Geophysical Investigation of Slope Aspect Effect on Soil and Rock Moisture Interactions

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I. Introduction

Soil moisture: unsaturated water storage in soil/regolith
Rock moisture: unsaturated water storage in weathered and/or fractured bedrock

- Rock moisture governs plant-water availability and streamflow generation [1]
- **Spatiotemporal dynamics are still unclear**
- Incorporating rock moisture improves accuracy of hydrological models [2]
- Electrical resistivity tomography (ERT) allows for noninvasive observations of spatial and temporal trends in subsurface resistivity as a proxy for soil/rock moisture

II. Site Description/Methods

Dry Creek Experimental Watershed, Boise, Idaho, USA

- Semi-arid mountain watershed
- Regolith is result of in situ weathering of granodiorite bedrock [2]
- Bedrock is heavily fractured that leaks to very deep groundwater
- Vegetation at the Treeline site is mainly sagebrush, small bushes, and small grasses

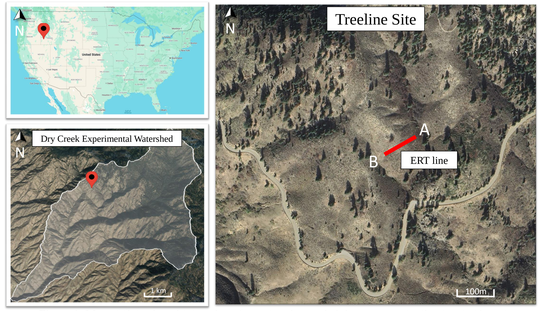

Figure 1: Map of field site with location of the electrical resistivity tomography line labeled in red

Treeline Site 2024 Water Year Meteorological Data

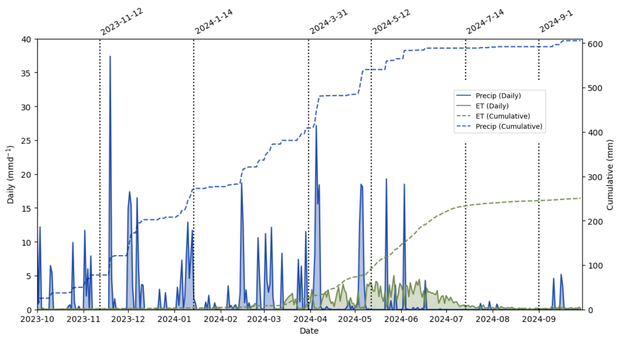

Figure 2: Meteorological data for the 2024 water year from the Treeline Site. Evapotranspiration was calculated using the Penmen-Monteith equation and the method in [3]. The vertical lines denote the dates of the resistivity measurements shown in the Results section.

Time-lapse Electrical Resistivity Tomography (ERT)

- Two electrodes inject direct current into the subsurface, two electrodes measure the resulting electric potential
- Varying the distance between electrodes gives different depths of investigation
- A 72 electrode Wenner array with 1m spacing and a Lippman 4point light 10W resistivity meter was employed
- The programmed measurement sequence ran once per day, **measurements were later averaged by week**
- The open-source Python package PyGIMLI [4] was used to invert the data and create the tomography images

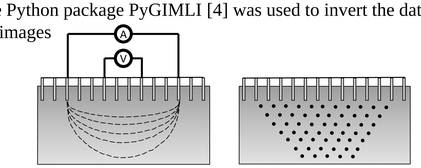

Figure 3: Schematic of a single resistivity measurement (left) and the "apparent" locations of all measurements of an array (right)

III. Results

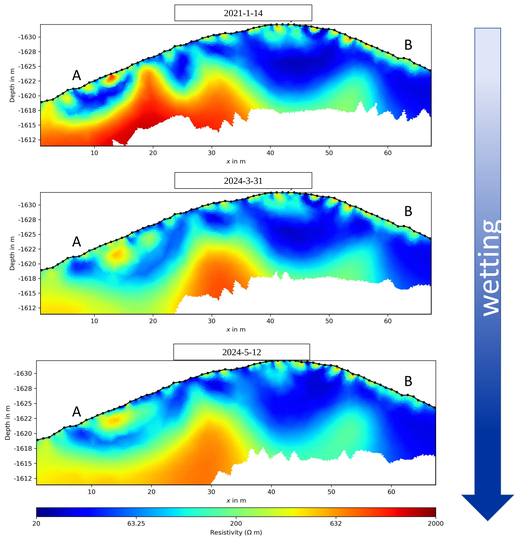

Figure 4: Three inverted resistivity measurements during the wetting period of the 2024 water year. The slope labeled 'A" faces northeast, the slope labeled 'B" faces southwest

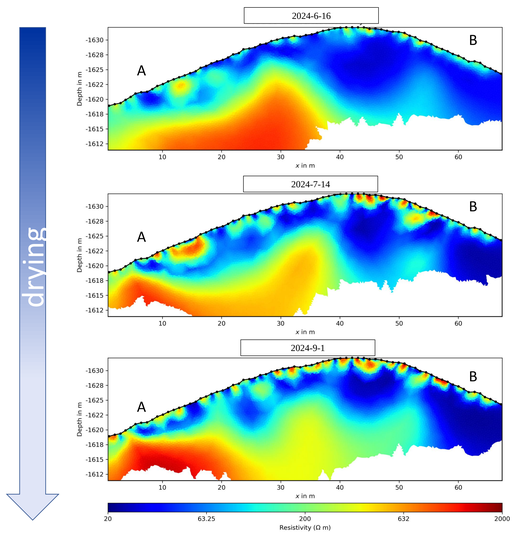

Figure 5: Three inverted resistivity measurements during the drying period of the 2024 water year. The slope labeled 'A' faces northeast, the slope labeled 'B' faces southwest

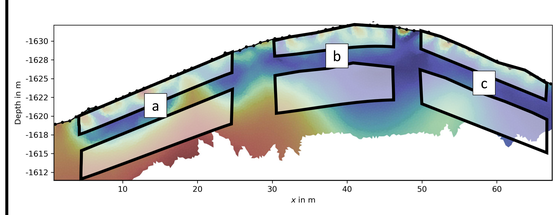

Figure 6: The locations used to create the resistivity timelines. Depth ranges are 0m-2m and 5m-10m. All the resistivity values within a boundary were averaged to create a single, bulk resistivity timeline for each bounded area.

Estimate Saturation with Archie's Law

- Archies Law relates resistivity and degree of saturation of porous media [5]:

$$\rho = \rho_w \phi^{-m} S^{-n}$$

ρ_w – resistivity of porewater (Ωm)
ϕ – porosity
S – saturation (saturated fraction of pore spaces)
m, n – fitting parameters

- Assume the minimum resistivity corresponds to the maximum saturation:

$$\rho_{min} = \rho_w \phi^{-m} S_{max}{}^{-n}$$

- Use ρ_{min} as a reference and take the ratio:

$$\frac{\rho}{\rho_{min}} = \left(\frac{S}{S_{max}}\right)^{-n} \rightarrow \frac{S}{S_{max}} = \left(\frac{\rho}{\rho_{min}}\right)^{-\frac{1}{n}}$$

$$S_{max} \approx 1 \rightarrow S = \left(\frac{\rho}{\rho_{min}}\right)^{-\frac{1}{n}}$$

Depth (m)	n
0m-2m	[1.5, 1.9]
5m-10m	[2, 2.2]

Table 1: range of n values used to calculate the saturation of the subsurface [5]

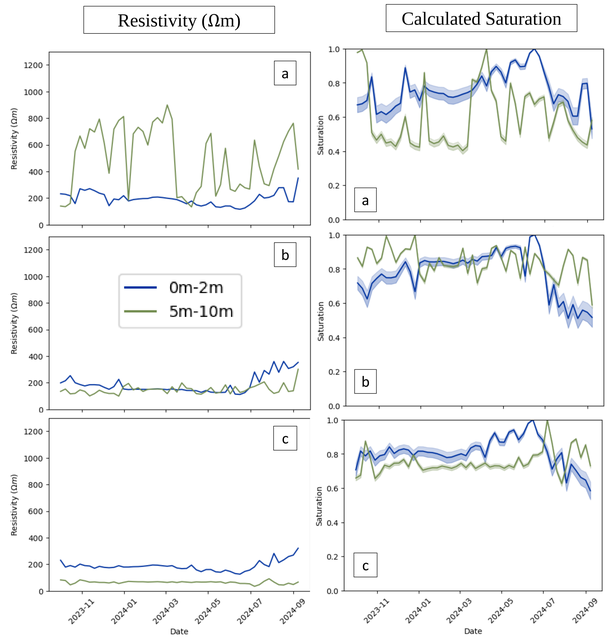

Figure 7: Timelines of resistivity (left column) and calculated saturation (right column) from the subsurface domains outlined in Figure 6. The saturation was calculated of the range of n values in Table 1. The plot of saturation shows the average (solid line) and the standard deviation (shading)

Key Takeaways

1) NE and SW slopes exhibit different spatial distributions of saturation
2) Temporal decoupling of shallow soil moisture and deep rock moisture
3) Timelapse ERT measurements make good observations of weekly long-term trends in subsurface water

IV. Discussion/Conclusions

Insights from Previous Studies at Treeline Site

- An adjacent hillslope was studied in [2]
- Regolith thickness ranges from <0.2m-2m
- Fractured/weathered bedrock thickness ranges from 0.2m-45m
- Northern-facing slopes have more vegetation

Spatial Trends

Northeast slope (A):

- Irregular resistivity/saturation along slope
- Significant infiltration only reaches 5m-10m depth

Southwest slope (B):

- Uniform resistivity/saturation along slope
- Uppermost 0-2m of soil has higher resistivity but higher saturation than the bedrock

Temporal Trends

- Soil moisture on both slopes follows expected wetting and drying trends
- Rock moisture in northeast slope exhibits large variations in saturation while southwest slope is steadier
- Soil and rock moisture is decoupled on both slopes

Week of S_{max}

	NE Slope	Top	SW Slope
Shallow [0m,2m]	June 16, 2024	May 26, 2024	June 16, 2024
Deep [5m,10m]	April 7, 2024	May 26, 2024	July 7, 2024
Lag Time	-10 weeks	~0 weeks	+3 weeks

Table 2: Week of peak saturation for each subsurface location. The lag time is reported as (+) if the shallow location leads and (-) if the deep location leads

V. Future Work

Near-Surface Geophysics

- Seismic refraction tomography survey
- Drone-based electromagnetic survey
- Spatial distribution of regolith depth
- Thickness of weathering front

Conceptual Model of Rock Moisture

- Physical vs chemical weathering
- Holding mechanism of weathered rocks

Figure 8: Skye downloads data from the ERT instrument in September 2024

Hydrologic Modeling

- Incorporate rock moisture spatial and temporal mechanisms

References
[1] Rempe and Dietrich (2018). Direct observations of rock moisture, a hidden component of the hydrologic cycle. Proceedings of the National Academy of Sciences, 115(11), 2664–2669
[2] Chen et al. (2023). Geophysics-Informed Hydrologic Modeling of a Mountain Headwater Catchment for Studying Hydrological Partitioning in the Critical Zone. Water Resources Research, 59(12)
[3] Kraft and McNamara (2022). Evapotranspiration across the rain–snow transition in a semi-arid watershed. Hydrological Processes, 36(3), e14519.
[4] Rücker et al. (2017). pyGIMLi: An open-source library for modelling and inversion in geophysics, Computers and Geosciences, 109, 106-123
[5] Archie (1942). The electrical resistivity log is an aid in determining some reservoir characteristics. Transactions of the AIME, 146(01), 54–62.

Acknowledgements
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Abstract