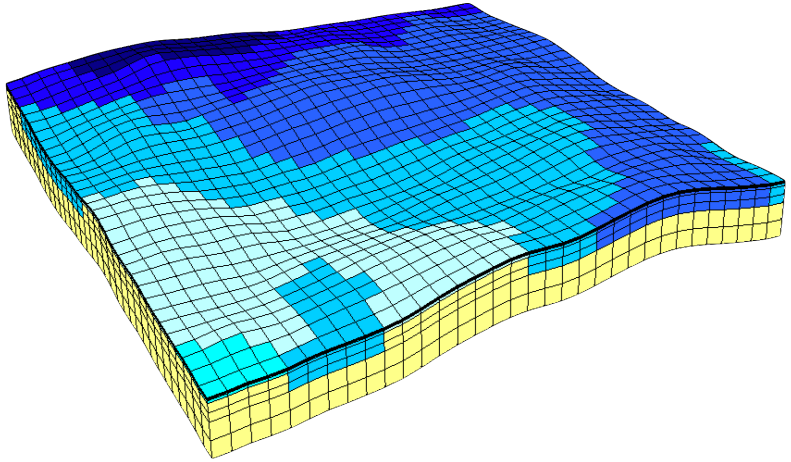




Variable soil

Subsurface sensitivity study to address uncertainty

Homogeneous Geology



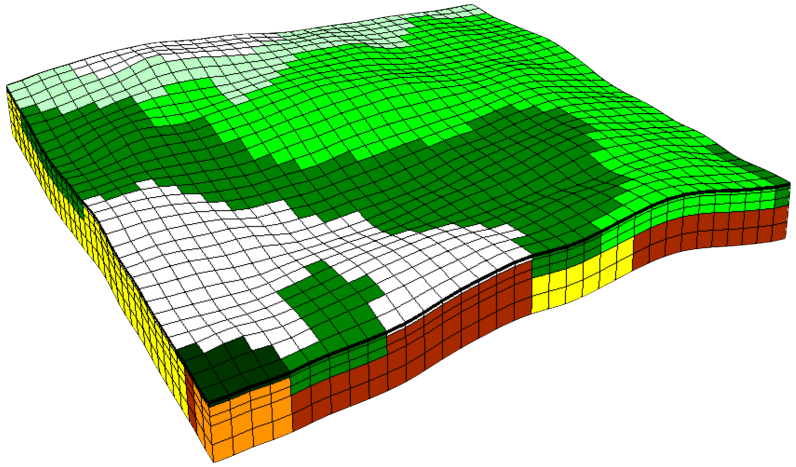
Soil

- 2.00×10^{-1} m/h
- 5.49×10^{-3} m/h
- 7.58×10^{-3} m/h
- 1.58×10^{-2} m/h
- 2.69×10^{-1} m/h
- 4.36×10^{-2} m/h

Geology

- 6.25×10^{-5} m/h
- 1.11×10^{-5} m/h
- 1.15×10^{-4} m/h
- 1.67×10^{-4} m/h

Double Permeability



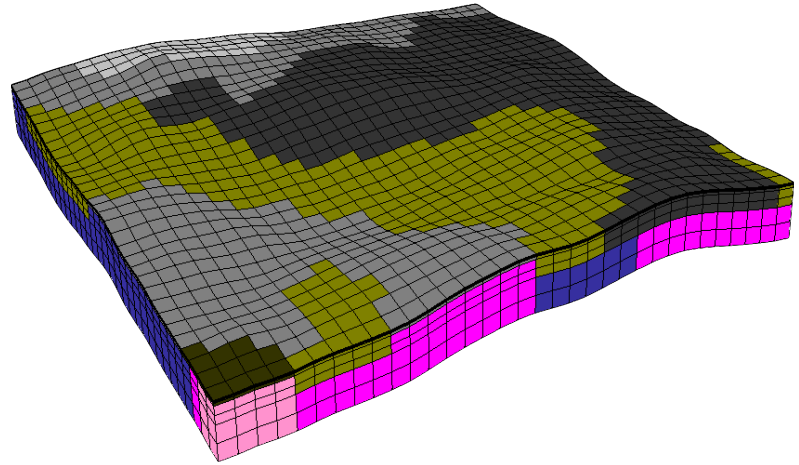
Soil

- 4.00×10^{-1} m/h
- 1.09×10^{-2} m/h
- 1.51×10^{-2} m/h
- 3.16×10^{-2} m/h
- 5.38×10^{-1} m/h
- 8.72×10^{-2} m/h

Geology

- 1.25×10^{-4} m/h
- 2.22×10^{-5} m/h
- 2.30×10^{-4} m/h
- 3.34×10^{-4} m/h

Quadruple Permeability

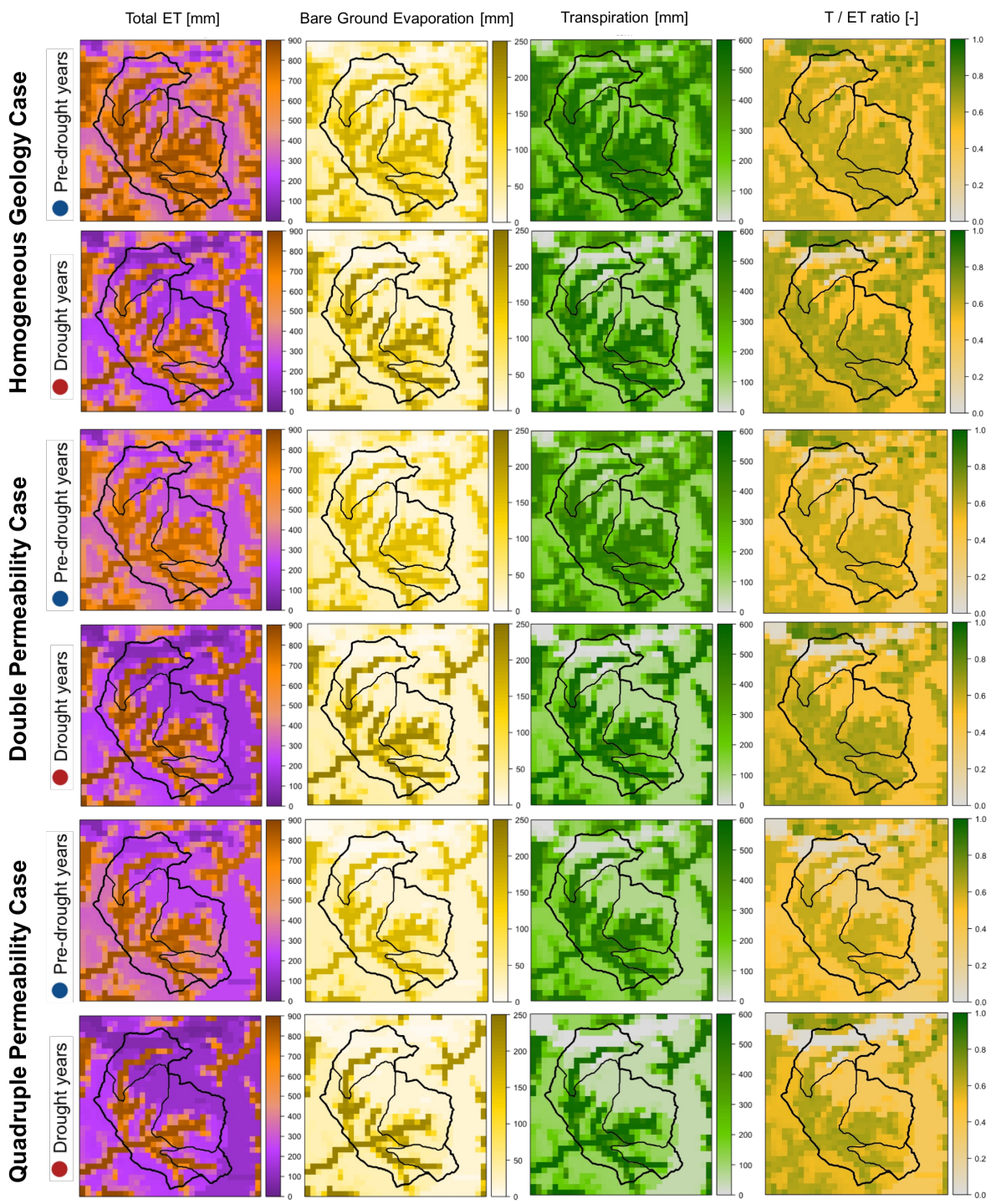


Soil

- 8.00×10^{-1} m/h
- 2.19×10^{-2} m/h
- 3.03×10^{-2} m/h
- 6.32×10^{-2} m/h
- 1.07×10^{0} m/h
- 1.74×10^{-1} m/h

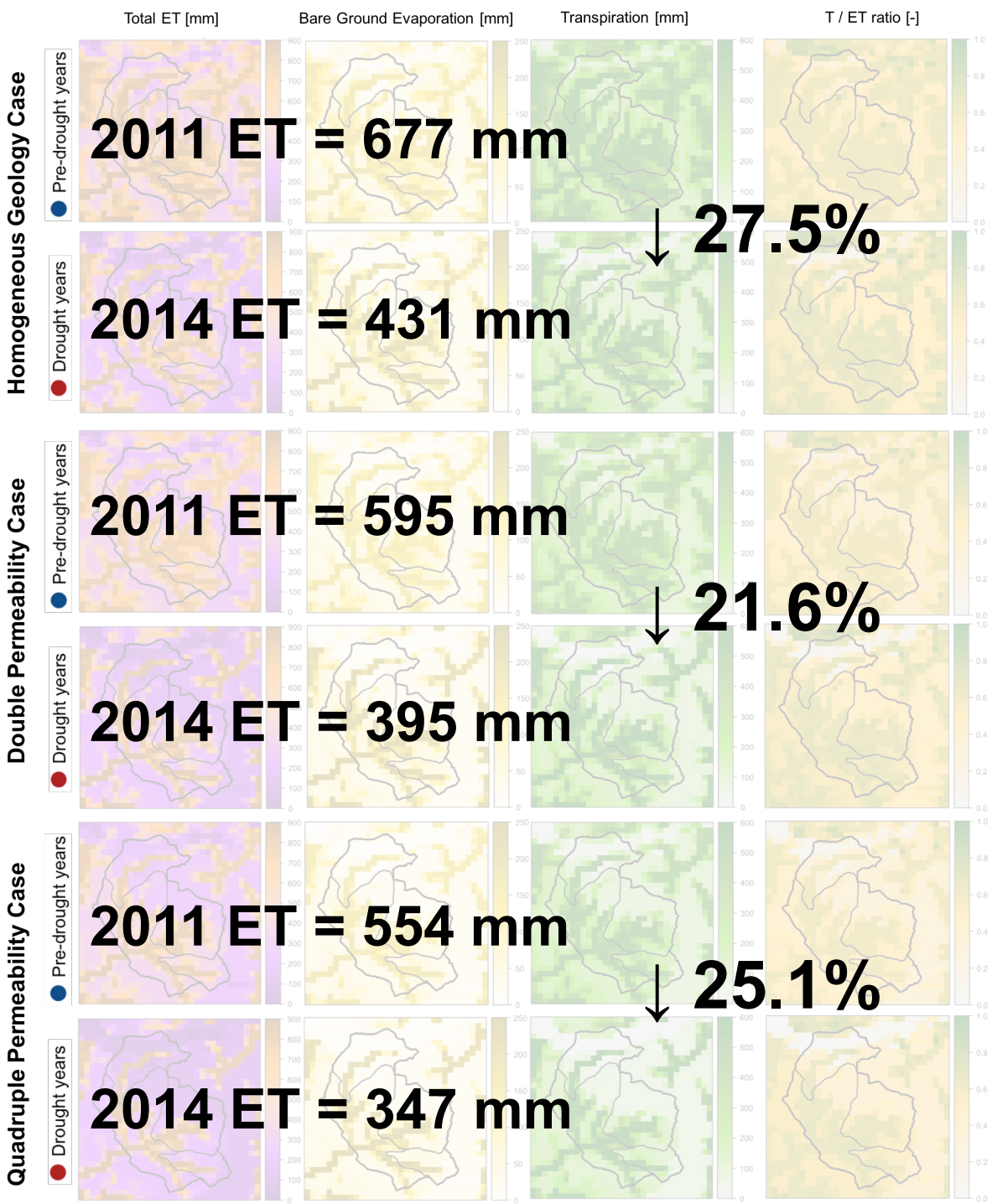
Geology

- 2.50×10^{-4} m/h
- 4.44×10^{-5} m/h
- 4.60×10^{-4} m/h
- 6.68×10^{-4} m/h



Despite model inputs, *behavior is consistent* across all sensitivity runs

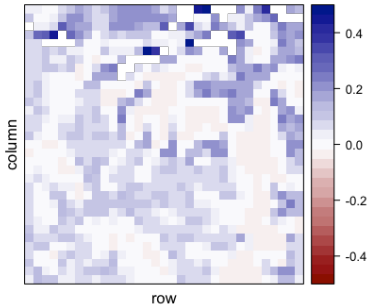
- **Transpiration:** Plant water stress is most pronounced in the ridges
- **Bare ground evaporation:** During the drought period, water-limited regions (ridges) decrease while not water-limited regions (convergence zones) increase



Despite model inputs, *behavior is consistent* across all sensitivity runs

Just a note…

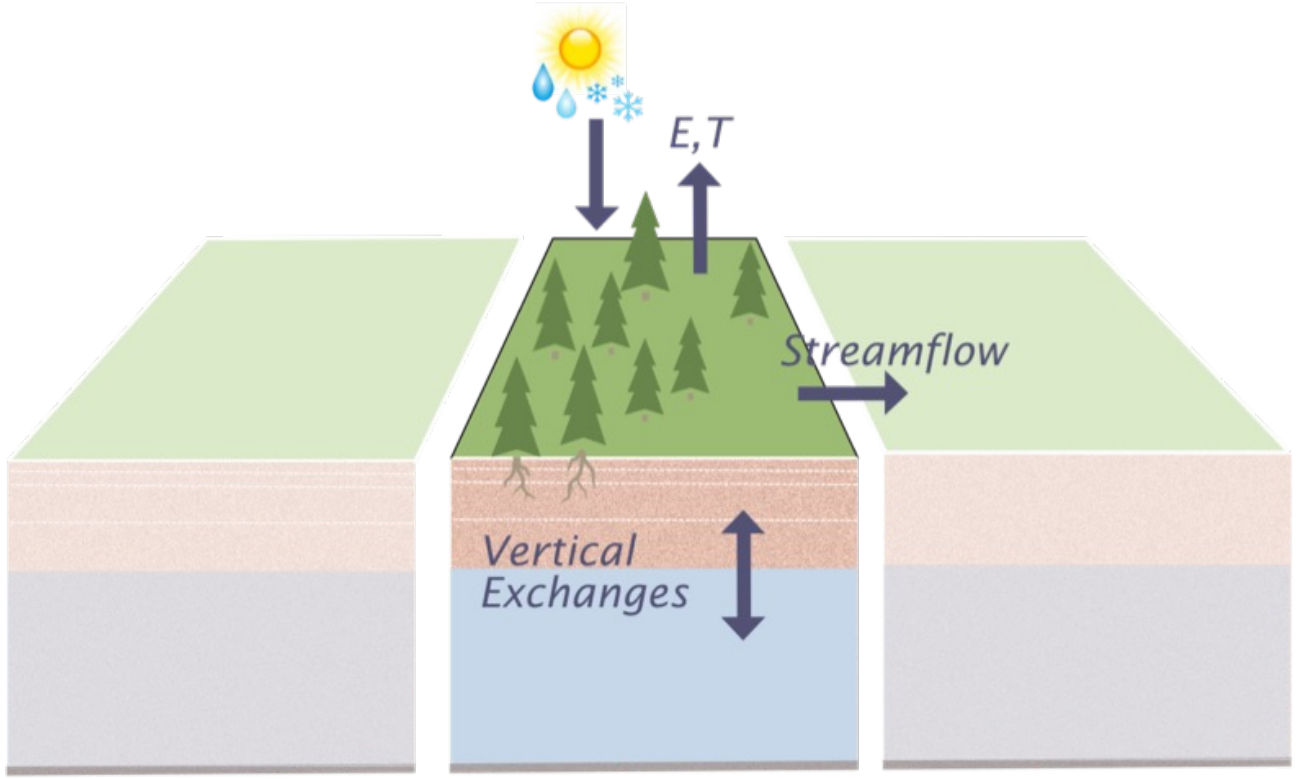
Compared to the Base Case, Homogeneous Geology Case ET component estimates vary for sub-watersheds (P301, P303, P304) but are the same for P300. This result suggests that at the P300 scale, capturing heterogeneity is less important for ET.



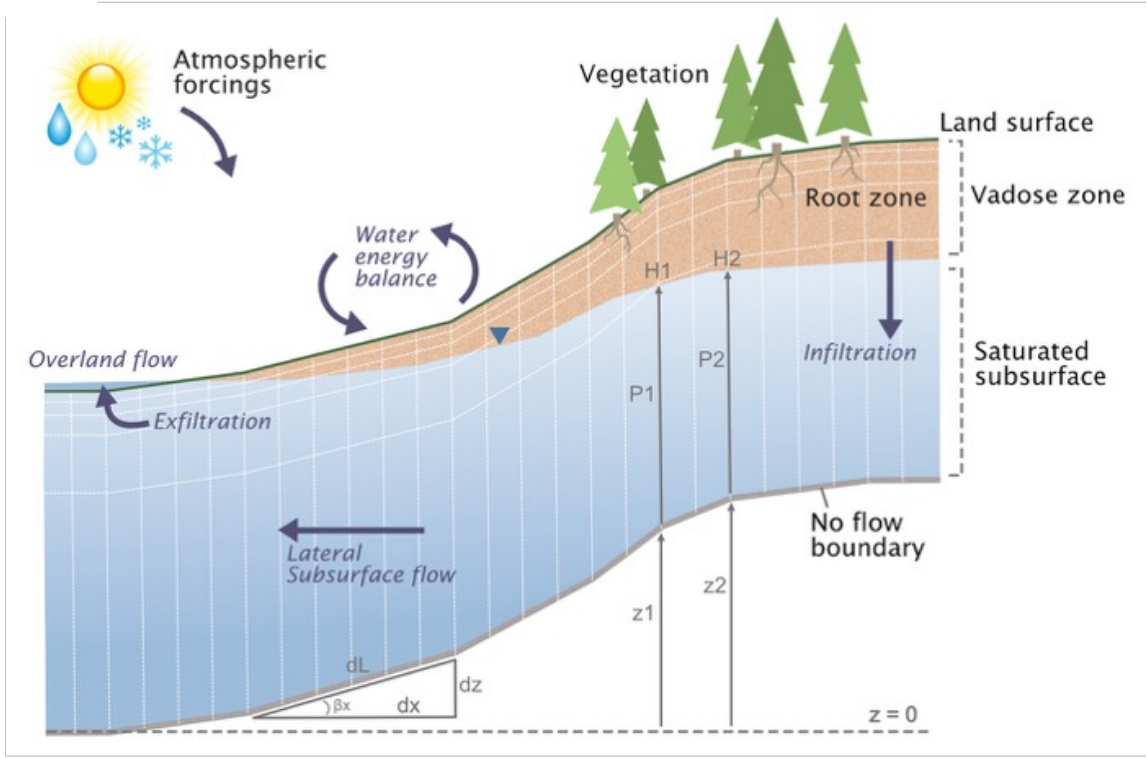
What is the effect of lateral groundwater flow on plant water use through drought?

ParFlow flexibility allows us to imitate traditional land surface models

Traditional LSM

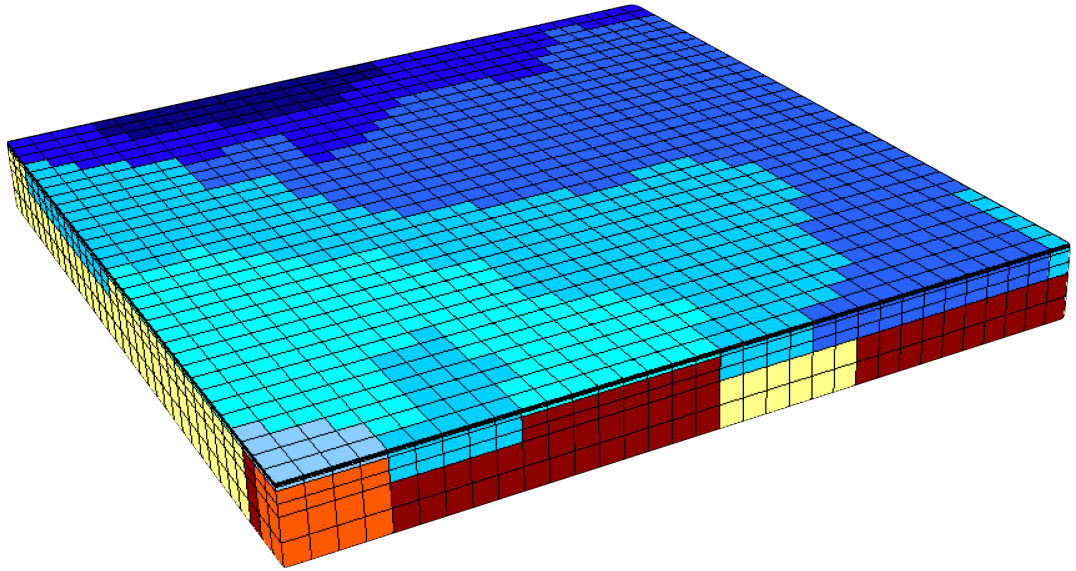


Integrated,
Physically-based Model

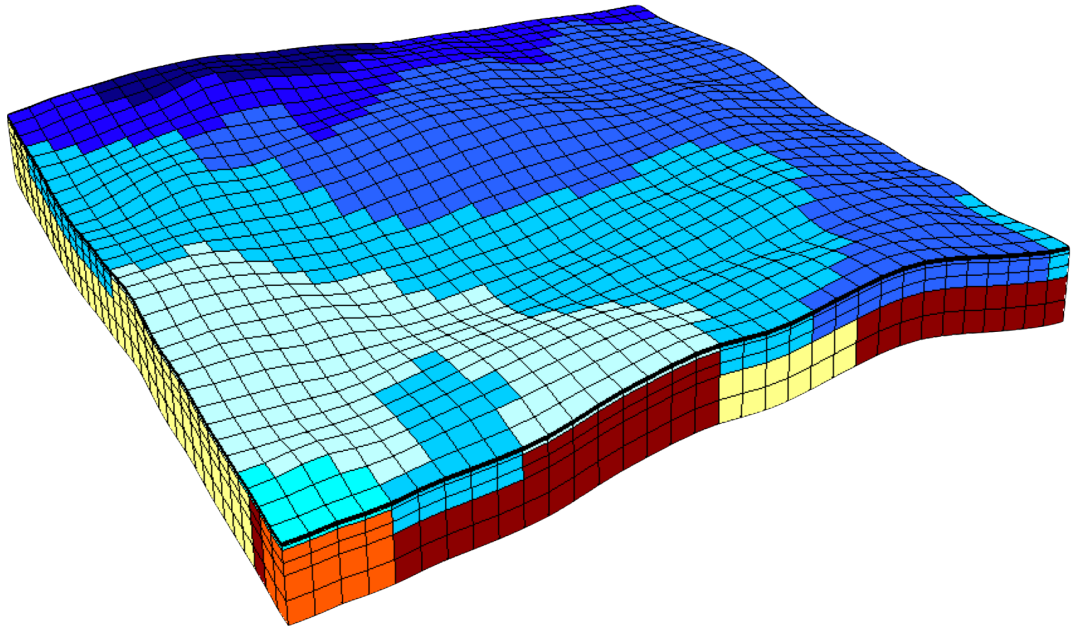


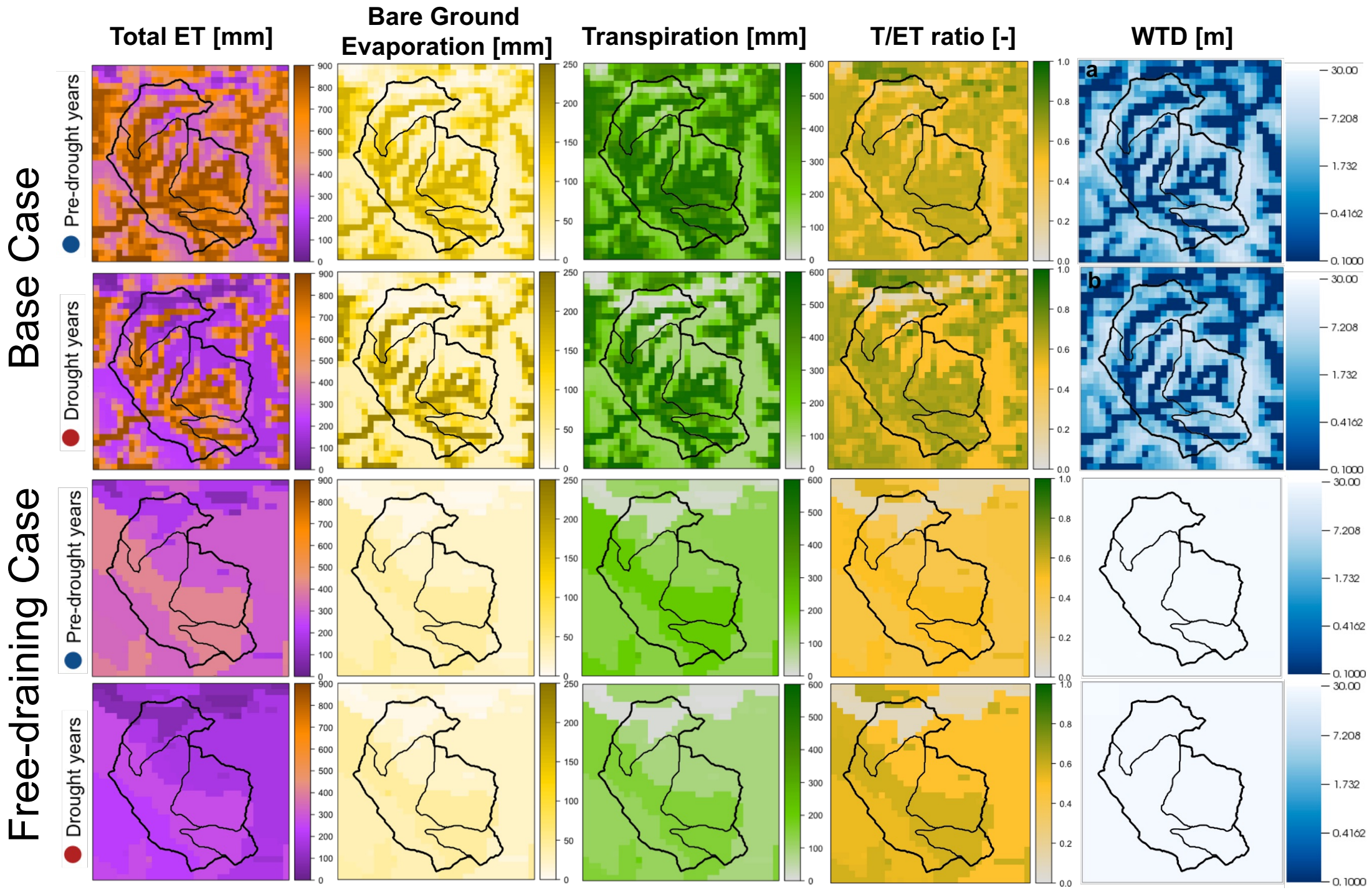
Numerical experiments to assess the effects of incorporating lateral groundwater flow in hydrology models

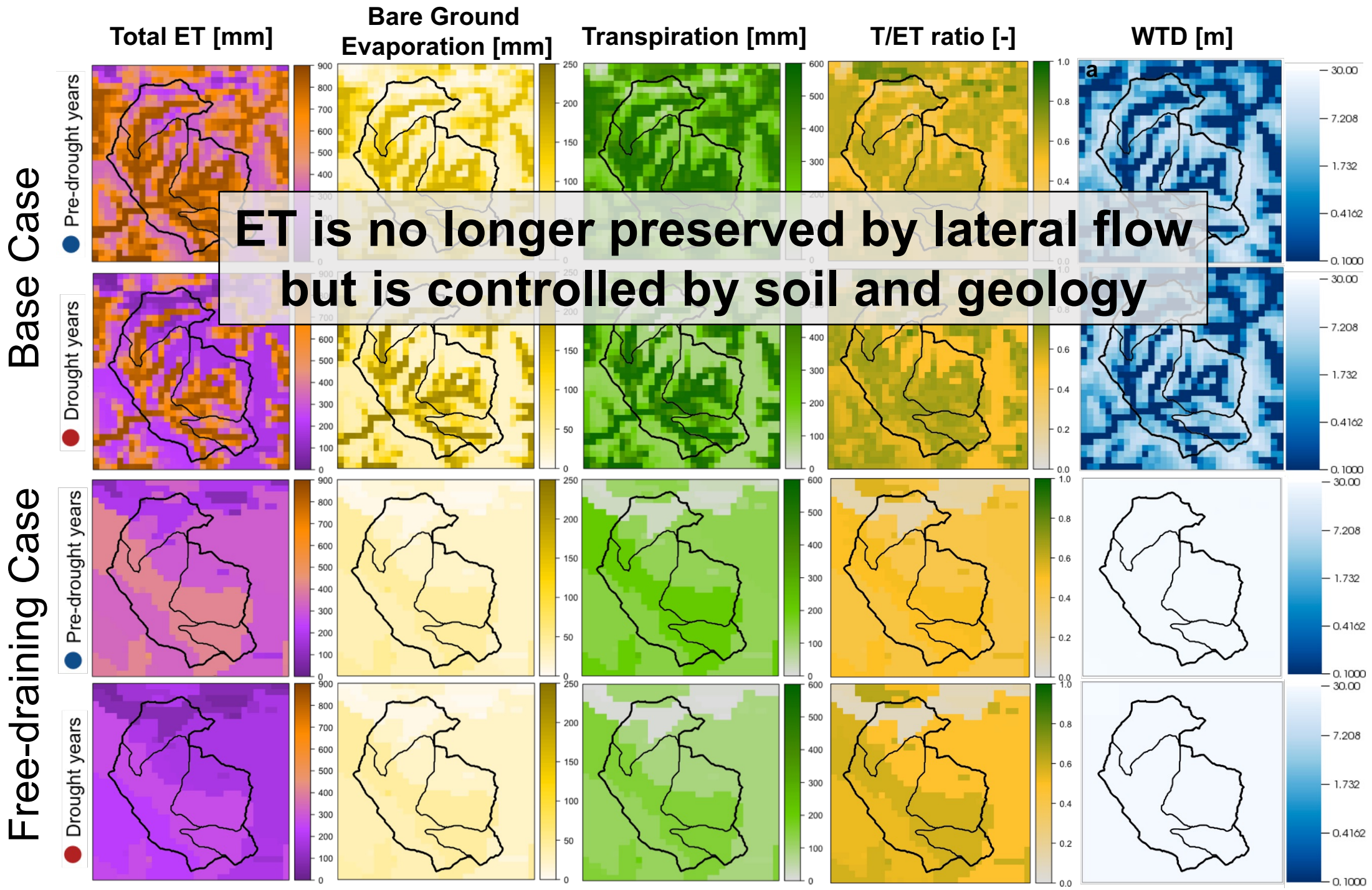
Free-draining Case

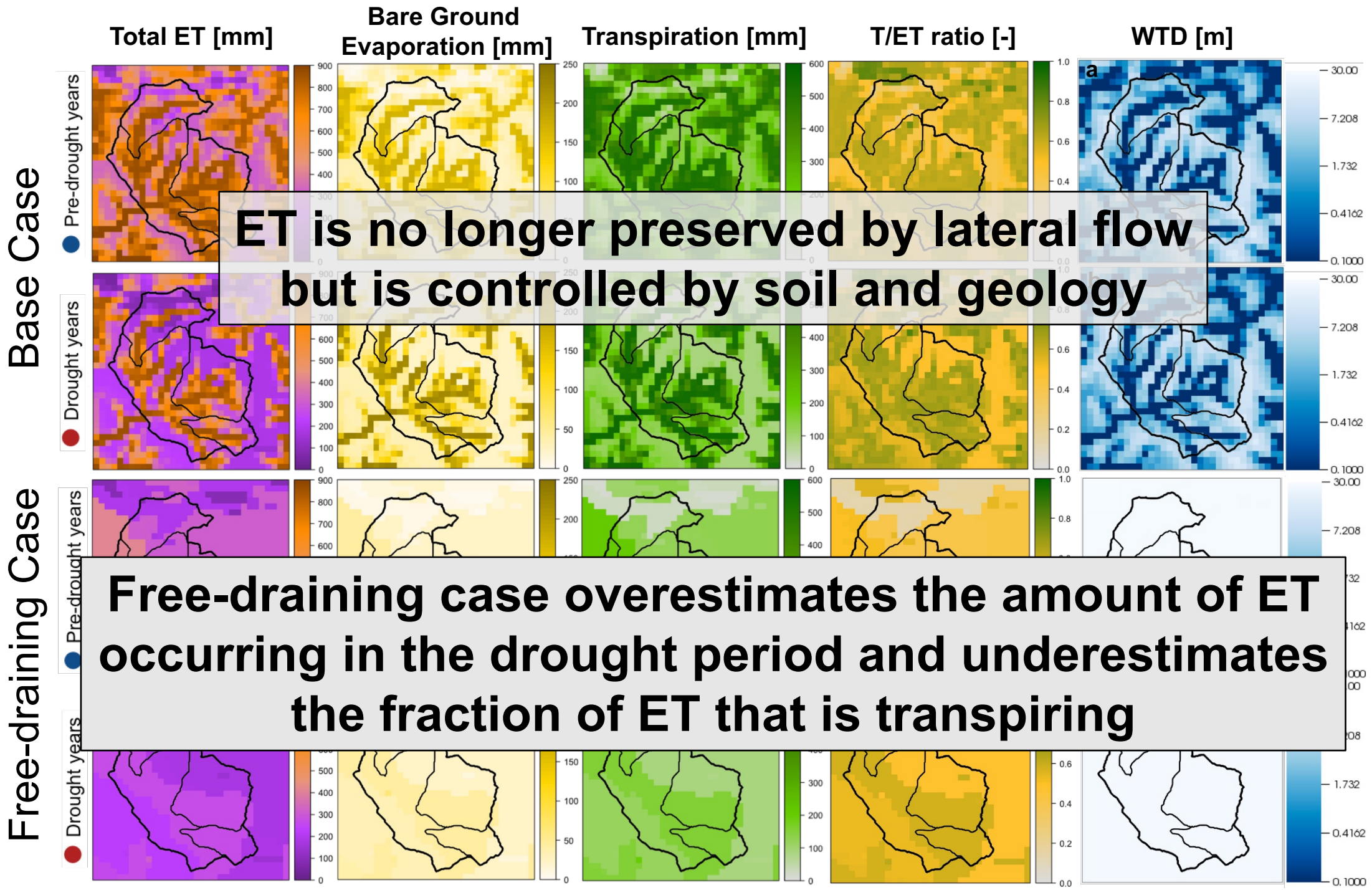


Base Case

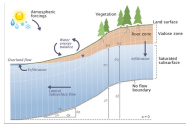



Total ET [mm]
Bare Ground Evaporation [mm]
Transpiration [mm]
T/ET ratio [-]
WTD [m]
Base Case
Free-draining Case
Pre-drought years
Drought years
Pre-drought years
Drought years
a
b
900
800
700
600
500
400
300
200
100
0
250
200
150
100
50
0
600
500
400
300
200
100
0
1.0
0.8
0.6
0.4
0.2
0.0
30.00
7.208
1.732
0.4162
0.1000


Total ET [mm]
Bare Ground Evaporation [mm]
Transpiration [mm]
T/ET ratio [-]
WTD [m]
Base Case
Free-draining Case
Pre-drought years
Drought years
Pre-drought years
Drought years
a
ET is no longer preserved by lateral flow
but is controlled by soil and geology

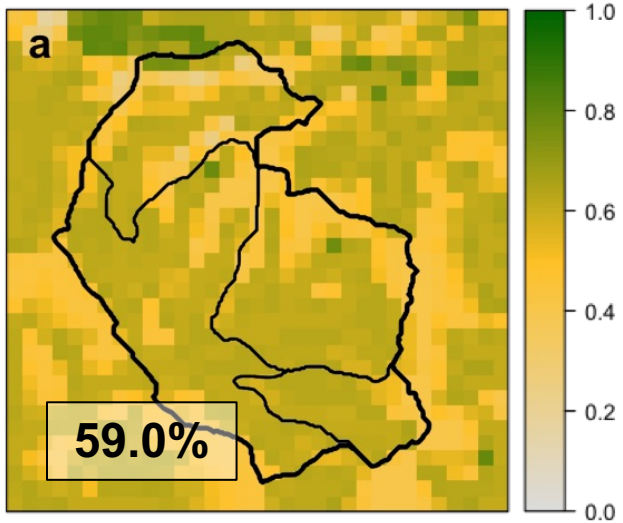

Total ET [mm]
Bare Ground Evaporation [mm]
Transpiration [mm]
T/ET ratio [-]
WTD [m]
Base Case
Free-draining Case
Pre-drought years
Drought years
Pre-drought years
Drought years
a
ET is no longer preserved by lateral flow but is controlled by soil and geology
Free-draining case overestimates the amount of ET occurring in the drought period and underestimates the fraction of ET that is transpiring

Incorporating lateral flow shows us *why* GW maintains transpiration through drought

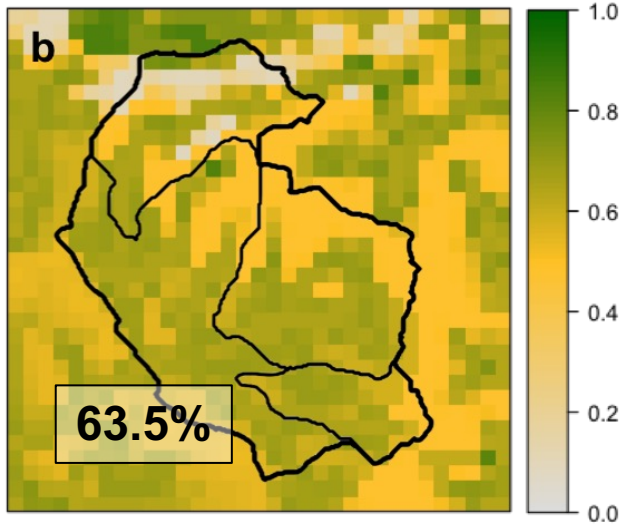


Base Case

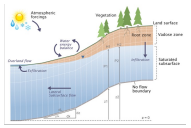
Pre-drought



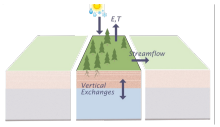
Drought



Incorporating lateral flow shows us *why* GW maintains transpiration through drought



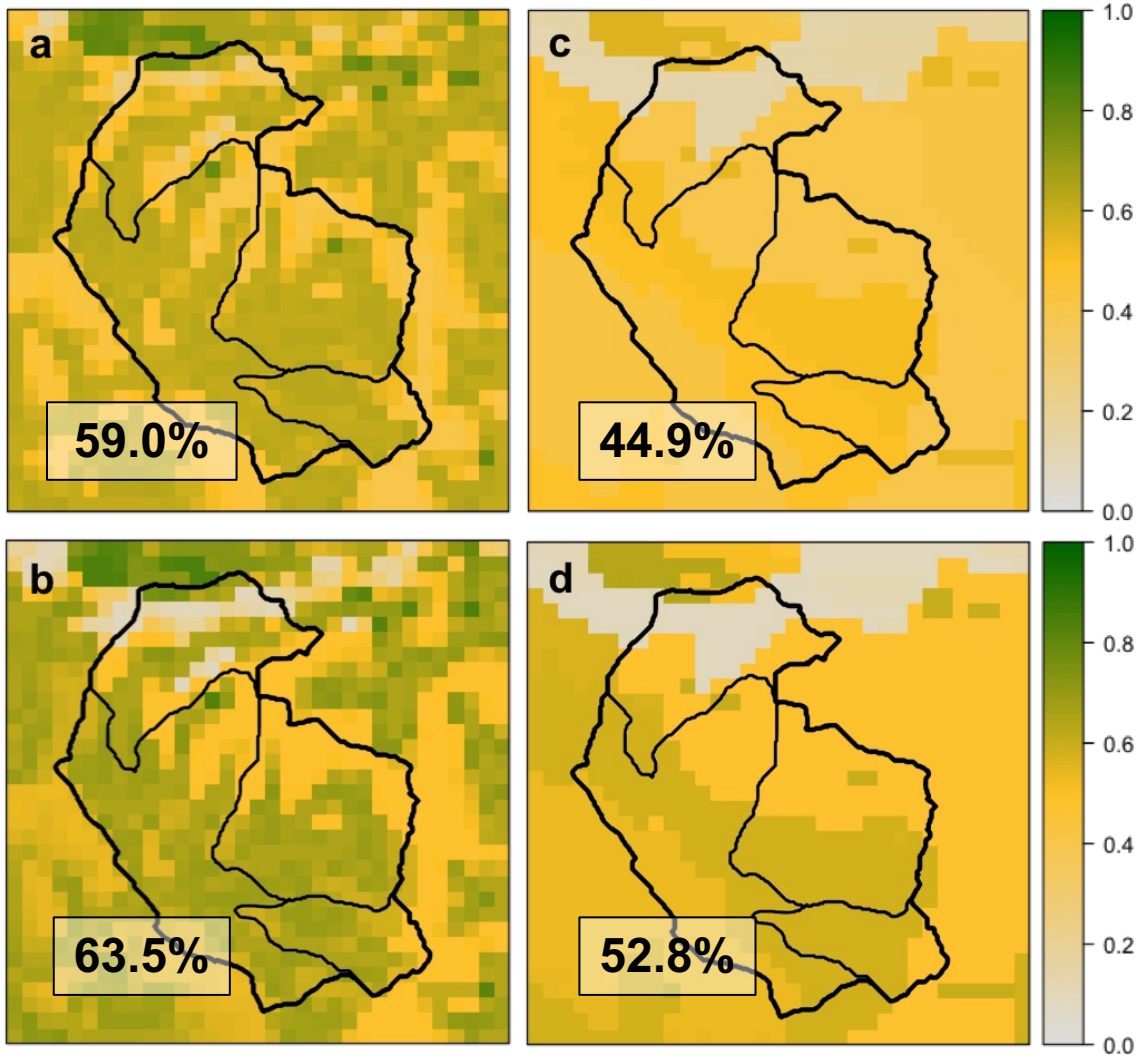
Base Case



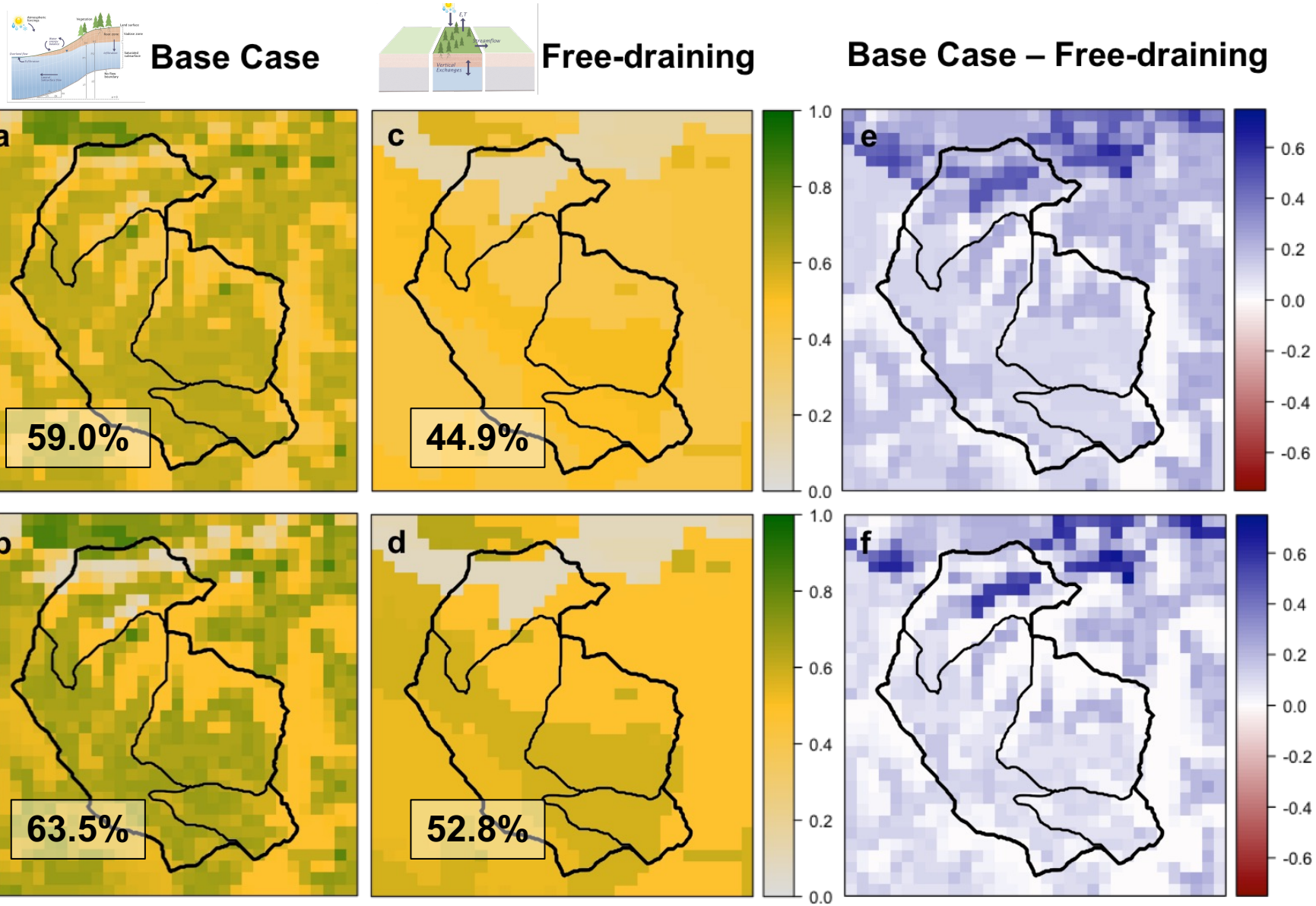
Free-draining

Pre-drought

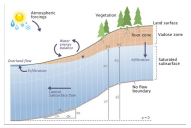
Drought

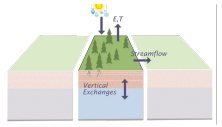


Incorporating lateral flow shows us *why* GW maintains transpiration through drought

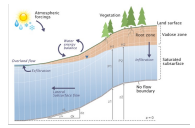


Incorporating lateral flow shows us *why* GW maintains transpiration through drought


Base Case


Free-draining

Base Case – Free-draining


Base Storage [m³]

Pre-drought

Drought

a

b

c

d

e

f

g

h

59.0%

63.5%

44.9%

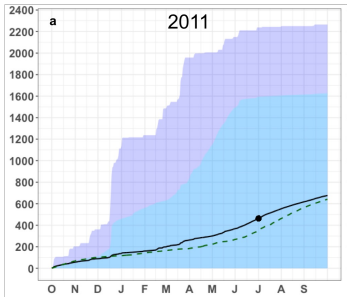
52.8%

1.0
0.8
0.6
0.4
0.2
0.0

0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6

150000
140000
130000
120000
110000
100000
90000
80000
70000
60000

Conclusions

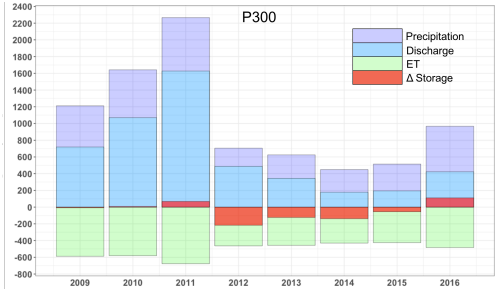


Can we use integrated physically-based models to accurately represent mountain hydrology?

1. Yes, integrated models accurately represent catchment behavior during drought

2. Integrated models can help bracket evapotranspiration (ET) estimates

Conclusions

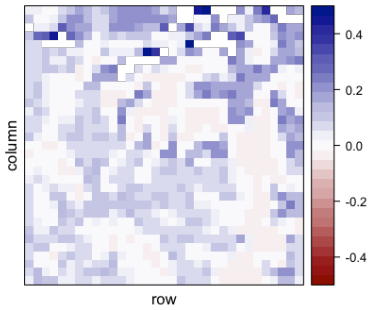


Is groundwater the missing link in understanding plant water use?

1. In my model simulations, groundwater storage is sustaining ET through drought

2. ET partitioning relationships with water table depth (WTD) should be used as tools to identify areas of plant water stress

Conclusions

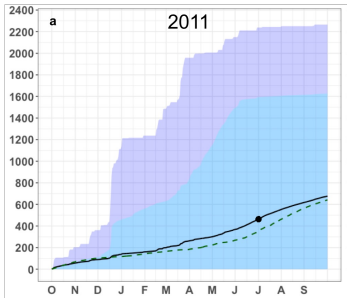


What is the effect of lateral groundwater flow on plant water use through drought?

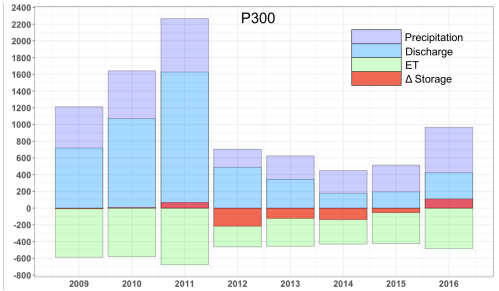
1. Incorporating lateral groundwater flow more accurately represents catchment behavior and response to drought

2. Lateral groundwater flow is the mechanism explaining how groundwater maintains transpiration through drought

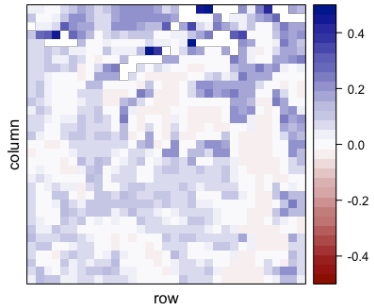
Takeaways



Integrated models accurately represent catchment behavior and help to bracket ET estimates

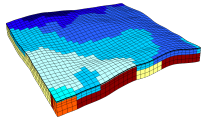


In my model simulations, groundwater storage is sustaining ET through drought

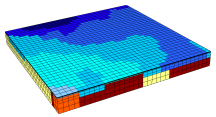


This suggests, lateral groundwater flow is the mechanism explaining how groundwater maintains transpiration through drought

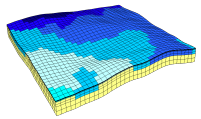
Future work



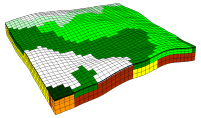
Decrease lateral and vertical grid resolution



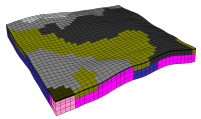
Further develop weathered bedrock (regolith) heterogeneity



Develop a more robust and site-unique meteorology



Incorporate dynamic vegetation



Particle tracking to identify plant water source and pathways

Acknowledgements



Lawrence Livermore National Lab



Department of Energy



Southern Sierra Critical Zone Observatory



Maxwell Research Group

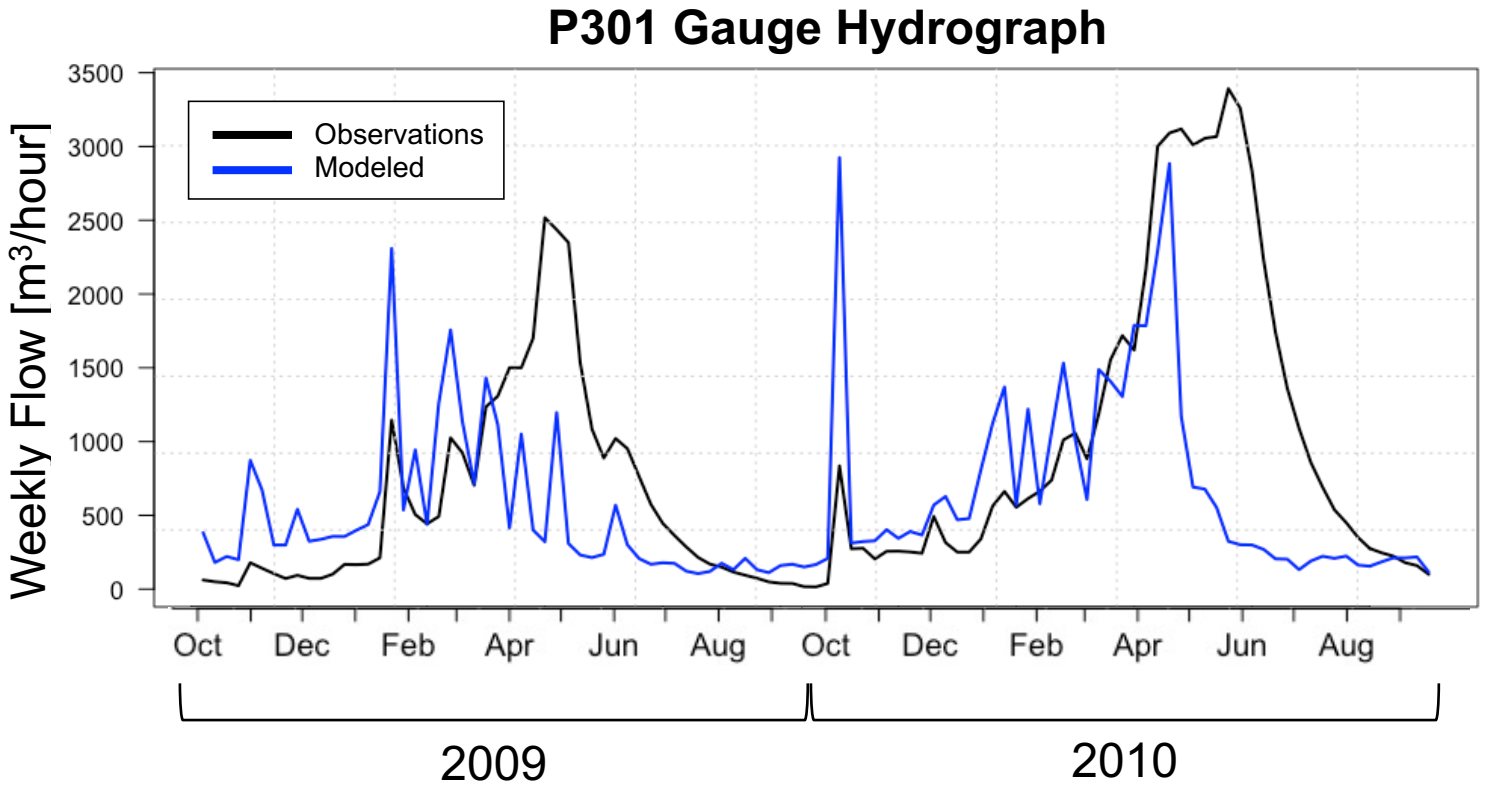
Thank you!
Questions?



Providence Creek watershed from the Upper MET station
Photo: SSCZO

Extra Slides

Stream behavior timing and baseflow magnitude is well-represented, despite precipitation bias

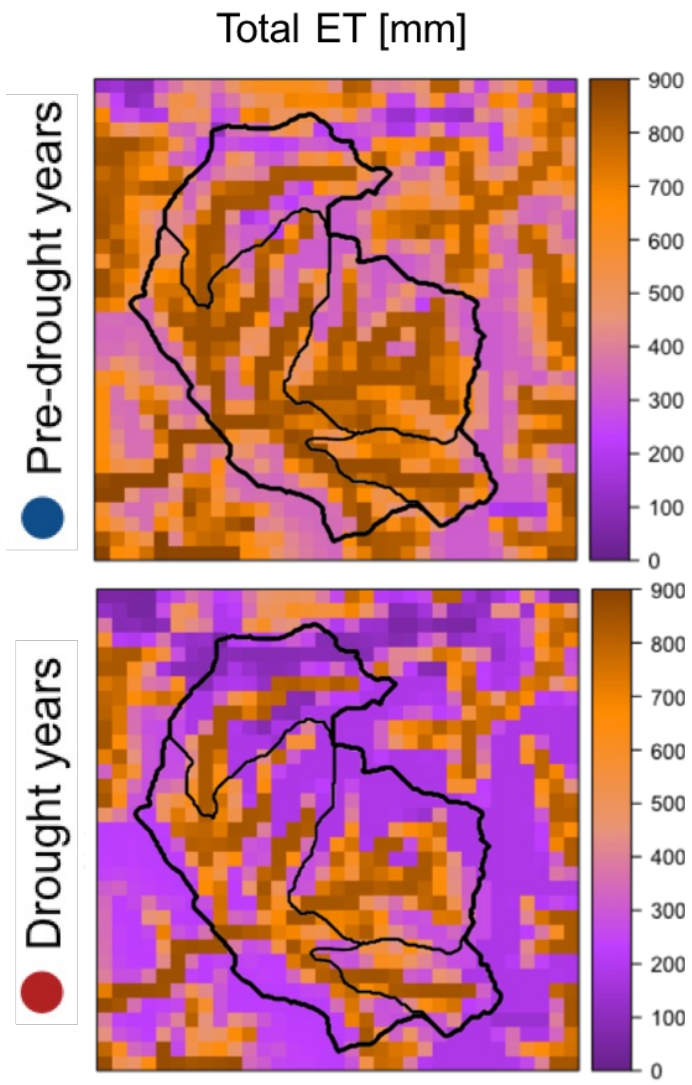


ParFlow underestimates 2009 flow volume by 17% and NLDAS-II underestimates precipitation volume at the lower MET station (near P301 gauge) by 25%

Water Balance for P300, P301, P303, P304, and Domain

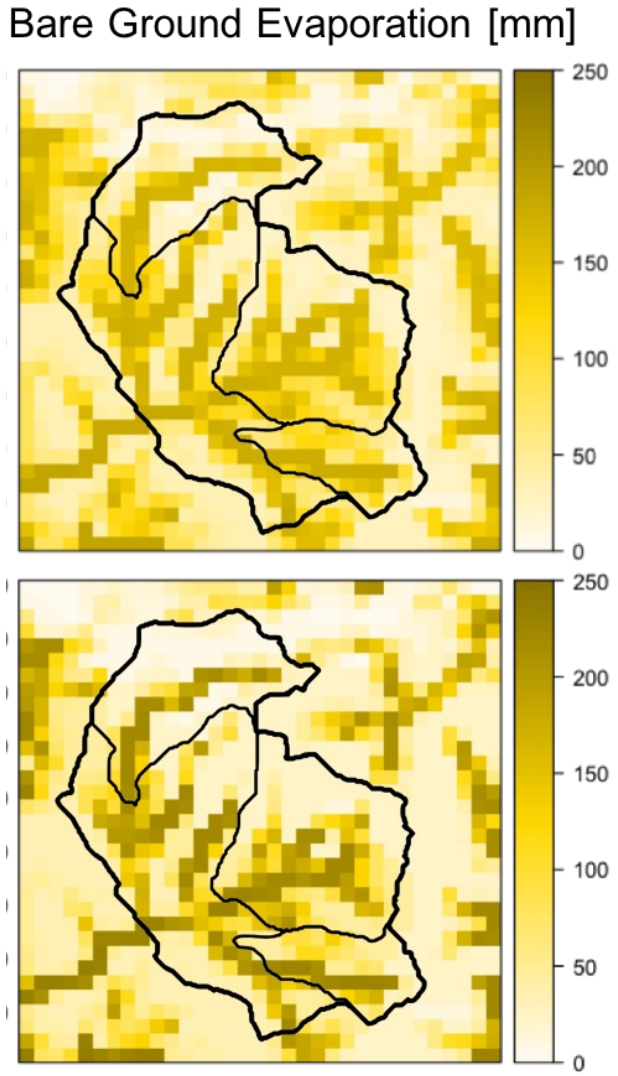
Water Balance Component	Model	Pre-Drought Years					Drought Years				
		P300	P301	P303	P304	Domain	P300	P301	P303	P304	Domain
Precipitation [mm]	NLDAS-II Precip	1706	1718	1713	1695	1706	652	657	652	647	653
Bare Ground Evaporation [mm]	Base Case	94	81	94	106	80	93	80	92	102	77
	Free-draining Case	33	23	35	42	29	32	22	33	39	28
	Homogeneous Geology Case	95	82	95	107	81	92	79	92	101	76
	Double Permeability Case	79	66	77	85	66	86	71	82	88	70
	Quadruple Permeability Case	67	54	62	68	56	73	62	64	73	59
Transpiration [mm]	Base Case	363	324	361	407	335	287	245	288	316	257
	Free-draining Case	157	112	167	192	140	115	77	121	142	103
	Homogeneous Geology Case	366	326	364	411	337	285	243	285	313	254
	Double Permeability Case	293	255	284	322	267	258	207	247	270	224
	Quadruple Permeability Case	248	199	234	260	220	211	170	186	210	179
Total Evapotranspiration [mm]	Base Case	615	561	613	672	568	452	396	452	490	403
	Free-draining Case	350	293	359	392	323	218	169	224	252	200
	Homogeneous Geology Case	619	564	616	677	571	449	394	449	486	401
	Double Permeability Case	529	477	517	565	486	415	349	401	431	364
	Quadruple Permeability Case	474	411	455	488	429	355	303	321	353	307
Runoff [mm]	Base Case	1139	77	1026	1581	536	325	13	282	443	157
	Free-draining Case	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Homogeneous Geology Case	1141	77	1030	1589	537	426	21	374	586	203
	Double Permeability Case	1170	74	1013	1617	559	383	13	345	501	187
	Quadruple Permeability Case	1124	53	952	1390	549	480	9	433	511	246
Runoff Ratio [-]	Base Case	0.65	0.04	0.59	0.91	0.31	0.49	0.02	0.43	0.67	0.24
	Free-draining Case	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Homogeneous Geology Case	0.66	0.04	0.59	0.92	0.31	0.69	0.03	0.61	0.96	0.33
	Double Permeability Case	0.67	0.04	0.58	0.94	0.32	0.59	0.02	0.54	0.78	0.29
	Quadruple Permeability Case	0.65	0.03	0.55	0.80	0.32	0.76	0.01	0.69	0.80	0.39
Δ Storage [mm]	Base Case	23	21	46	37	16	-85	-66	-113	-98	-78
	Free-draining Case	978	945	941	987	985	-334	-346	-337	-326	-336
	Homogeneous Geology Case	19	19	39	28	11	-71	-52	-92	-81	-64
	Double Permeability Case	74	59	122	99	64	-108	-94	-141	-127	-102
	Quadruple Permeability Case	138	131	163	167	143	-152	-136	-181	-162	-158

Evapotranspiration components can be explored spatially



P300 ET decreased by 26.5% from an annual average of 615 mm during the pre-drought period to 452 mm annual average during the drought period

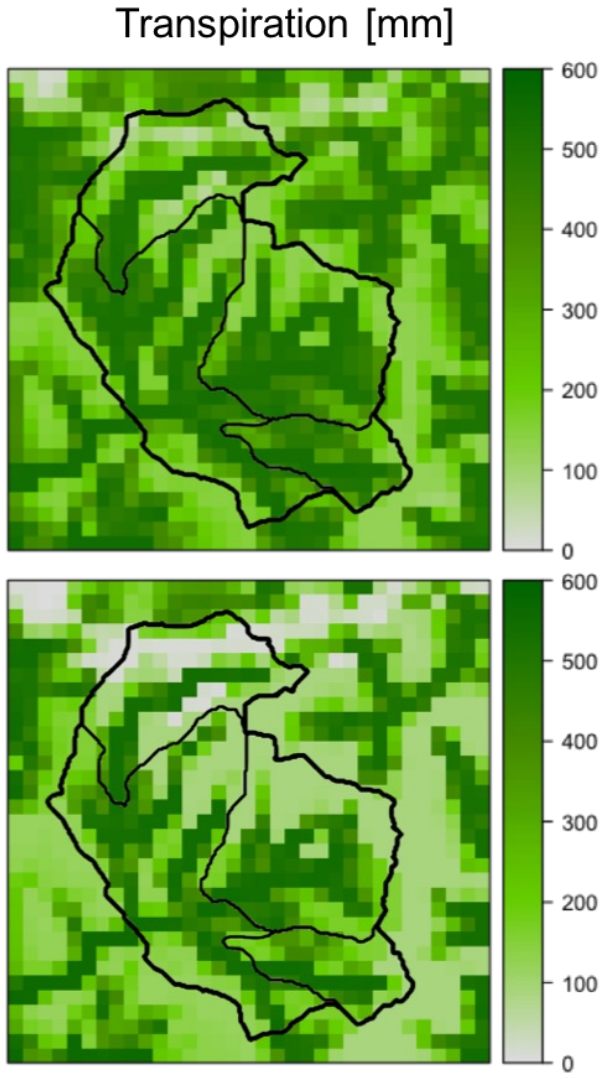
Evapotranspiration components can be explored spatially



P300 E decreased by 1.1% from an annual average of 94 mm during the pre-drought period to 93 mm annual average during the drought period

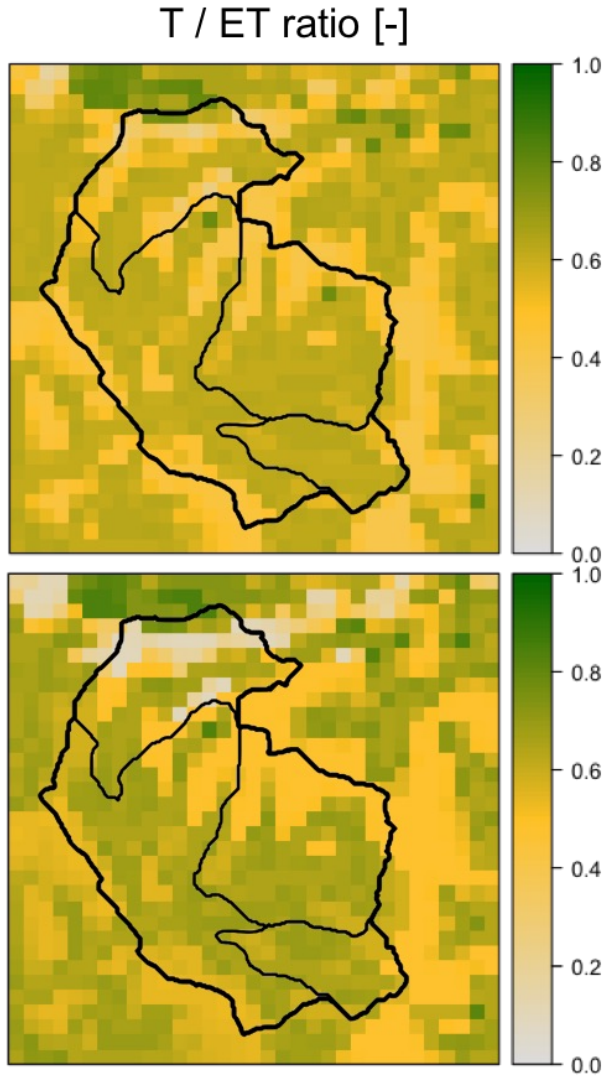
Evapotranspiration components can be explored spatially

P300 T decreased by 20.9% from an annual average of 363 mm during the pre-drought period to 287 mm annual average during the drought period

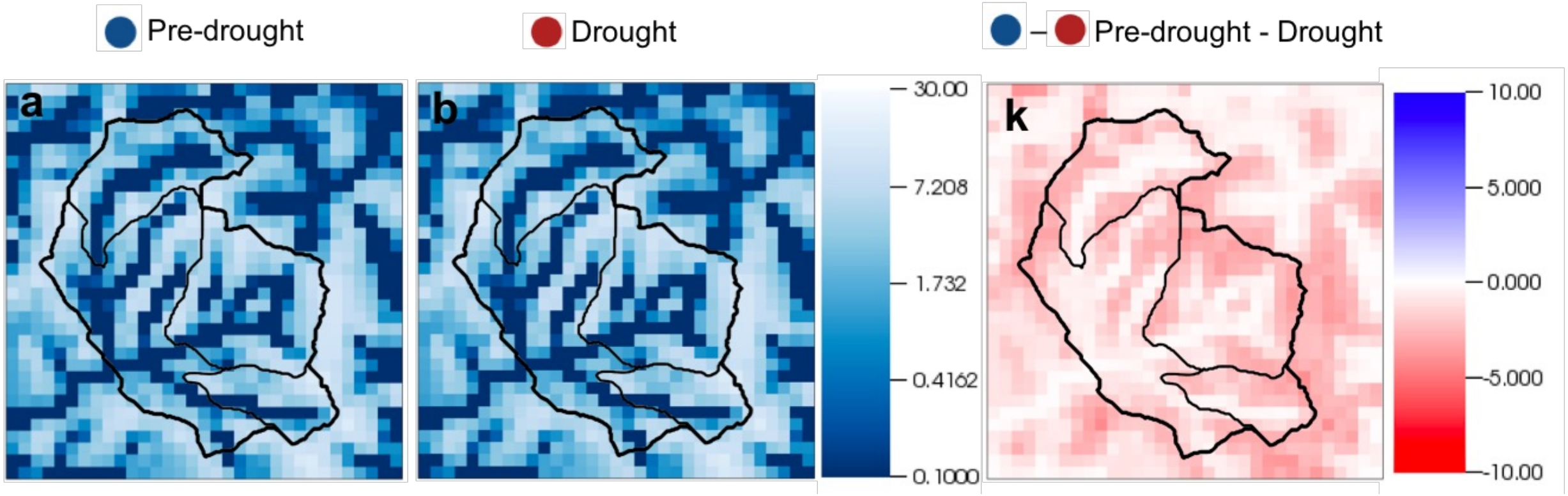


Evapotranspiration components can be explored spatially

P300 T/ET increased from an annual average of 59.0% during the pre-drought period to 63.5% annual average during the drought period.

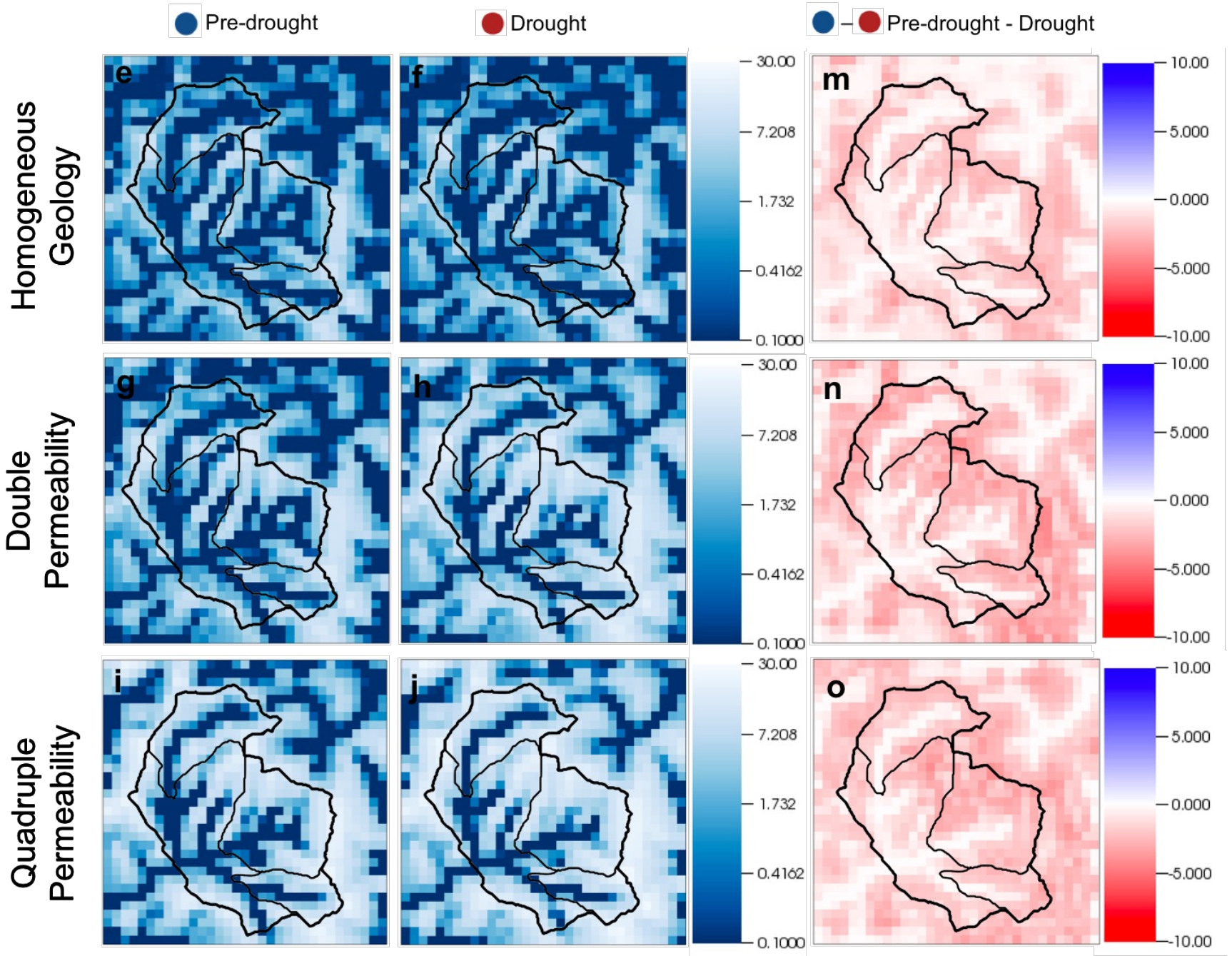


Despite large localized reductions in ridges, overall water table depth (WTD) response to drought conditions is negligible

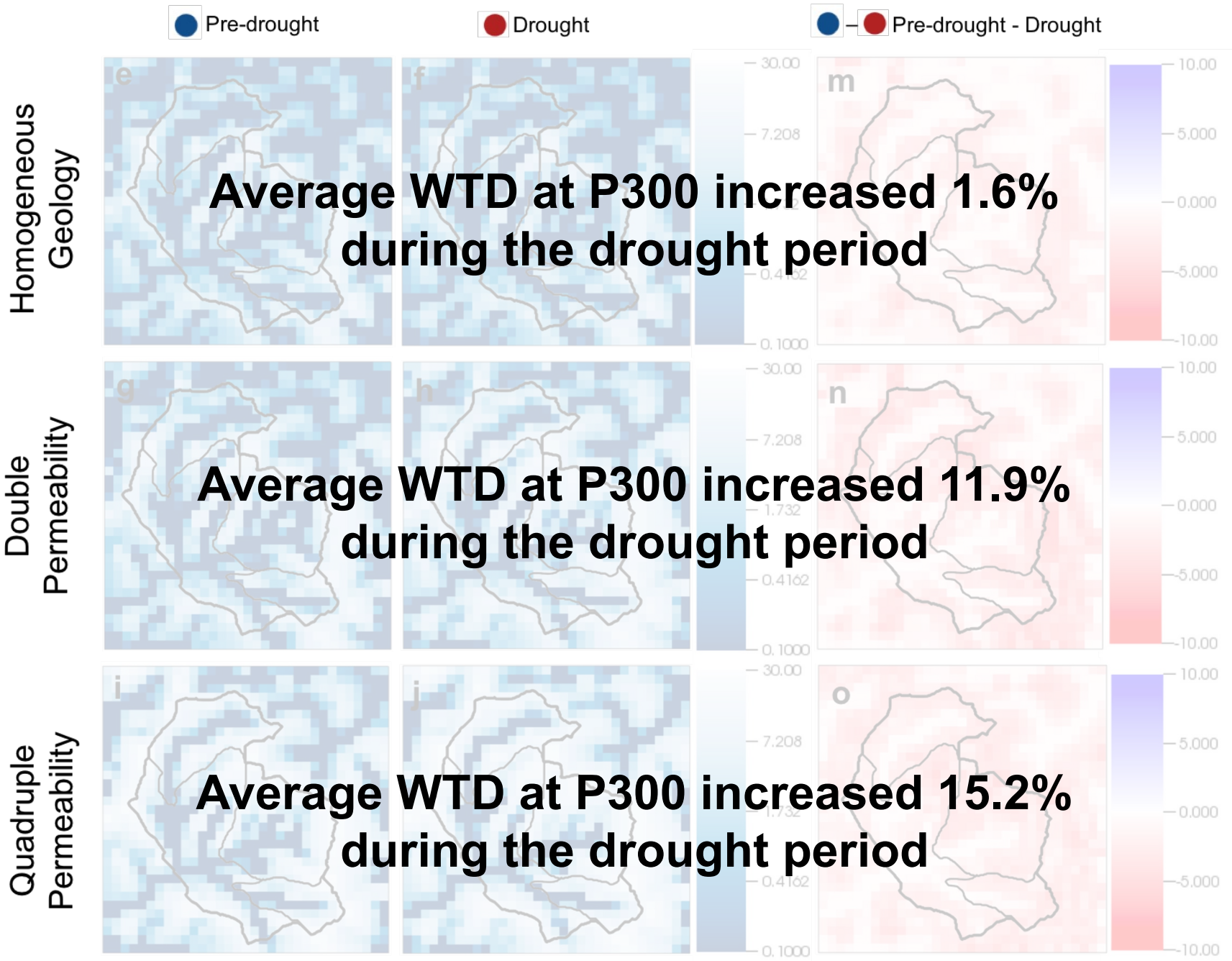


The average WTD at P300 increased 3.2% during the drought period

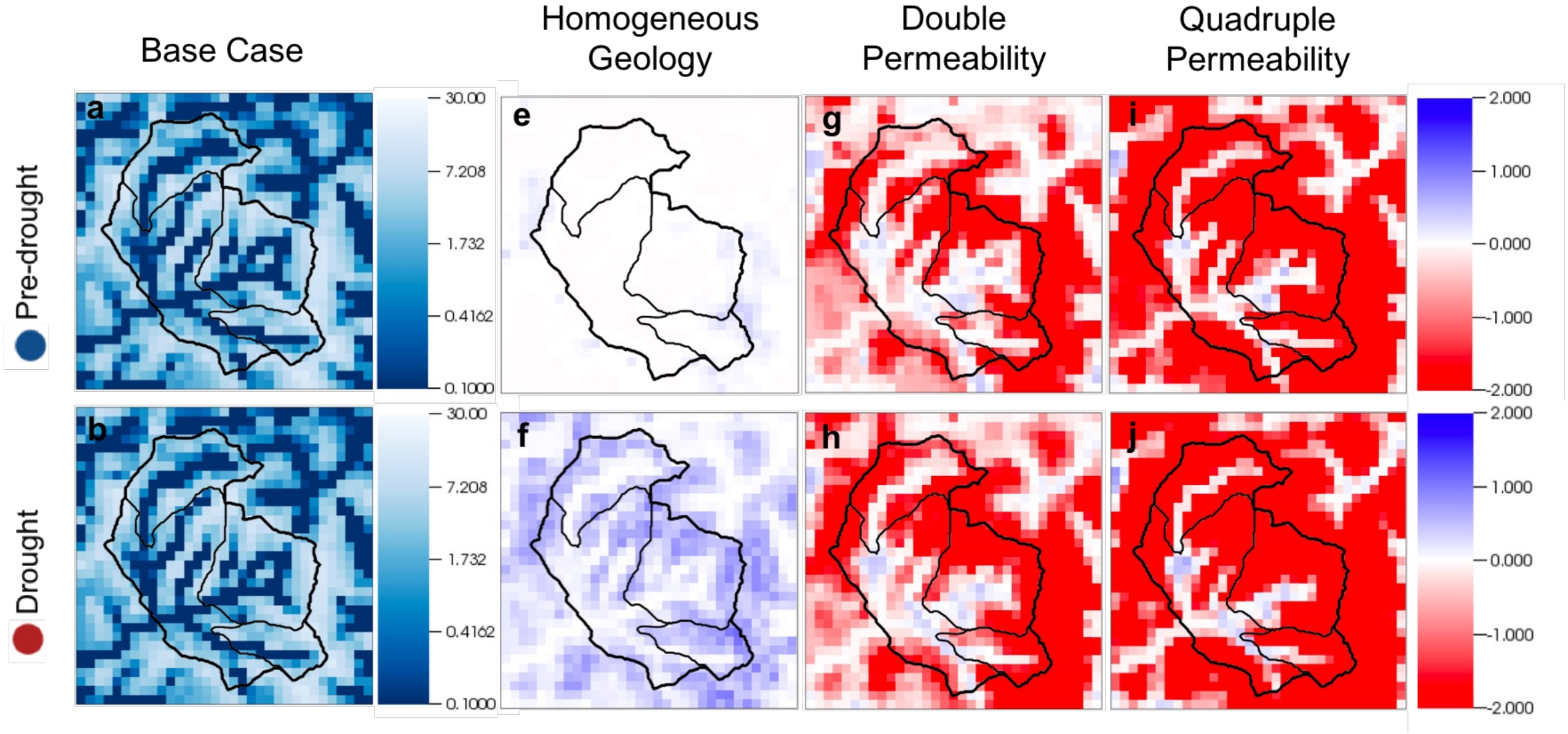
Water table depth (WTD) at P300 is sensitive to effective subsurface permeability but lateral groundwater flow maintains stream network through drought



Water table depth (WTD) at P300 is sensitive to effective subsurface permeability but lateral groundwater flow maintains stream network through drought



WTD depends on subsurface characterization



Free-draining case overestimates the amount of ET occurring in the drought period and underestimates the fraction of ET that is transpiring

